Evaluation of the Current Resistance Factors for High-Strength Bolts

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ABSTRACT

To investigate the possibility of a more economical design of bolted connections, a large quantity of high-strength structural bolts were tested. The current resistance factor in ANSI/AISC 360-05 is 0.75 for structural bolts in tension and shear, which is believed to be conservative and based on insecurities about the estimate of loads on fasteners and on ductility concerns rather than on statistical analyses. A total of 1533 structural bolts, consisting of four different bolt grades and six different diameters, up to five inches in length, were tested in direct tension and shear with the threads excluded and not excluded from the shear plane. Resistance factors, based on reliability indices and statistical reduction, were calculated from data reported in literature and from the bolts tested. Based on the test data, some conclusions on dimensions, strength, and strength ratios were made. After a statistical reduction of the results, an increase of the resistance factor is recommended.

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CHAPTER 1

INTRODUCTION

Currently, in the steel industry, structural connections can be made using either welds or structural bolts. Welds are mostly used when the fabrication takes place in the shop whereas bolts are used more commonly in the field. According to the Commentary for Section J1.10 of the AISC Specification for Structural Steel Buildings (2005), “pretensioned bolts, slip-critical bolted connections, or welds are required whenever connection slip can be detrimental to the performance of the structure or there is a possibility that nuts will back off. Snug-tightened high-strength bolts are recommended for all other connections.”

Before the 1950s connections were primarily constructed using rivets. In connections where slip was to be prevented, the use of rivets was problematic (Kulak 2005). High-strength bolts became available during the 1950s. At that time rivets became less common since the “installation of rivets required more equipment and manpower” (Kulak 2005). Besides the installation of rivets having its disadvantages, high-strength bolts also offered more strength. A plot of stress versus strain of a coupon taken from rivets and high-strength bolts is shown in Figure 1-1 (Kulak 2005). Other advantages high-strength bolts have over rivets include: greater friction gripping, faster erection, less erection noise, reduced fire risk, and improved inspection (Munse 1976).

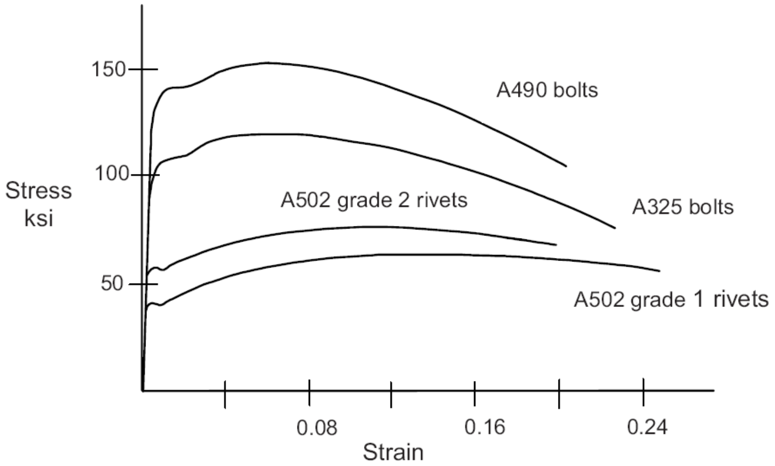

Figure 1-1: Stress vs. Strain of Coupons from Rivets and Bolts (Kulak 2005)

Research on high-strength bolts was performed starting in the 1930s. “The possibility of using high-preload bolts in steel-framed construction was first demonstrated by Batho and Bateman in their report included in the publication of the second report of the Steel Structures Research Committee in 1934” (Fisher and Beedle 1967). Batho and Bateman found “that bolts having a yield strength of at least 54 ksi could be pretensioned sufficiently to prevent slip of connected material” (Kulak 2005).

In 1947 the Research Council on Riveted and Bolted Structural Joints was formed. They were the main drive for the rapid development of high-strength bolts in the United States. “The American Society of Testing Materials (ASTM) in conjunction with the Research Council prepared a tentative specification for the materials for high-strength bolts, a specification which was approved in 1949 and revised in 1951 under ASTM designation A325” (Fisher and Beedle 1967). The use of high-strength structural fasteners started becoming more favorable in steel connections after the 1950s.

High-strength bolts are an important method for assembling steel structures and millions were used every year in the 1970s (Munse 1976). For example one million high-strength fasteners were used in the erection of a 526 foot building at the John F. Kennedy Space Center (Munse 1976). In 1974 it was estimated that over 50 million high-strength bolts were used in the United States (Munse 1976).

When designing bolted connections today engineers are required by the specification to account for only 75% of the bolt's tension or shear strength based on Load and Resistance Factor Design (AISC 2005). In other words, the current resistance factor is a conservative value of 0.75 for the tensile and shear strength of both A325 and A490 structural bolts (AISC 2005). Since only 75% of the fastener's strength is used in the design of connections with structural bolts, they can be more costly than welded connections given that more bolts are needed to meet the required capacity.

Instead of the resistance factor of 0.75 being based purely on statistical analyses, it is believed that this conservative value is based more on uncertainties on the determination of loads on fasteners combined with questions on their ductility. This is particularly true of A490 fasteners. "Connection design is a vital part in the structural design process because improperly designed connections may fail prematurely or they may deform excessively under low loads, thereby rendering the structure unfit for use. Conversely, overdesigned connections may be grossly inefficient and expensive" (Galambos and Ravindra 1975). To ensure a more economical design of bolted connections, the main goal of this research project is to provide a more accurate statistical basis for the calibration of resistance factors for high-strength fasteners using modern materials. This project was sponsored by the Research Council on Structural Connections (RCSC).

1.1 Objective

The primary objective of this project is to recalibrate the current resistance factor for high-strength fasteners based on tests of a meaningful, statistical population of A325, F1852, A490, and F2280 bolts in both direct tension and shear. Past research on tension and shear of structural bolts will also be examined when determining a recommended resistance factor. Resistance factors will be calculated based on reliability indices and statistical reduction. The ductility of A325, F1852, A490, and F2280 fasteners will also be investigated.

With an increased resistance factor, bolted connections have the potential to become more competitive with respect to welded connections, since a higher percentage of the structural bolt's tensile and shear strength can be accounted for while designing. With a higher resistance factor in the specification, a lower number of bolts would be required in each connection which can represent significant savings in the overall cost of a project.

1.2 Outline

This report is broken down into six major chapters. The present chapter serves as an introduction, discussing goals, objectives, and scope of work. Chapter Two will discuss the background. Included in that chapter will be a background of the Load and Resistance Factor Design (LRFD) philosophy. Also, incorporated in Chapter Two are the equations required to calculate resistance factors and the process used to determine the number of structural bolts to be tested for a statistical analysis. Chapter Three contains a literature review. Chapter Four contains the test methods used for testing in direct tension and shear, including the American Society for Testing and Materials (ASTM) Standards. The data obtained from the tension and shear tests are presented in Chapter Five. Chapter Six contains conclusions and recommendations. There are also three appendices. Appendix A incorporates tables showing all of the tension and shear data of the tests performed. Example calculations for the resistance factor are found in Appendix B. Appendix C contains the material data sheets which were obtained for most of the A325, F1852, A490, and F2280 bolts tested.

CHAPTER 2

PROJECT BACKGROUND

This chapter consists of the project background. It starts with an extensive discussion on the manufacturing of bolts in the United States including their availability and distribution. The background of the Load and Resistance Factor Design (LRFD) as well as the calculations required to determine the resistance factor follows. Lastly, this chapter includes the method used to determine the number of bolts to be tested for a statistical analysis.

2.1 Development of Bolts

The three most commonly used structural bolts are (1) A307 grade A carbon steel bolts (2) A325 high-strength steel bolts and (3) A490 high-strength alloy steel bolts. There are also two grades of tension control high-strength structural bolts that correspond to A325 and A490 which are F1852 and F2280, respectively. The carbon steel bolts, A307, are "primarily used in light structures, subjected to static loads" (Kulak et al. 2001) and will not be considered in this research.

ASTM A325 (2004) "covers two types of quenched and tempered steel heavy hex structural bolts having a minimum tensile strength of 120 ksi for sizes 1.0 in. and less and 105 ksi for sizes over 1.0 to 1-1/2 in., inclusive".[1] Typically, A325 bolts are supplied as plain or galvanized. The two types of A325 bolts are denoted by chemical composition. Type 1 is made of a medium carbon, carbon boron, or medium carbon alloy steel whereas Type 3 is made from a weathering steel. Type 3 bolts are distinguished by underlining the "A325" on the bolt head as shown in Figure 2-1 (RCSC 2004). Medium carbon alloy steel with copper, nickel, and chromium additions make up the chemical composition of Type 3 A325 bolts for weathering purposes.

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[1] According to ASTM A325 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

Type 3 A325 bolts are used mostly in structures when connecting weathering steel (Kulak 2005). Type 3 bolts are used generally in outdoor structures where the bolts are subjected to corrosion such as bridges or stadiums. Type 2 was withdrawn in November 1991 (ASTM 325-04b).

Figure 2-1: Head Marking for A325 Type 3 (RCSC 2004)

Structural bolts of grade A490 comprise two types of quenched and tempered alloy steel and have a tensile strength of 150 to 173 ksi[2]. The A490 bolts were developed for use with high-strength steel members (Kulak et al. 2001). A490 bolts are manufactured in diameters from 1/2-inch to 1-1/2-inches. Unlike A325 bolts, A490 bolts are only permitted to be supplied with a plain finish, meaning they can not be galvanized. The two types of A490 bolts are also designated by chemical composition, like A325. Type 1 is made from medium carbon alloy steel and Type 3 is produced from weathering steel (ASTM A490-04a). Like A325, Type 3 is distinguished by the line under "A490" on the bolt head as shown in Figure 2-2 (RCSC 2004). A490 Type 3 fasteners are used for the same purposes as A325 Type 3 bolts, as previously discussed. Type 2 was withdrawn in 2002 from ASTM A490 (ASTM A490-04a).

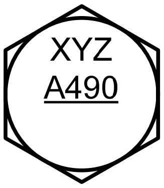

Figure 2-2: Head Marking for A490 Type 3 (RCSC 2004)

To prevent embrittlement in structural bolts, a limit of 200 ksi tensile strength is set. If the tensile strength is higher than 200 ksi, the bolts "are subject to embrittlement if hydrogen is permitted to remain in the steel and the steel is subjected to high tensile stress" (RCSC 2004). The tensile strength for A325 bolts is 120 ksi or 105 ksi, depending on the diameter, which is

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[2] RCSC states 170 ksi maximum tensile strength for A490 bolts.

well below the limit of 200 ksi. The A490 bolts have a maximum tensile strength of 173 ksi which is approximately 14% below 200 ksi (ASTM A490-04a). It should be noted that RCSC states that A490 bolts have a maximum tensile strength of 170 ksi which provides a 15% margin below the limit of 200 ksi (RCSC 2004). Since "manufacturers must target their production slightly higher than the required minimum, ASTM A490 bolts close to the critical range of tensile strength must be anticipated" (RCSC 2004).

Tension control bolts are similar to A325 and A490 in chemical properties but have special features pertaining to the installation. "The bolt has a splined end that extends beyond the threaded portion of the bolt and an annular groove between the threaded portion of the bolt and the splined end" (Kulak 2005), as shown in Figure 2-3 (Kulak 2005). The tension control bolt shown in Figure 2-3 (Kulak 2005) has a round head, also known as a button or dome head. However, tension control bolts can also have a heavy hex head like an A325 or A490 bolt. Tension control bolts are produced in diameters from 1/2- to 1-1/8-inch. Like A325 and A490 structural bolts, tension control bolts also come in two types. Tension control bolts with ASTM Specification F1852 correspond to an A325 bolt and have a minimum tensile strength of 120 ksi for diameters smaller than and including 1 inch and a minimum tensile strength of 105 ksi for diameter of 1-1/8-inches (ASTM F1852 -05)[3]. Type 1 is manufactured from plain carbon, carbon boron, or alloy steel and Type 3 is made from weathering steel for an F1852 bolt. ASTM Specification F2280 corresponds to an A490 structural bolt which has a required tensile strength of 150 to 173 ksi (ASTM F2280-06). Like A490, F2280 Type 1 is made from alloy steel and Type 3 is made from weathering steel.

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[3] According to ASTM F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

Figure 2-3: Tension Control Bolt (Kulak 2005)

The chemical composition, manufacturing process, and dimensions will be discussed in the next few sections.

2.1.1 Chemical Composition of Structural Bolts

Steel is produced by purifying pig iron and introducing "impurities in the form of alloys to impart the desired characteristics" (Pollack 1988). Carbon steels are categorized into three categories. Low-carbon steels have carbon ranging from 0 to 0.25 percent, medium carbon steels typically have carbon ranging from 0.25 to 0.55 percent, and high-carbon steels typically have carbon above 0.55 percent. Boron which is found in some types of A325 and F1852 bolts increase hardenability (Pollack 1988). "Alloying has the effect of improving wear, heat corrosion, and fatigue resistance" (Pollack 1988). Adding the proper alloys to steel can increase the hardness as well as possibly increasing the strength and toughness, while machinability may also be improved (Pollack 1988).

Type 1 structural bolts made from alloy steel are more commonly used than Type 3. Table 2-1 (ASTM A325-04b; ASTM A490-04a) shows the chemical composition of A325 and A490 Type 1. Table 2-2 (ASTM F1852-05; ASTM F2280-06) shows the chemical composition of F1852 and F2280 Type 1. Type 3 structural fasteners "are made out of an alloy steel with copper, chromium, and nickel. As the surface of the steel corrodes or rusts, instead of forming a coarse, flaky rust, the Type 3 material forms a fine-textured oxide coating that tightly adheres to the base metal. This oxide coating seals the surface of the base metal from further corrosion" (Nucor Fastener Division). Table 2-3 (ASTM A325-04b; ASTM A490-04a) shows the chemical composition or A325 and A490 Type 3 bolts. The chemical composition of F1852 and F2280 Type 3 is shown in Table 2-4 (ASTM F1852-05; ASTM F2280-06).

Table 2-1: Chemical Composition for A325 and A490 Type 1 (ASTM A325-04b; ASTM A490-04a)

	A325 - Type 1				A490 Type 1
	Carbon Steel	Carbon Boron Steel	Alloy Steel	Alloy Boron Steel	
Carbon	0.30-0.52%	0.30-0.52%	0.30-0.52%	0.30-0.52%	0.30-0.48% *
Manganese, min	0.60%	0.60%	0.60%	0.60%	--
Phosphorus, max	0.040%	0.040%	0.035%	0.035%	0.040%
Sulfur, max	0.050%	0.050%	0.040%	0.040%	0.040%
Silicon	0.15-0.30%	0.10-0.30%	0.15-0.35%	0.15-0.35%	--
Boron	--	0.0005-0.003%	--	0.0005-0.003%	--
Alloying Elements	--	--	†	†	†

* For diameter of 1½" the required carbon content is 0.35-0.53%

† Steel, as defined by the American Iron and Steel Institute, shall be considered to be alloy when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: Manganese, 1.65%; silicon, 0.60%; copper, 0.60% or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recongnized field of contructional alloy steels: aluminum, chromium up to 3.99%, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying elements added to obtain a desired alloying effect.

Table 2-2: Chemical Composition for F1852 and F2280 Type 1 (ASTM F1852-05; ASTM F2280-06)

	F1852 - Type 1			F2280 Type 1
	Carbon Steel	Carbon Boron Steel	Alloy Steel	
Carbon	0.30-0.52%	0.30-0.52%	0.30-0.52%	0.30-0.48%
Manganese, min	0.60%	0.60%	0.60%	--
Phosphorus, max	0.040%	0.040%	0.035%	0.040%
Sulfur, max	0.050%	0.050%	0.040%	0.040%
Silicon	0.15-0.30%	0.10-0.30%	0.15-0.35%	--
Boron	‡	0.0005-0.003%	‡	--
Alloying Elements	--	--	†	†

* For diameter of 1½" the required carbon content is 0.35-0.53%

† Steel, as defined by the American Iron and Steel Institute, shall be considered to be alloy when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: Manganese, 1.65%; silicon, 0.60%; copper, 0.60% or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recongnized field of contructional alloy steels: aluminum, chromium up to 3.99%, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying elements added to obtain a desired alloying effect.

‡ Heats of steel which boron has been intentionally added shall not be permitte

Table 2-3: Chemical Composition for A325 and A490 Type 3 (ASTM A325-04b; ASTM A490-04a)

	A325 - Type 3 *						A490 Type 3
	A	B	C	D	E	F	
Carbon	0.33-0.40%	0.38-0.48%	0.15-0.25%	0.15-0.25%	0.20-0.25%	0.20-0.25%	0.20-0.53% **
Manganese	0.90-1.20%	0.70-0.90%	0.80-1.35%	0.40-1.20%	0.60-1.00%	0.90-1.20%	0.40% min
Phosphorus	0.035% max	0.06-0.12%	0.035% max	0.035% max	0.035% max	0.035% max	0.035% max
Sulfur	0.040% max	0.040% max	0.040% max	0.040% max	0.040% max	0.040% max	0.040% max
Silicon	0.15-0.35%	0.30-0.50%	0.15-0.35%	0.25-0.50%	0.15-0.35%	0.15-0.35%	--
Copper	0.25-0.45%	0.20-0.40%	0.20-0.50%	0.30-0.50%	0.30-0.60%	0.20-0.40%	0.20-0.60%
Nickel	0.25-0.45%	0.50-0.80%	0.25-0.50%	0.50-0.80%	0.30-0.60%	0.20-0.40%	‡
Chromium	0.45-0.65%	0.50-0.75%	0.30-0.50%	0.50-1.00%	0.60-0.90%	0.45-0.65%	0.45% min
Vanadium	†	†	0.020% min	†	†	†	--
Molybdenum	†	0.06% max	†	0.10% max	†	†	‡
Titanium	†	†	†	0.05% max	†	†	--

* A, B, C, D, E, and F are classes of material used for Type 3 bolts. Selection of a class shall be at the option of the bolt manufacturer

** For sizes larger than 0.75 inch (not including 0.75 inch) 0.30-0.53%

† These elements are not specified or required.

‡ Either 0.20% minimum nickel or 0.15% minimum molybdenum

Table 2-4: Chemical Composition for F1852 and F2280 Type 3 (ASTM F1852-05; ASTM F2280-06)

	F1852 - Type 3						F2280 Type 3
	A	B	C	D	E	F	
Carbon	0.33-0.40%	0.38-0.48%	0.15-0.25%	0.15-0.25%	0.20-0.25%	0.20-0.25%	0.20-0.53% **
Manganese	0.90-1.20%	0.70-0.90%	0.80-1.35%	0.40-1.20%	0.60-1.00%	0.90-1.20%	0.40% min
Phosphorus	0.040% max	0.06-0.12%	0.035% max	0.040% max	0.040% max	0.040% max	0.035% max
Sulfur	0.050% max	0.050% max	0.040% max	0.050% max	0.040% max	0.040% max	0.040%
Silicon	0.15-0.35%	0.30-0.50%	0.15-0.35%	0.25-0.50%	0.15-0.35%	0.15-0.35%	--
Nickel	0.25-0.45%	0.50-0.80%	0.25-0.50%	0.50-0.80%	0.30-0.60%	0.20-0.40%	‡
Copper	0.25-0.45%	0.20-0.40%	0.20-0.50%	0.30-0.50%	0.30-0.60%	0.20-0.40%	0.20-0.60%
Chromium	0.45-0.65%	0.50-0.75%	0.30-0.50%	0.50-1.00%	0.60-0.90%	0.45-0.65%	0.45-0.90%
Vanadium	†	†	0.020% min	†	†	†	--
Molybdenum	†	0.06% max	†	0.10% max	†	†	‡
Titanium	†	†	†	0.05% max	†	†	--

* Designations A, B, C, D, E, and F are classes of material used for Type 3 tension control bolts. Selection of a class shall be at the option of the bolt manufacturer

** For sizes 7/8" to 1-1/8" 0.30-0.53%

† These elements are not specified or required. They shall be present only as residuals.

‡ Either 0.20-0.60% nickel or 0.15-0.25% molybdenum

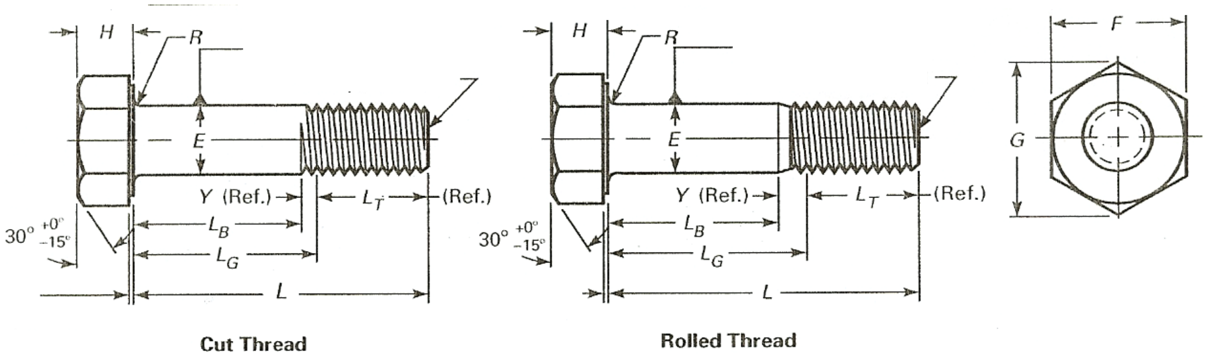
Alloying elements shown in the past few tables have various effects on fasteners, as explained below. Chromium is found in all Type 3 bolts (A325, F1852, A490 and F2280). Chromium has a moderate effect on the hardenability of the steel and contributes to resisting corrosion and abrasion (Pollack 1988). Also found in some bolts made from weathering steel (Type 3) is molybdenum which has a strong effect on hardenability and adds abrasion resistance (Pollack 1988). Another element that is added to Type 3 (weathering steel) fasteners is copper. According to Pollack (1988), copper improves resistance to corrosion. Vanadium is found only in A325-III-C and F1852-III-C: it has a strong effect on hardenability (Pollack 1988). An element that is found in every type of bolt is phosphorus which increases hardenability and improves machinability (Pollack 1988). Lastly, silicon which is found only in A325 and F1852 Type I bolts has a moderate effect on hardenability (Pollack 1988).

2.1.2 Bolts Manufacturers

There are exactly five cold heading structural bolt manufactures in North America: Nucor Fastener Division; Unytite, Inc.; Infasco Division of Ifastgroupe; SLSB, LLC dba St. Louis Screw and Bolt; Lake Erie Products (Mike Friel, personal communication, October 9, 2006). Unytite currently only produces tension control bolts (F1852 and F2280). Besides the manufacturers in North America there are two major Asian Manufactures that export structural bolts into North America. The two Asian companies are Korea Bolt of South Korea and Jinn Herr which has manufacturing plants in Taiwan and China (Mike Friel, personal communication, October 9, 2006). Some of the listed manufacturers produce structural bolts for other companies. For example, “Unytite, Inc. produces private label bolts for LeJeune Bolt Company, and Korea Bolt produces private label bolts for Lohr Structural Fasteners” (Mike Friel, personal communication, October 9, 2006). There are also a few manufacturers that use the hot heading process such as Cardinal Fastener, Haydon Bolts, and BBC Fasteners, which are just a few of the larger companies (Mike Friel, personal communication, October 9, 2006).

2.1.3 Dimensions of Structural Bolts

The dimensions of A325, F1852, A490, and F2280 bolts are established in ASME B18.2.6 (2006). The basic dimensions are defined in Figure 2-4 (ASME B18.2.6 2006) for hex-head structural bolts. Table 2-5 (ASME B18.2.6 2006) lists the dimensions of heavy hex-head structural bolts. Figure 2-5 and Figure 2-6 (ASME B18.2.6 2006) depicts the basic dimensions for tension control bolts with a round head and a heavy hex head, respectively. It should be noted that Figure 2-5 (ASME B18.2.6 2006) shows a tension control bolt with cut threads. However, according to ASTM F1852 and ASTM F2280, Section 6.2, threads of tension control bolts shall be rolled. Table 2-6 and Table 2-7 (ASME B18.2.6 2006) lists the dimension of tension control bolts with a round head and a heavy hex head, respectively. Structural bolts are generally stocked up to a length of eight inches. Lengths come in 1/4-inch increments up to five inches in length and 1/2-inch increments over a length of five inches. Unlike general application bolts, heavy-hex structural bolts have the same size head as the hex nut. This allows the ironworker to use the same wrench or socket on the bolt head and/or the nut. To exclude the threads of structural bolts from the shear plane (which is preferable), they have a shorter threaded length when compared to general application bolts.



Cut Thread

Rolled Thread

Figure 2-4: Hex-Head Bolt Dimensions (ASME B18.2.6 2006)

Table 2-5: Dimensions for Heavy Hex Structural Bolts (ASME B18.2.6 2006)

Nominal Bolt Diameter (inches)	Body Diameter (E) (inches)		Width Across Flat (F) (inches)			Width Across Corners (G) (inches)		Height (H) (inches)			Radius of Fillet (R) (inches)		Thread Length (L_T) (inches)	Transition Thread Length (Y) (inches)
	Max	Min	Nominal	Max	Min	Max	Min	Nominal	Max	Min	Max	Min	Reference	Reference
1/2	0.515	0.482	7/8	0.875	0.850	1.010	0.969	5/16	0.323	0.302	0.031	0.009	1.00	0.19
5/8	0.642	0.605	1 1/16	1.062	1.031	1.227	1.175	25/64	0.403	0.378	0.062	0.021	1.25	0.22
3/4	0.768	0.729	1 1/4	1.250	1.212	1.443	1.383	15/32	0.483	0.455	0.062	0.021	1.38	0.25
7/8	0.895	0.852	1 7/16	1.438	1.394	1.660	1.589	35/64	0.563	0.531	0.062	0.031	1.50	0.28
1	1.022	0.976	1 5/8	1.625	1.575	1.876	1.796	39/64	0.627	0.591	0.093	0.062	1.75	0.31
1 1/8	1.149	1.098	1 13/16	1.812	1.756	2.093	2.002	11/16	0.718	0.658	0.093	0.062	2.00	0.34
1 1/4	1.277	1.223	2	2.000	1.938	2.309	2.209	25/32	0.813	0.749	0.093	0.062	2.00	0.38
1 3/8	1.404	1.345	2 3/16	2.188	2.119	2.526	2.416	27/32	0.878	0.810	0.093	0.062	2.25	0.44
1 1/2	1.531	1.470	2 3/8	2.375	2.300	2.742	2.622	15/16	0.974	0.902	0.093	0.062	2.25	0.44

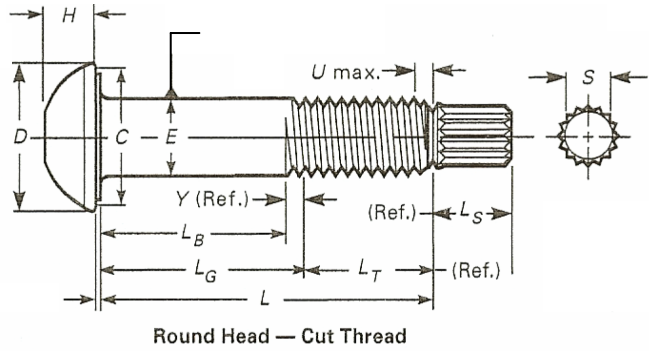


Figure 2-5: Tension Control Bolt Dimensions with Round Head (ASME B18.2.6 2006)

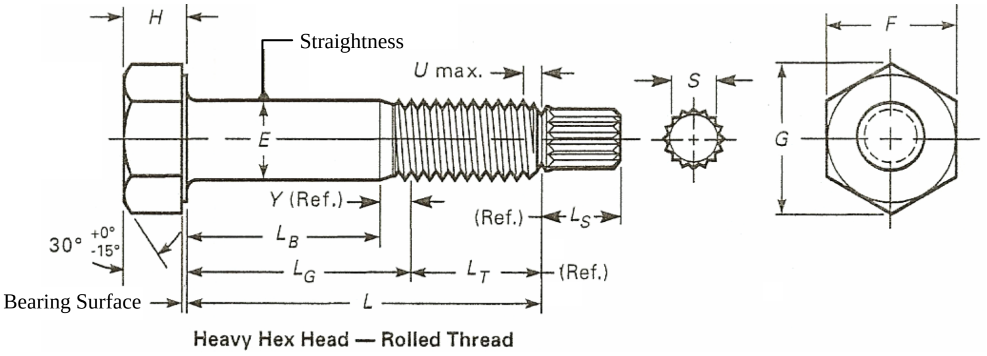


Figure 2-6: Tension Control Bolt Dimensions with Heavy Hex Head (ASME B18.2.6 2006)

Table 2-6: Dimensions for Tension Control Structural Bolts with Round Head (ASME B18.2.6 2006)

Nominal Bolt Diameter (inches)	Head Height (H) (inches)		Body Diameter (E) (inches)		Bearing Diameter (C) (inches)	Head Diameter (D) (inches)	Thread Length (L_T) (inches)	Spline Length (L_S) (inches)	Spline Width Across Flats (S) (inches)	Center of Groove to First Fully Formed Thread (U) (inches)	Transition Thread Length (Y) (inches)
	Max	Min	Max	Min	Min	Max	Reference	Reference	Reference	Max	Reference
1/2	0.323	0.302	0.515	0.482	0.890	1.126	1.00	0.50	0.32	0.192	0.19
5/8	0.403	0.378	0.642	0.605	1.102	1.313	1.25	0.60	0.43	0.227	0.22
3/4	0.483	0.455	0.768	0.729	1.338	1.580	1.38	0.65	0.53	0.250	0.25
7/8	0.563	0.531	0.895	0.852	1.535	1.880	1.50	0.72	0.61	0.278	0.28
1	0.627	0.591	1.022	0.976	1.771	2.158	1.75	0.80	0.70	0.313	0.31
1 1/8	0.718	0.658	1.149	1.098	1.991	2.375	2.00	0.90	0.80	0.367	0.34
1 1/4	0.813	0.749	1.277	1.223	2.213	2.760	2.00	1.00	0.90	0.367	0.38
1 3/8	0.878	0.810	1.404	1.345	2.434	2.910	2.25	1.10	1.00	0.417	0.44
1 1/2	0.974	0.902	1.531	1.470	2.655	3.160	2.25	1.20	1.10	0.417	0.44

Note: This table is from ASME B18.2.6 however ASTM F1852 and F2280 specifies that tension

Table 2-7: Dimensions for Tension Control Structural Bolts with Heavy Hex Head (ASME B18.2.6 2006)

Nominal Bolt Diameter (inches)	Width Across Flat (F) (inches)		Width Across Corners (G) (inches)		Head Height (H) (inches)		Body Diameter (E) (inches)		Thread Length (L_T) (inches)	Spline Length (L_S) (inches)	Spline Width Across Flats (S) (inches)	Center of Groove to First Fully Formed Thread (U) (inches)	Transition Thread Length (Y) (inches)
	Max	Min	Max	Min	Max	Min	Max	Min	Reference	Reference	Reference	Max	Reference
1/2	0.875	0.850	1.010	0.969	0.323	0.302	0.515	0.482	1.00	0.50	0.32	0.192	0.19
5/8	1.062	1.031	1.227	1.175	0.403	0.378	0.642	0.605	1.25	0.60	0.43	0.227	0.22
3/4	1.250	1.212	1.443	1.383	0.483	0.455	0.768	0.729	1.38	0.65	0.53	0.250	0.25
7/8	1.438	1.394	1.660	1.589	0.563	0.531	0.895	0.852	1.50	0.72	0.61	0.278	0.28
1	1.625	1.575	1.876	1.796	0.627	0.591	1.022	0.976	1.75	0.80	0.70	0.313	0.31
1 1/8	1.812	1.756	2.093	2.002	0.718	0.658	1.149	1.098	2.00	0.90	0.80	0.367	0.34
1 1/4	2.000	1.938	2.309	2.209	0.813	0.749	1.277	1.223	2.00	1.00	0.90	0.367	0.38
1 3/8	2.188	2.119	2.526	2.416	0.878	0.810	1.404	1.345	2.25	1.10	1.00	0.417	0.44
1 1/2	2.375	2.300	2.742	2.622	0.974	0.902	1.531	1.470	2.25	1.20	1.10	0.417	0.44

Note: This table is from ASME B18.2.6 however ASTM F1852 and F2280 specifies that tension

To clarify a few of the dimensions in the previous tables a brief explanation of some of the items will now be given. The head height, H, for heavy hex structural bolts and for tension control bolts, is the distance from the top of the head to the bearing surface measured parallel to the axis of the bolt and shall include the thickness of the washer face. The head height shall exclude the raised grade and manufacturer's identification.

The body diameters for heavy hex structural bolts and for tension control bolts were given in Table 2-5, Table 2-6, and Table 2-7. According to ASME B18.2.6 (2006), "any swell or fin under the head or any die seam on the body shall not exceed the basic bolt diameter" by the following:

(a) 0.030 inch for sizes 1/2-inch

(b) 0.050 inch for sizes 5/8-inch and 3/4-inch

(c) 0.060 inch for sizes over 3/4-inch through 1-1/4-inch

(d) 0.090 inch for sizes over 1-1/4-inch

The bolt length for heavy hex structural bolts is the distance from the bearing surface of the head to the extreme end of the bolt including the point measured parallel to the axis of the fastener. The distance from the bearing surface of the bolt head to the center point of the groove measured parallel to the axis of the bolt is the bolt length for tension control bolts. According to ASME B18.2.6 (2006) the bolt length has tolerances as shown in Table 2-8 (ASME B18.2.6 2006) for both heavy hex structural bolts and for tension control bolts.

Table 2-8: Length Tolerance for Heavy Hex and Tension Control Bolts (ASME B18.2.6 2006)

Nominal Bolt Diameter (inches)	Nominal Bolt Length Tolerance (inches)	
	Through 6 inch length	Over 6 inch length
1/2	-0.12	-0.19
5/8	-0.12	-0.25
3/4 through 1	-0.19	-0.25
1 1/8 though 1 1/2	-0.25	-0.25

From Table 2-5 (ASME B18.2.6 2006), Table 2-6 (ASME B18.2.6 2006), and Table 2-7 (ASME B18.2.6 2006), the thread length, L_T, was stated to be a reference dimension. The thread length is measured from the extreme end of a fastener to the last complete thread for a heavy hex structural bolt. For a tension control bolt the thread length is the distance from the center point of the groove to the last complete thread. According to ASME B18.2.6 (2006), the thread length is intended for calculation purposes only and is controlled by the grip gaging length (L_G from the previous figures) and the body length (L_B from the previous figures). The grip gaging length, L_G, is a criterion for inspection and is the distance “from the underhead bearing surface to the face of a noncounterbored or noncountersunk standard GO thread ring gage , assembled by hand as far as the thread will permit” (ASME B18.2.6 2006) measured parallel to the axis of the fastener. A noncounterbored or noncountersunk standard GO thread ring gage is a ring gage, as shown in Figure 2-7 (Thread Check Inc. 2007), that has the countersink/chamfer grounded off (Roger Hamilton, personal communication, July 27, 2007). The maximum grip gaging length for bolts not fully threaded, reported to the hundredths, is calculated as the nominal bolt length minus the thread length $\left(L_{G,\,max} = L_{nominal} - L_T\right)$ (ASME B18.2.6 2006). The maximum grip gaging length "represents the minimum design grip length of the bolt and may be used for determining thread availability when selecting bolt lengths even though usable threads may extend beyond this point" (ASME B18.2.6 2006). This means that the thread length, L_T, may be longer than the reference value tabulated previously, which could cause problems when designing a bolt in shear. The body length, L_B, from the previous figures, is the distance from the underhead bearing surface of the fastener to the last scratch of the threads for cut threads or to the top of the extrusion angle for rolled threads measured parallel to the axis of the bolt. Like the grip gaging length, the body length is a criterion for inspection. The maximum grip gaging length minus the transition thread length, Y, $\left(L_{B,\,min} = L_{G,\,max} - Y\right)$, gives the minimum body length for structural bolts, which is reported to two decimal places (ASME B18.2.6 2006). The transition thread length, Y, is a reference dimension, that "represents the length of incomplete threads and tolerance on grip gaging length" (ASME B18.2.6 2006). The transition thread length is only intended for calculation purposes. The maximum grip gaging lengths and the minimum body lengths for heavy hex structural bolts are shown in Table 2-9 (ASME B18.2.6 2006).

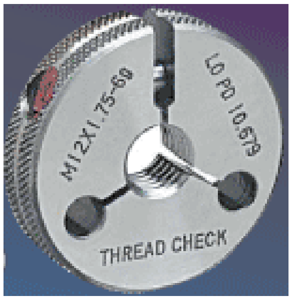


Figure 2-7: Non-Ground Ring Gage (Thread Check Inc. 2007)

Table 2-9: Minimum Grip Gaging and Minimum Body Lengths (ASME B18.2.6 2006)

Nominal Length (L) (inches)	Nominal Diameter (inches)																	
	1/2		5/8		3/4		7/8		1		1 1/8		1 1/4		1 3/8		1 1/2	
	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)	L_G Max (in.)	L_B Min (in.)
1 1/2	0.50	0.31	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1 3/4	0.75	0.56	0.50	0.28	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2	1.00	0.81	0.75	0.53	0.62	0.38	--	--	--	--	--	--	--	--	--	--	--	--
2 1/4	1.25	1.06	1.00	0.78	0.88	0.62	0.75	0.47	--	--	--	--	--	--	--	--	--	--
2 1/2	1.50	1.31	1.25	1.03	1.12	0.88	1.00	0.72	0.75	0.44	--	--	--	--	--	--	--	--
2 3/4	1.75	1.56	1.50	1.28	1.38	1.12	1.25	0.97	1.00	0.69	--	--	--	--	--	--	--	--
3	2.00	1.81	1.75	1.53	1.62	1.38	1.50	1.22	1.25	0.94	1.00	0.66	1.00	0.62	--	--	--	--
3 1/4	2.25	2.06	2.00	1.78	1.88	1.62	1.75	1.47	1.50	1.19	1.25	0.91	1.25	0.88	--	--	--	--
3 1/2	2.50	2.31	2.25	2.03	2.12	1.88	2.00	1.72	1.75	1.44	1.50	1.16	1.50	1.12	1.25	0.81	--	--
3 3/4	2.75	2.56	2.50	2.28	2.38	2.12	2.25	1.97	2.00	1.69	1.75	1.41	1.75	1.38	1.50	1.06	--	--
4	3.00	2.81	2.75	2.53	2.62	2.38	2.50	2.22	2.25	1.94	2.00	1.66	2.00	1.62	1.75	1.31	1.75	1.31
4 1/4	3.25	3.06	3.00	2.78	2.88	2.62	2.75	2.47	2.50	2.19	2.25	1.91	2.25	1.88	2.00	1.56	2.00	1.56
4 1/2	3.50	3.31	3.25	3.03	3.12	2.88	3.00	2.72	2.75	2.44	2.50	2.16	2.50	2.12	2.25	1.81	2.25	1.81
4 3/4	3.75	3.56	3.50	3.28	3.38	3.12	3.25	2.97	3.00	2.69	2.75	2.41	2.75	2.38	2.50	2.06	2.50	2.06
5	4.00	3.81	3.75	3.53	3.62	3.38	3.50	3.22	3.25	2.94	3.00	2.66	3.00	2.62	2.75	2.31	2.75	2.31

For the heavy hex structural bolts, the point (as shown in Figure 2-4) "shall be chamfered or rounded at the manufacturer's option from approximately 0.016 in. below the minor diameter of the thread" (ASME B18.2.6 2006). Tension control bolts do not need to be pointed unless otherwise specified. The distance, U, given in Table 2-6 and Table 2-7, is measured "from the center of the groove to the first fully formed thread crest and shall not exceed 2.5 times the thread pitch" (ASME B18.2.6 2006).

For heavy hex structural bolts and for tension control bolts with nominal lengths less than and including 12 inches, the camber shall be less than 0.006 inch per inch of bolt length. The maximum camber shall be 0.008 inch per inch of fastener length for bolts with nominal lengths between 12 and 24 inches.

The spline length and the width across the flats, as given in Table 2-6 and Table 2-7, are reference dimensions. The groove diameter, E_1, as shown in Figure 2-8 (ASME B18.2.6 2006), is at the discretion of the manufacturer, as well as the spline, to assure proper function of the tension control bolt. The groove diameter "is approximately equal to 80% of the thread maximum minor diameter" (ASME B18.2.6 2006).

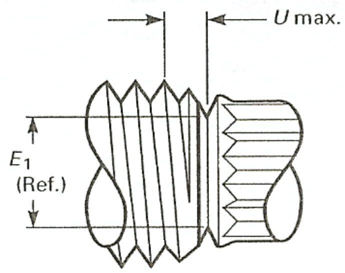


Figure 2-8: Tension Control Bolt's Groove Diameter (ASME B18.2.6 2006)

According to ASME B18.2.6 (2006), the threads on structural bolts shall be in accordance with ASME B1.1 Unified (UN) Coarse, Class 2A. Coarse refers to the thread series and distinguishes the number of threads per inch based on the diameter. The letter A is used to denote an external thread since pitch diameter tolerances are different for external and internal threads (ASME B1.1 2004). The thread class number, in this case 2, distinguishes the amount of tolerance and allowance (ASME B1.1 2004). As the class number increases the tolerance decreases (ASME B1.1 2004). Figure 2-9 (ASME B1.1 2004) shows the basic profile for UN and UNR screw threads. The pitch, P, is one divided by the number of threads per inch. The basic dimensions are shown in Table 2-10(ASME B1.1 2004).

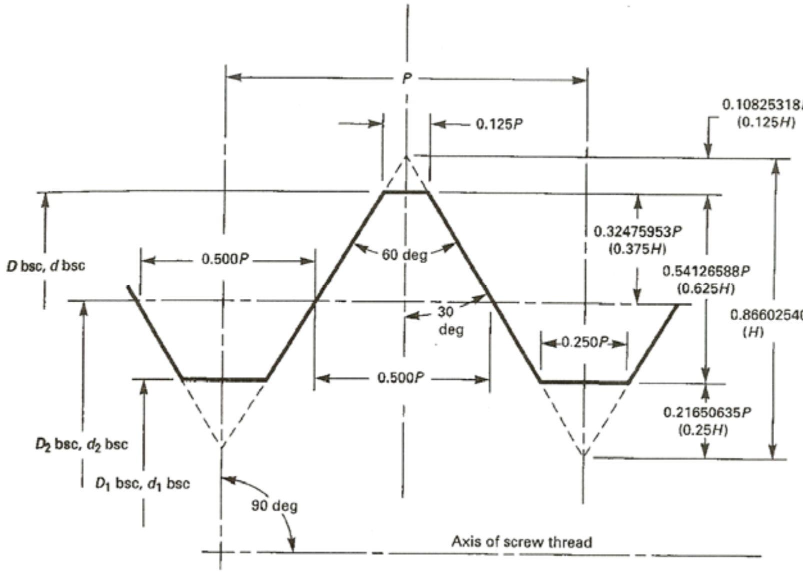


Figure 2-9: Profile for UN and UNR Screw Threads (ASME B1.1 2004)

Table 2-10: Basic Threading Dimensions for UNC/UNRC (ASME B1.1 2004)

Nominal Size (inches)	Basic Major Diameter (D) (inches)	Number of Threads per Inch	Basic Pitch Diameter (D_2) (inches)	Basic Minor Diameter (D_1) (inches)
5/8	0.625	11	0.5660	0.5266
3/4	0.750	10	0.6850	0.6417
7/8	0.875	9	0.8028	0.7547
1	1.000	8	0.9188	0.8647
1 1/8	1.125	7	1.0322	0.9704
1 1/4	1.250	7	1.1572	1.0954

The design profile for external UN and UNR screw threads is shown in Figure 2-10 (ASME B1.1 2004). For UN threads a flat root contour is specified but it is "permissible to provide for some threading tool crest wear. Therefore, a rounded root contour cleared beyond the 0.250P flat width of the basic profile is optional" (ASME B1.1 2004). A rounded root is preferred over a flat root thread because a rounded root improves fatigue strength and reduces the rate of threading tool crest wear (ASME B1.1 2004).

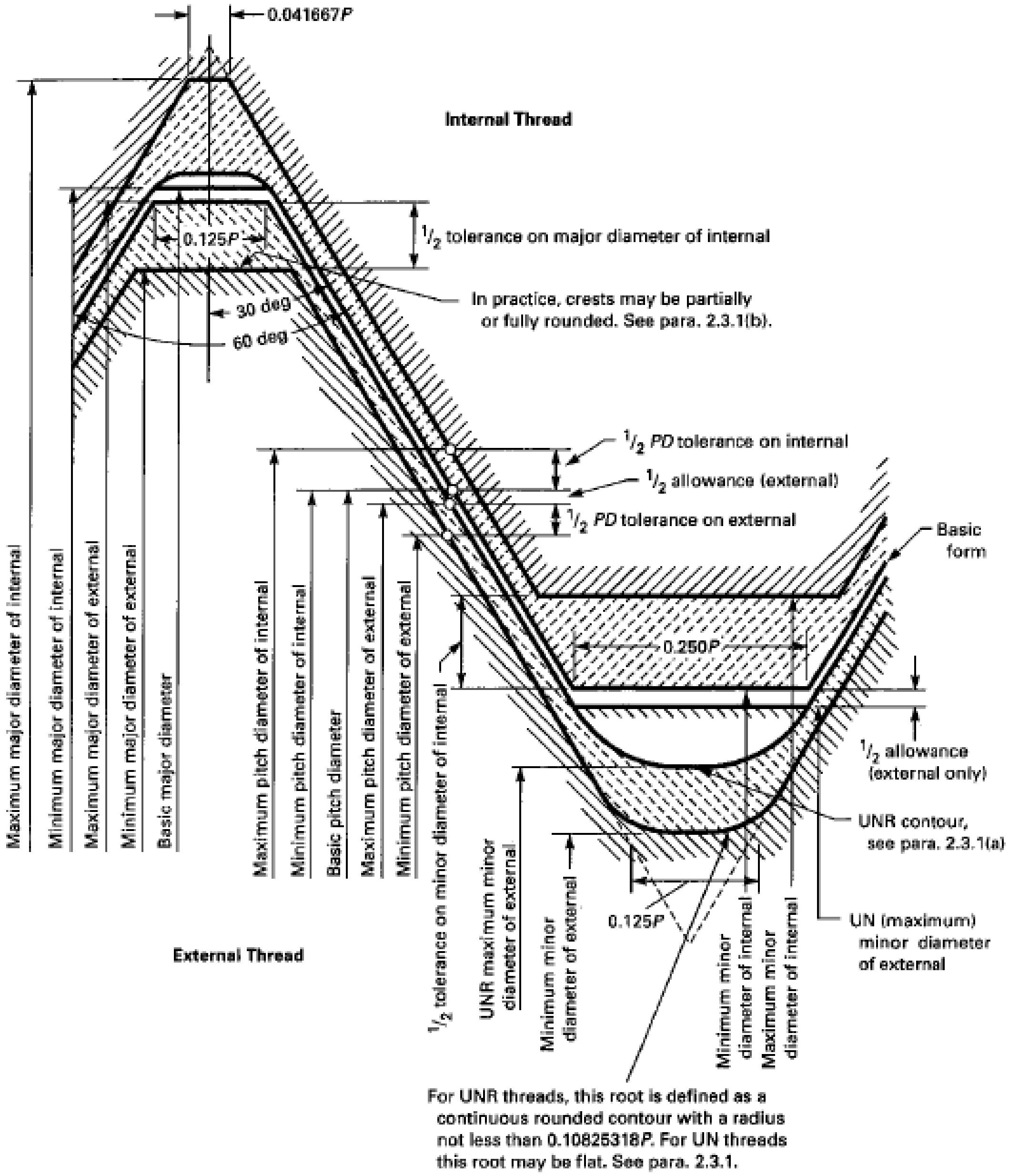


Figure 2-10: Disposition of Diametral Tolerances, Allowance, and Crest Clearance for UN and UNR Screw Threads (ASME B1.1 2004)

2.2 Tensile Strength of Structural Bolts

The tensile strength of high-strength bolts is given by the product of the bolt's ultimate tensile stress and an area calculated according to various criteria. If a failure is considered through the shank of the bolt, the cross sectional area would be given by

$$A_{shank} = \frac{\pi}{4}(d)^2 \tag{2-1}$$

where d is the nominal shank diameter.

The threads are the weakest section of any fastener in tension, therefore when calculating the tensile strength an area through the threads is required. This area is not readily apparent. One could use the minor diameter of the threads, known as the root area. The root area, A_r, is calculated as (Barron 1998)

$$A_r = \frac{\pi}{4}\left(d - \frac{1.3}{n}\right)^2 \tag{2-2}$$

where d is the nominal shank diameter and n is the number of threads per inch. The tensile strength predicted by the material and the root area underestimate the tensile strength of the fastener when compared to bolts tested in tension (Barron 1998). "An empirical formula was developed that accounts for this phenomenon" (Barron 1998). An effective area calculated from the mean of the mean root and pitch diameters is a better estimate of the threaded area (ASTM A370-05; AISC 2005; Kulak et al. 2001; Barron 1998; Wallaert and Fisher 1965). In this case

$$A_{eff} = \frac{\pi}{4}\left(d - \frac{0.9743}{n}\right)^2 \tag{2-3}$$

Table 2-11 shows the shank area, the root area, and the effective area calculated from Equations (2-1) through (2-3), respectively, for the most common sizes of high-strength structural bolts. Table 2-11 also compares the root area and effective area to the shank area.

Table 2-11: Areas of Common Size Bolts

Bolt Diameter d_b (inch)	Threads per inch	Shank Area A_{shank} (square inches)	Root Area A_r (square inches)	Effective Area A_{eff} (square inches)	Ratio of Root Area to Shank Area	Ratio of Effective Area to Shank Area
1/2	13	0.196	0.126	0.142	0.640	0.723
5/8	11	0.307	0.202	0.226	0.658	0.737
3/4	10	0.442	0.302	0.334	0.683	0.757
7/8	9	0.601	0.419	0.462	0.697	0.768
1	8	0.785	0.551	0.606	0.701	0.771
1 1/8	7	0.994	0.693	0.763	0.697	0.768
1 1/4	7	1.23	0.890	0.969	0.725	0.790

For easier design purposes, the effective area is estimated as seventy-five percent of the nominal cross-sectional area of the shank for usual sizes of structural bolts. As can be seen from the right most column in Table 2-11, the ratio of the effective area to the shank area only varies from 0.737 for 5/8-inch diameter bolts to 0.790 for 1-1/4-inch diameter bolts. The AISC Specification (2005) tabulates the nominal tensile stress as 90 ksi for A325 bolts and 113 ksi for A490 bolts. AISC obtained these nominal tensile stress values by taking seventy-five percent of the tensile strength of the bolt material, which is 120 ksi for A325 bolts and 150 ksi for A490 bolts. Modifying the tensile strength of the bolt material allows the nominal area of the bolt to be used in the design calculations. Therefore based on the AISC Specification (2005) the tensile strength of a high-strength bolt is given by (equation J3-1)

$$R_n = F_{nt} A_b = \left(0.75 F_u\right) A_b \tag{2-4}$$

Equation (2-4), which estimates the effective area as seventy-five percent of the gross area, yields a slightly conservative approximation of the tensile strength for most diameters.

2.3 Shear Strength of Structural Bolts

It has been shown in literature that the strength of a single fastener with the threads excluded from the shear plane is approximately equal to 62% of the tensile strength of the bolt material regardless of the bolt grade (Kulak et al. 2001). When more than two bolts are in the line of force in a lap splice, the distribution of the shear force in the bolts is non-uniform (RCSC 2004). As a result, as the joint length increases the average strength of all the bolts in the joint decrease

(Kulak et al. 2001). "Rather than provide a decreasing function that reflects this decrease in average fastener strength with joint length, a single reduction factor of 0.80 is applied…" (RCSC 2004). This modification accommodates fasteners in joints up to fifty inches in length and does not critically affect the economy of very short joints (RCSC 2004). As a result, the strength of a fastener with the threads excluded from the shear plane in a group of fasteners is $0.80\left(0.62 A_b F_u\right) = 0.50 A_b F_u$.

Finally, it was observed that a fastener with the threads not excluded from the shear plane had a strength approximately equal to 83% of the strength of a fastener with the threads excluded, with a standard deviation of 0.03 (RCSC 2004). The strength of a fastener with the threads not excluded from the shear plane in a group of fasteners, taking eighty-three percent as roughly eighty percent, is $0.80\left(0.50 A_b F_u\right) = 0.40 A_b F_u$.

In the most general terms, both AISC and RCSC present the strength of bolts with threads not excluded from the shear plane as $0.40 A_b F_u$ and with threads excluded from the shear plane as $0.50 A_b F_u$ (ANSI/AISC 2005). These equations were determined as discussed previously.

With this explanation in mind, let us determine the shear strength of one high-strength bolt. As previously explained the equations in AISC and RCSC are based on bolts in a joint less than fifty inches long. To calculate the shear strength of one fastener and not a group of fasteners in a joint, let us divide the AISC and RCSC equations by 0.80, which accounted for the decrease in the fastener strength with the joint length. Therefore, for one bolt with the threads not excluded from the shear plane:

$$R_n = \frac{F_{nv,N} A_b}{0.80} = \frac{0.4 F_u A_b}{0.80} = 0.5 F_u A_b \tag{2-5}$$

and for one bolt with the threads excluded from the shear plane:

$$R_n = \frac{F_{nv,X} A_b}{0.80} = \frac{0.5 F_u A_b}{0.80} = 0.625 F_u A_b \approx 0.62 F_u A_b \tag{2-6}$$

Thus equations (2-5) and (2-6) reflect the spirit of the shear strength models presented in AISC and RCSC in the context of the strength of a single fastener.

2.4 Background of LRFD

The Load and Resistance Factor Design (LRFD) philosophy is based on the use of reliability indices and resistance factors. LRFD is based on the following general equation

$$\phi R_n \geq \sum_{\mathrm{i}=1}^{\mathrm{n}} \gamma_{\mathrm{i}} Q_{\mathrm{i}m} \tag{2-7}$$

where the factored resistance (design strength) shall be greater than or equal to the factored loads. The capacity (resistance) of the structure is represented by the left side of the equation; whereas the right side of the equation corresponds to the loads acting on the structure, or “the required strength computed by structural analysis” (ANSI/AISC 2005). The nominal resistance, R_n, is the design strength computed according to design equations in the AISC Specification and is based on nominal material and cross-sectional properties. The resistance factor, ϕ, which is always less than or equal to one, takes into account the uncertainties associated with the design equation and the material.

2.4.1 Calculating Resistance Factors

Resistance factors are a function of the mean and variability of the material, geometric properties, and load. In addition, the resistance factor takes into account “the ability of the equation itself to predict capacity” (Franchuk et al. 2004). Resistance factors can be calculated based on two different equations. The first equation, identified herein as Method 1, is (Fisher et al. 1978) (Ravindra and Galambos 1978)

$$\phi = \Phi_{\beta} \frac{R_m}{R_n} e^{-\alpha \beta V_R} \tag{2-8}$$

and Method 2 is given by (Galambos 1998)

$$\phi = \Phi_{\beta} \rho_R \; e^{-\alpha_R \beta V_R} \tag{2-9}$$

where:

Φ_{β} → adjustment factor

α = 0.55 → coefficient of separation

β → safety index or reliability index

The three variables defined above are identical between the two different methods and will be discussed in detail in Section 2.4.1.1 through Section 2.4.1.3. Section 2.4.1.4 and Section 2.4.1.5 will discuss Methods 1 and 2, respectively.

2.4.1.1 Reliability Index

As previously stated, LRFD philosophy is based on equation (2-7). In order to determine the resistance factor, ϕ, for high-strength bolts in tension and shear, as well as R_n, γ, and Q_m a "first-order" probabilistic design procedure is used. This simplified method uses only two statistical parameters (mean values and coefficients of variation) and β, a relationship between them (Ravindra and Galambos 1978). The reliability index, β, "has a direct correspondence to the probability of failure of a given structural element considering both the variability of loads and resistances; a higher safety index indicates a lower probability of failure, and, hence, a higher level of safety" (Franchuk et al. 2004). The reliability index "is obtained by calibration to existing standard designs. Thus, it is intended that successful past practice will be the starting point for LRFD" (Fisher et al. 1978).

Safety is a function of two random variables: R, the resistance of the fastener, and Q, the load effect acting on it. Figure 2-11 shows the safety margin, that is the frequency distribution of the random variable (R-Q). When the resistance, R, is less than the load effect, Q, the result is failure. Based on Figure 2-11 the probability of failure, p_F, is equal to

$$p_F = P\left[\left(R - Q\right) < 0\right] \tag{2-10}$$

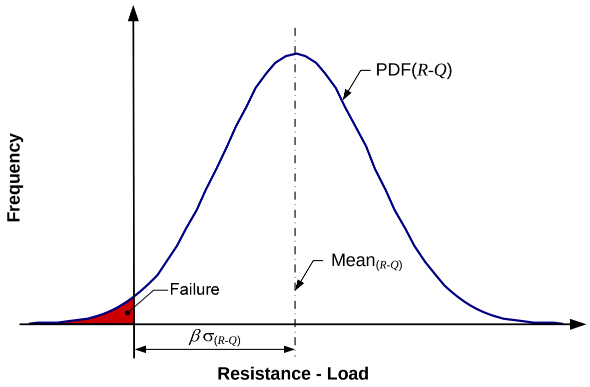


Figure 2-11: Probabilistic Model

To develop the LRFD criteria, Figure 2-12 shows an equivalent representation where the probability distribution of $\ln(R/Q)$ is given instead. Now the probability of failure is given by

$$p_F = P\left[\ln\left(\frac{R}{Q}\right) < 0\right] \tag{2-11}$$

which is shown as the area under the curve in Figure 2-12.

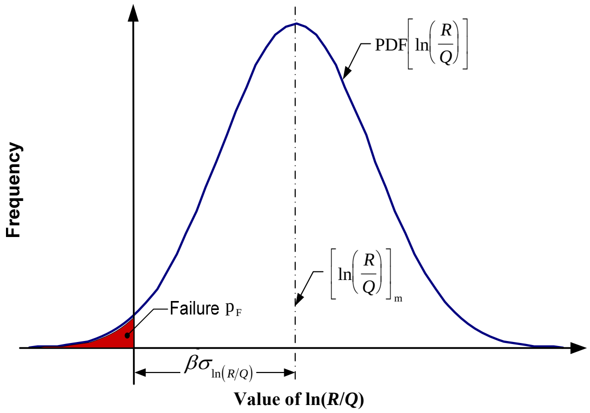


Figure 2-12: Safety Index

Introducing the standardized variate, z, which measures the distance from the mean in units of the standard deviation, is given by

$$\mathrm{z} = \frac{\mathrm{x} - \mu}{\sigma} \tag{2-12}$$

where x is the random variable, $\ln(R/Q)$, μ is the mean, $\left[\ln(R/Q)\right]_{\mathrm{m}}$, and σ is the standard deviation, $\sigma_{\ln(R/Q)}$. Therefore,

$$\mathrm{z} = \frac{\ln\left(\frac{R}{Q}\right) - \left[\ln\left(\frac{R}{Q}\right)\right]_{\mathrm{m}}}{\sigma_{\ln(R/Q)}} \tag{2-13}$$

The reliability index, β, is given by the quantity (Galambos and Ravindra 1973) (Ravindra and Galambos 1978)

$$\beta = \frac{\left[\ln(R/Q)\right]_{\mathrm{m}}}{\sigma_{\ln(R/Q)}} \tag{2-14}$$

"If the probability distribution of (R/Q) were known, β would directly indicate a value of the probability of failure" (Ravindra and Galambos 1978). However, the probability distribution of R/Q is unknown in practice. Using first-order probability theory the reliability index, β, can be simplified into (Galambos and Ravindra 1973) (Ravindra and Galambos 1978) (Fisher et al. 1978) (AISC Specification 2005)

$$\beta \approx \frac{\ln\left(\frac{R_m}{Q_m}\right)}{\sqrt{V_R^2 + V_Q^2}} \tag{2-15}$$

where:

R_m → mean value of the resistance

Q_m → mean value of the load effect

V_R and V_Q → corresponding coefficients of variation

The mean value of the load effect, Q_m, and the corresponding coefficient of variation, V_Q, is given by (Ravindra and Galambos 1978)

$$Q_m = c_D A_m D_m + c_L B_m L_m \tag{2-16}$$

$$V_Q \approx \sqrt{V_E^2 + \frac{c_D^2\ A_m^2\ D_m^2\left(V_A^2 + V_D^2\right) + c_L^2\ B_m^2\ L_m^2\left(V_B^2 + V_L^2\right)}{\left(c_D A_m D_m + c_L B_m L_m\right)^2}} \tag{2-17}$$

where:

c_D and c_L → “deterministic influence coefficients that transform the load intensities to load effects” (Ravindra and Galambos 1978)

$A_m = 1.0$ → mean value of the random variable reflecting the uncertainties in the transformation of the dead load into load effects (Ravindra and Galambos 1978)

$V_A = 0.04$ → coefficient of variation of the random variable reflecting the uncertainties in the transformation of the dead load into load effects (Ravindra and Galambos 1978)

$B_m = 1.0$ → mean value of the random variable reflecting the uncertainties in the transformation of the live load into load effects (Ravindra and Galambos 1978)

$V_B = 0.20$ → coefficient of variation of the random variable reflecting the uncertainties in the transformation of the live load into load effects (Ravindra and Galambos 1978)

$D_m = D_c$ → mean value of the random variable representing dead load intensity (Ravindra and Galambos 1978)

$V_D = 0.04$ → coefficient of variation of the random variable representing dead load intensity (Ravindra and Galambos 1978)

$V_E = 0.05$ → coefficient of variation of the random variable representing the uncertainties in structural analysis (Ravindra and Galambos 1978)

L_m → mean of the lifetime maximum live load for office occupancy (Ravindra and Galambos 1978)

$$L_m = 14.9 + \frac{763}{\sqrt{A_I}} \tag{2-18}$$

V_L → coefficient of variation of the lifetime maximum live load for office occupancy (Ravindra and Galambos 1978)

$$V_L = \frac{\sigma_L}{L_m} = \frac{\sqrt{11.3 + \frac{15000}{A_I}}}{14.9 + \frac{763}{\sqrt{A_I}}} \tag{2-19}$$

where:

A_I → influence area which equals twice the tributary area, A_T (Ravindra and Galambos 1978)

The mean value of the resistance, R_m, for high-strength bolts is given by (Fisher et al. 1978) equation (2-20) for tension and equation (2-21) for shear

$$R_m = \left(\frac{\sigma_u}{F_u}\right)_m \frac{A_t}{A_g}\frac{F_u}{F_t} c\left(D_c + L_{rc}\right) \tag{2-20}$$

$$R_m = \left(\frac{\tau_u}{\sigma_u}\right)_m \left(\frac{\sigma_u}{F_u}\right)_m \frac{F_u}{F_v} c\left(D_c + L_{rc}\right) \tag{2-21}$$

where:

c → “influence coefficient transforming load intensity to member force” (Fisher et al. 1978)

$$\left(\frac{\sigma_u}{F_u}\right)_m = \begin{cases} 1.20 \text{ for A325 bolts} \\ 1.07 \text{ for A490 bolts} \end{cases} \text{ (Fisher et al. 1978)}$$

$$\left(\frac{\tau_u}{\sigma_u}\right)_m = 0.625 \text{ (Fisher et al. 1978)}$$

$$\frac{A_t}{A_g} \approx 0.75 \text{ (Fisher et al. 1978)}$$

F_u → specified minimum tensile strength (Fisher et al. 1978)

$$F_u = \begin{cases} 120 \text{ ksi for A325 bolts} \\ 150 \text{ ksi for A490 bolts} \end{cases}$$

F_t → allowable tensile stress (Fisher et al. 1978)

$$F_t = \begin{cases} 44 \text{ ksi for A325 bolts} \\ 54 \text{ ksi for A490 bolts} \end{cases}$$

F_v → allowable shear stress (Fisher et al. 1978)

$$F_v = \begin{cases} 30 \text{ ksi for A325 bolts - X} \\ 21 \text{ ksi for A325 bolts - N} \\ 40 \text{ ksi for A490 bolts - X} \\ 28 \text{ ksi for A490 bolts - N} \end{cases}$$

$$L_{rc} = L_c(1 - RF) \text{ (Galambos and Ravindra 1973)} \tag{2-22}$$

where:

σ_u → ultimate tensile strength of the bolts (Fisher et al. 1978)

τ_u → ultimate shear strength of the bolts (Fisher et al. 1978)

A_t → tensile stress area of the bolt (Fisher et al. 1978)

A_g → area of the bolt corresponding to the nominal diameter (Fisher et al. 1978)

$$RF = \min \begin{cases} \begin{cases} 0 & \text{for } A_T \le 150\text{ft}^2 \\ 0.0008A_T & \text{for } 150\text{ ft}^2 < A_T < 750\text{ft}^2 \\ 0.60 & \text{for } A_T \ge 750\text{ft}^2 \end{cases} \\ 0.23\left(1 + \frac{D_c}{L_c}\right) \end{cases}$$

The coefficient of variation of the resistance, V_R, for A325 and A490 bolts, are 0.09 and 0.05 in direct tension and equals 0.10 and 0.07 in shear, respectively (Galambos and Ravindra 1975) (Fisher et al. 1978).

The reliability index, β, is calculated using equation (2-15). "Instead of limiting the calibration to one preselected data point, a complete spectrum of design situations, characterized by different tributary areas and dead loads…" (Ravindra and Galambos 1978) was evaluated in order to choose a representative value for the reliability index. Table 2-12 shows values for the reliability index for a live-load of 50 pounds per square foot, for dead-loads of 50, 75, and 100 pounds per square foot, and for tributary areas ranging from 200 square feet to 1,000 square feet. The values of the reliability index tabulated in Table 2-12 are similar to the results summarized in Fisher et al. (1978). Figures 2-13 through 2-15 shows the reliability index versus the tributary area for a dead-load of 50, 75, and 100 pounds per square foot, respectively.

Table 2-12: Reliability Index, β

Dead Load (pounds per square foot)	Tributary Area (square feet)	Reliability Index, β			
		Tension		Shear	
		A325	A490	A325	A490
50	200	4.81	4.75	5.84	5.27
50	400	5.28	5.33	6.34	5.84
50	575	5.18	5.25	6.27	5.76
50	800	5.57	5.72	6.66	6.20
50	1000	5.81	6.02	6.90	6.48
75	200	5.50	5.63	6.59	6.12
75	400	5.97	6.26	7.07	6.71
75	720	5.71	6.02	6.85	6.47
75	1000	6.01	6.41	7.15	6.83
100	200	5.99	6.31	7.11	6.75
100	400	6.42	6.92	7.54	7.30
100	600	6.35	6.89	7.49	7.26
100	750	6.16	6.68	7.32	7.06
100	1000	6.37	6.97	7.53	7.33

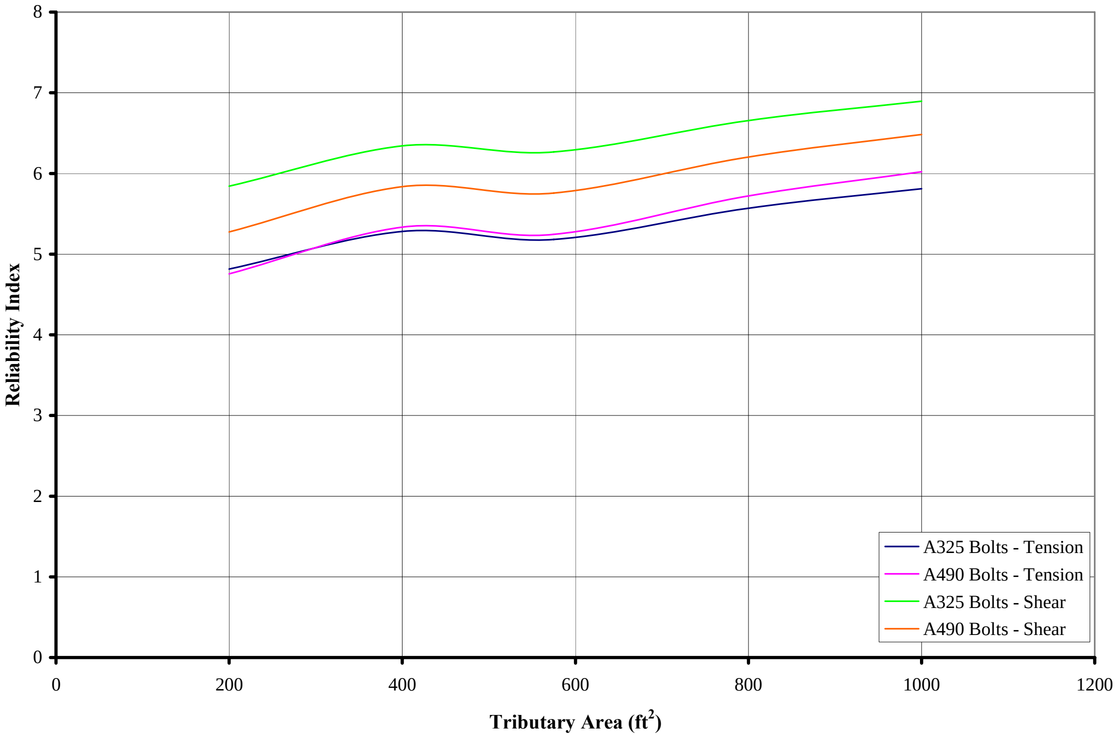


Figure 2-13: Reliability Index versus Tributary Area – Dead Load is 50 psf

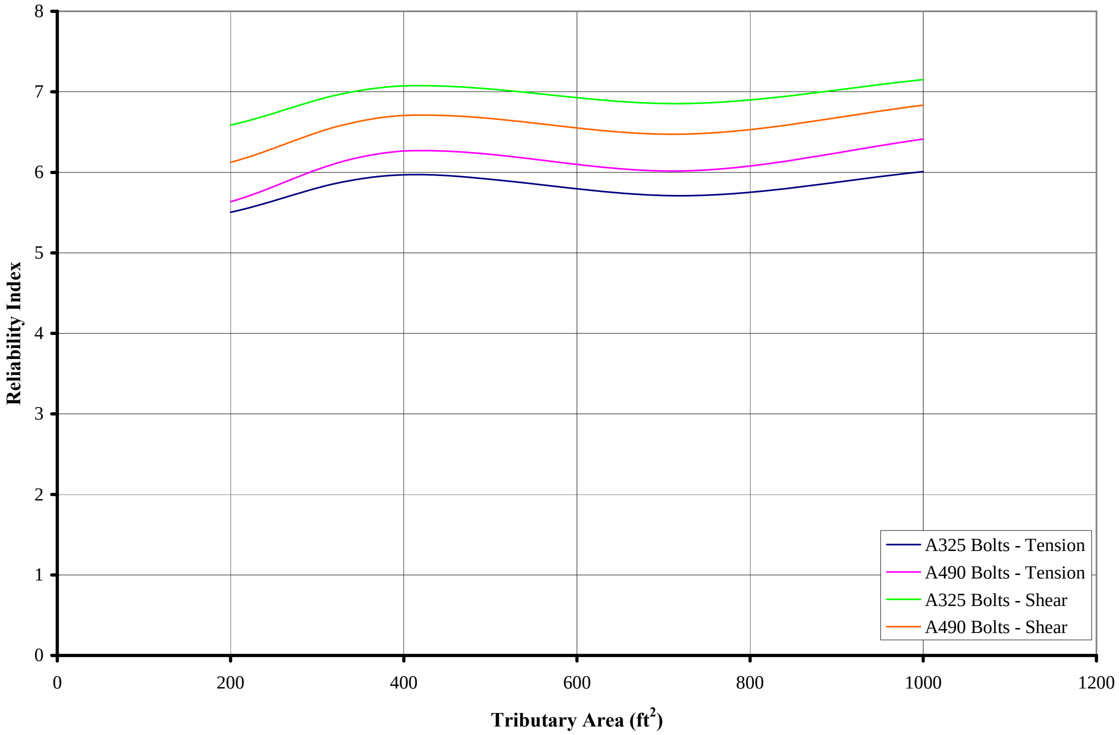


Figure 2-14: Reliability Index versus Tributary Area – Dead Load is 75 psf

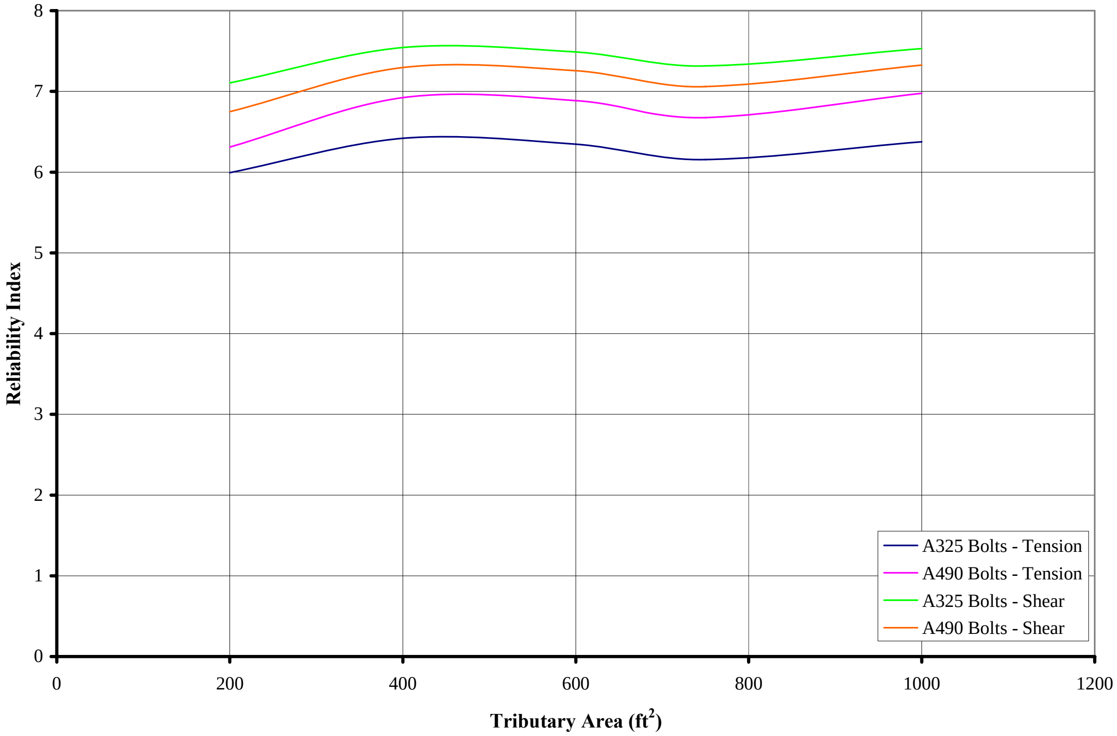


Figure 2-15: Reliability Index versus Tributary Area – Dead Load is 100 psf

From the range of reliability indexes obtained, one index is chosen. For beams and columns the reliability index of 3.0 was chosen (Fisher et al. 1978). Since it is desirable to have a higher safety index for connections, the reliability index equals 4.5 for the strength limit state and 1.5 for the serviceability state (Fisher et al. 1978). "The higher value of β [,for the strength limit state,] for connectors reflects the fact that traditionally connections are designed stronger than the elements that are connected by them" (Ravindra and Galambos 1978). However, according to the Commentary in the AISC Specification (2005), the reliability index equals 4.0 for connections and 2.6 for members. Both values of the reliability index for connections (4.0 and 4.5) will be considered.

2.4.1.2 Coefficient of Separation

According to Galambos and Ravindra (1973) $\alpha_R = 0.55$. This "is a reasonable approximation required to effectively separate the resistance and load effect terms…" (Galambos and Ravindra 1973).

2.4.1.3 Adjustment Factor

In equations (2-8) and (2-9), Φ_β is the adjustment factor, which accounts for the interdependence of the resistance and load factors when the reliability index, β, does not equal 3.0 (Galambos 1998). For values of β less than 3.0, the adjustment factor is greater than 1.0. Likewise for values of β greater than 3.0, the adjustment factor is less than 1.0 (Fisher et al. 1978).

Considering only dead and live load, equation (2-7) can be written in terms of the mean dead and live load effects, Q_{Dm} and Q_{Lm}, respectively, as

$$\phi R_n \geq \gamma_D Q_{Dm} + \gamma_L Q_{Lm} \tag{2-23}$$

where γ_D and γ_L are the dead and live load factors, respectively. Writing this equation in terms of the dead and live load intensities equation (2-23) becomes (Ravindra and Galambos 1978; Fisher et al. 1978)

$$\phi R_n \geq \gamma_E \left(c_D \gamma_D D_m + c_L \gamma_L L_m \right) \tag{2-24}$$

where:

$$\gamma_E = e^{\alpha \beta V_E} \rightarrow \text{load factor representing uncertainties in analysis} \tag{2-25}$$

$$\gamma_D = 1 + \alpha\beta\sqrt{V_A^2 + V_D^2} \tag{2-26}$$

$$\gamma_L = 1 + \alpha\beta\sqrt{V_B^2 + V_L^2} \tag{2-27}$$

From Fisher et al. (1978) the following values are given: $V_E = 0.05$, $V_A = 0.04$, $V_B = 0.20$, $V_D = 0.04$, and $V_L = 0.13$.

The ratio

$$\frac{\left[\gamma_E\left(c_D\gamma_D D_m + c_L\gamma_L L_m\right)\right]_{\beta=3.0}}{\left[\gamma_E\left(c_D\gamma_D D_m + c_L\gamma_L L_m\right)\right]_{\beta}} \tag{2-28}$$

was calculated for reliability indices, β, ranging from 1.0 to 5.0 and for live-to-dead load ratios ranging from 0.25 to 3.0. A plot of the adjustment factor, Φ_{β}, versus the reliability index, β, for different live-to-dead load ratios is shown in Figure 2-16. For each live-to-dead load ratio, equations to approximate the adjustment factor in terms of the reliability index were obtained by a least square regression analysis with a second degree polynomial approximate. Table 2-13 summarizes the equations and correlation coefficients, R^2, for each live-to-dead load ratio.

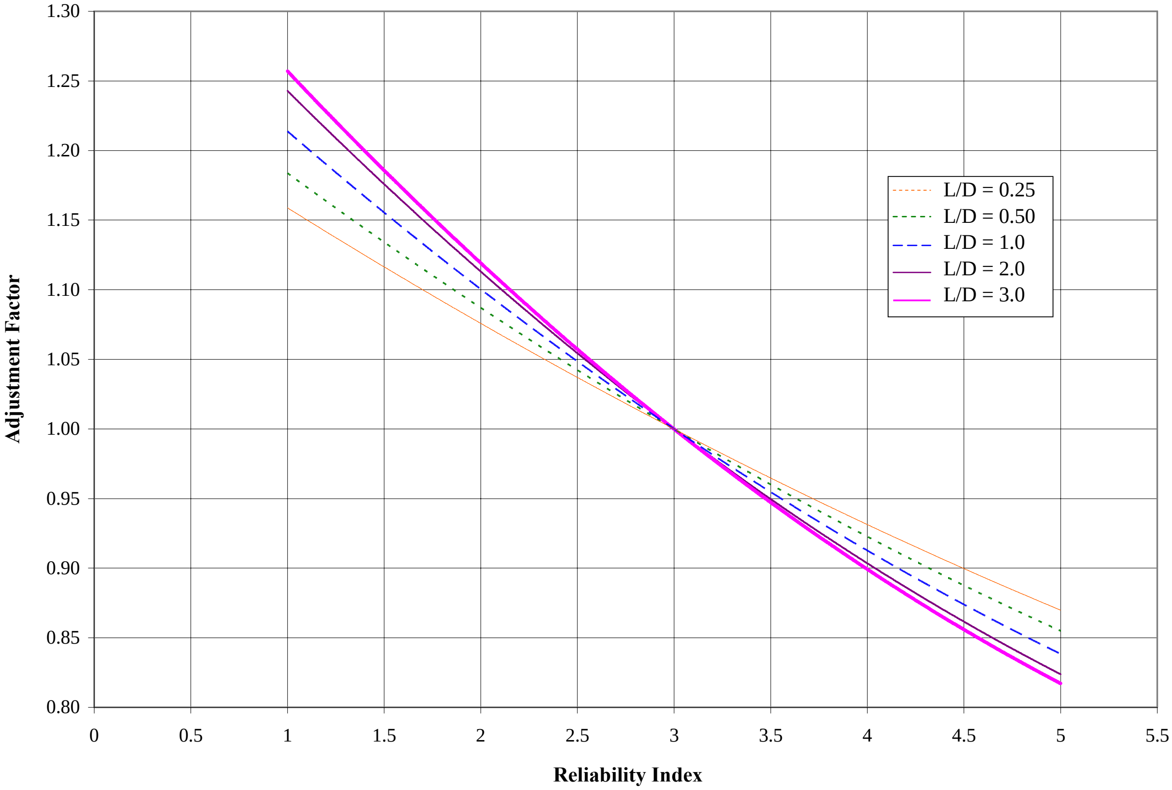


Figure 2-16: Adjustment Factor versus Reliability Index for Different Live-to-Dead Ratios

Table 2-13: Adjustment Factor Equations based on Live-to-Dead Load Ratio

Live-to-Dead Load Ratio	Equation	Correlation Coefficient
0.25	$0.0036\beta^2 - 0.0938\beta + 1.249$	1.0
0.50	$0.0048\beta^2 - 0.1112\beta + 1.2901$	1.0
1.0	$0.0065\beta^2 - 0.1331\beta + 1.3404$	1.0
2.0	$0.0084\beta^2 - 0.1549\beta + 1.3894$	1.0
3.0	$0.0093\beta^2 - 0.1658\beta + 1.4135$	0.9999

Fisher et al. (1978) stated that the adjustment factor, Φ_β, "varies only from 0.86 to 0.90 as the live-load to dead-load effect goes from 2 to 0.25" with a reliability index, β, equal to 4.5, which can be seen from Figure 2-16. Fisher et al. (1978) recommends an adjustment factor of 0.88 be used for connections with a reliability index, β, equal to 4.5. However, the adjustment factor for this research will be calculated based on the equations summarized in Table 2-13. The resistance factors will be calculated using both a live-to-dead ratio of 1.0 and 3.0, respectively, which are summarized here.

$$\Phi_\beta = 0.0065\beta^2 - 0.1331\beta + 1.3404 \tag{2-29}$$

$$\Phi_\beta = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

2.4.1.4 Method 1

Calculating resistance factors per Method 1 is based on equation 27 from Fisher et al. (1978) and equation 24 from Ravindra and Galambos (1978) and is repeated here for convenience.

$$\phi = \Phi_\beta \frac{R_m}{R_n} e^{-\alpha \beta V_R} \tag{2-8}$$

where:

R_m → average value of the resistance R of the bolts tested (kips)
R_n → nominal resistance (kips)

V_R → coefficient of variation of R_m

From equation (2-8), R_m is the average value of the resistance of the bolts tested in kips. When the bolts fail the maximum load is recorded for each of the bolts tested. The value of R_m is the average of these loads.

The nominal resistance, R_n, can be calculated in one of two ways for tension. The first model to calculate R_n in tension is a simplified approach, identified herein as Model A. In the simplified approach the nominal resistance in tension was given by equation (2-4) as previously described in Section 2.2. The equation is repeated here.

$$R_n = \left(0.75F_u\right)A_b \tag{2-4}$$

The ultimate stress, F_u, equals 120 ksi for A325/F1852 bolts and 150 ksi for A490/F2280 bolts. The area, A_b, is the nominal bolt area or area of the shank.

The second model to calculate R_n in tension, identified as Model B, is the fundamental way based on the effective area of a bolt given by

$$R_n = F_u A_{eff} \tag{2-31}$$

The ultimate stress, F_u, equals 120 ksi[4] or 150 ksi for A325/F1852 bolts and A490/F2280 bolts, respectively. The effective area, in inches, was given by equation (2-3) which is repeated here, where d is the nominal bolt diameter and n is the thread pitch.

$$A_{eff} = \frac{\pi}{4}\left(d - \frac{0.9743}{n}\right)^2 \tag{2-3}$$

The nominal resistance, R_n, in shear is given by the equation

$$R_n = F_{nv} A_b \tag{2-32}$$

---

[4] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

where F_{nv} is the nominal shear strength and A_b is the area of the shank. The shear strength of the fasteners depends on the location of the shear plane. When the threads are not excluded from the shear plane (N) (the shear plane is located in the threads) the shear strength is 50% of the ultimate stress or

$$F_{nv,N} = 0.50 F_u \tag{2-33}$$

The shear strength is 62% of the ultimate stress when the threads are excluded from the shear plane (X) (the shear plane is located in the shank) or

$$F_{nv,X} = 0.62 F_u \tag{2-34}$$

The shear strength for the two locations of the shear plane was determined previously in Section 2.3 for a single bolt.

In conclusion, the nominal resistance in shear for a single bolt when the threads are not excluded from the shear plane is given by equation (2-35) and when the threads are excluded from the shear plane is given by equation (2-36).

$$R_n = 0.50 F_u A_b \tag{2-35}$$

$$R_n = 0.62 F_u A_b \tag{2-36}$$

The coefficient of variation, V_R, equals the standard deviation divided by the average of the resistance of the bolts tested, R_m.

2.4.1.5 Method 2

The equation for Method 2 (Galambos 1998) resistance factors is restated here for convenience.

$$\phi = \Phi_{\beta} \rho_R \, e^{-\alpha_R \beta V_R} \tag{2-9}$$

where:

ρ_R → bias coefficient for the resistance

V_R → coefficient of variation associated with ρ_R

The bias coefficient, ρ_R, is the average value of the ratio of the measured resistance to the nominal resistance. The bias coefficient for the resistance is given by

$$\rho_R = \rho_G \, \rho_M \, \rho_P \tag{2-37}$$

where ρ_G, ρ_M, and ρ_P are the bias coefficients for the cross-sectional geometry, material strength, and professional factor, respectively.

The coefficient of variation associated with ρ_R, V_R, is

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \tag{2-38}$$

where V_G, V_M, and V_P are the coefficients of variation of the cross-sectional geometry, material strength, and professional factor, respectively. The coefficient of variation is given by the standard deviation divided by the average.

2.4.1.5.1 Method 2 – Bias Coefficient – Geometry:

The bias coefficient for the cross-sectional geometry, ρ_G, is the ratio of the average applicable geometric property to the nominal value. The value of the bias coefficient for the cross-sectional geometry is given by the equation

$$\rho_G = \frac{\text{Actual Area}}{\text{Nominal Area}} = \frac{\text{Average}\left(\dfrac{\pi\left(d_{avg}\right)^2}{4}\right)}{\left(\dfrac{\pi\left(d_{nominal}\right)^2}{4}\right)} = \frac{\text{Average}\left(\left(d_{avg}\right)^2\right)}{\left(d_{nominal}\right)^2} \tag{2-39}$$

The diameter is measured using calipers at five different locations along the shank. The average of these five values is d_{avg}.

2.4.1.5.2 Method 2 – Bias Coefficient – Material Strength

The bias coefficient for the material strength, ρ_M , is the ratio of the average appropriate material property (F_u) to the nominal value given in the AISC manual (2005).

$$\rho_M = \frac{\text{Actual } F_u}{\text{Nominal } F_u} = \frac{F_{u,\,exp}}{F_{u,\,nominal}} \tag{2-40}$$

The ultimate strength, $F_{u,\,exp}$, is determined by

$$F_{u,\,exp} = \frac{P_{exp}}{A'_{eff}} \tag{2-41}$$

where P_{exp} is the experimental load at which the bolt failed in tension. The effective area, A'_{eff} , is given by equation (2-3) except it is calculated using d_{avg} (the average measured shank diameter) instead of d

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

The nominal ultimate stress, $F_{u,\ nominal}$, equals 120 ksi[5] and 150 ksi for A325/F1852 bolts and A490/F2280 bolts, respectively.

To determine the material strength, four test specimens were machined from a lot of 7/8-inch A325 and A490 bolts which were 4-1/4-inches in length. The eight test specimens had “their shanks machined concentric with the axis of the bolt…, leaving the bolt head and threaded section intact” (ASTM F606-05) as shown in Figure 2-17 (ASTM F606-05). The bolt specimens were tested with the threads completely threaded into the tension fixture and with a proof washer. Two different load rates were used when testing the specimens.

---

[5] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter. If 105 ksi were used for the 1-1/8-inch and 1-1/4-inch bolts the bias coefficient for the material strength might be too high therefore 120 ksi was used.

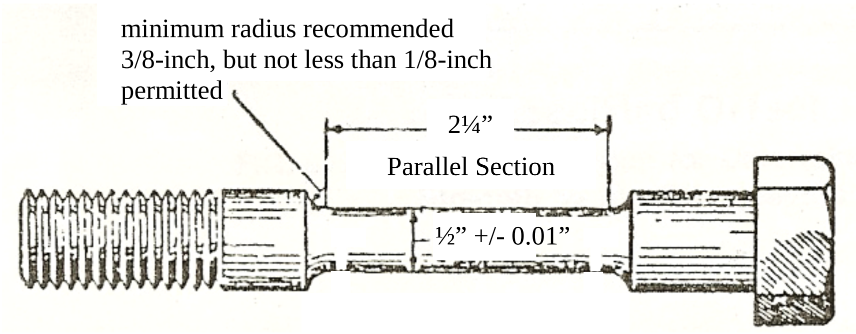


Figure 2-17: Tension Test Specimen for Bolts with Turned-Down Shank (ASTM F606-05)

Table 2-14 summarizes the tensile load and stress of the eight bolt specimens. The average ultimate strength, $F_{u,\,exp}$, from equation (2-41) for the same lot of 7/8-inch A325 bolts tested full scale was 154.6 ksi. Likewise, the average ultimate strength for the same lot of 7/8-inch A490 bolts was 164.2 ksi. Comparing the tensile strength from the bolt specimens, Table 2-14, and from the full bolts tested the percent error is 3.9 percent and 4.2 percent for the A325 and A490 bolts, respectively. Due to the low percent error the above equations for the bias coefficient for material strength, ρ_M, are justified and bolt coupons are not needed to determine the material strength for each lot.

Table 2-14: Results of Bolt Tension Specimens

Grade	Load Rate (in/min)	Tensile Load (pounds)	Tensile Stress (ksi)	Average Tensile Stress (ksi)
A325	0.225	28762	146.48	148.74
		29563	150.56	
	0.75	28979	147.59	
		29519	150.34	
A490	0.225	30428	154.97	157.60
		31066	158.22	
	0.75	31386	159.85	
		30896	157.35	

2.4.1.5.3 Method 2 – Bias Coefficient – Professional Factor

The bias coefficient for the professional factor, ρ_P, is the ratio of the average tested strength, determined experimentally, to the predicted strength, as calculated by a design equation using measured dimensions and material properties.

$$\rho_P = \frac{\text{Actual Strength}}{\text{Predicted Strength}} = \frac{\text{Average}\left(P_{exp}\right)}{R_n \text{ based on measured values}} \tag{2-43}$$

The details of the bias coefficient for the professional factor are dependant on whether the bolts were tested in tension or shear. The two applications are explored in the following two sections.

Method 2 – Bias Coefficient – Professional Factor - Tension

Two models are prevalent for predicting the tensile strength of bolts. The first, identified herein as Model A, is based on the approximation that, for commonly used bolt sizes, the effective tensile area is approximately equal to seventy-five percent of the nominal area of the shank. Using equation (2-4) with measured dimensions and material properties to predict the strength, the bias coefficient for the professional factor is

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.75 A_b' F_{u,exp}} \tag{2-44}$$

where

$$A_b' = \frac{\pi}{4}\left(d_{avg}\right)^2 \tag{2-45}$$

The second model, identified as Model B, is based on the effective area calculated using the average measured shank diameters, as previously shown in equation (2-42).

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{A_{eff}' F_{u,exp}} \tag{2-46}$$

where

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \qquad (2\text{-}42)$$

It should be noted that the parameters used to compute the predicted strength (denominator of equation (2-43)) in equations (2-44) and (2-46), are calculated using measured values. The value for $F_{u,exp}$ is computed using equations (2-41) and (2-42) where d_{avg} is the average of the measured diameters.

Method 2 – Bias Coefficient – Professional Factor - Shear

Two situations exist in shear, the case where the threads are not excluded from the plane of shear (N) and the case where the threads are excluded from the plane of shear (X). These situations were considered in equations (2-5) and (2-6), respectively.

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.50 A'_b F_{u,\,exp}} \qquad (2\text{-}47)$$

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.62 A'_b F_{u,\,exp}} \qquad (2\text{-}48)$$

where

$$A'_b = \frac{\pi}{4}\left(d_{avg}\right)^2 \qquad (2\text{-}45)$$

The value of $F_{u,exp}$ is determined based on equation (2-41).

Equations (2-47) and (2-48) reflect the spirit of the shear strength models presented in AISC and RCSC in the context of the strength of a single fastener. This was determined in Section 2.3.

Resistance factors were calculated using the equations described previously based on five different levels of detail, as shown in Figure 2-18. For instance, resistance factors were first calculated based on the diameter and grade of each bolt (Level V). Secondly, resistance factors were calculated based on just the grade (A325, F1852, A490, and F2280) of the bolts and not based on the diameter, indicated as Level IV. Level III calculates resistance factors based on the strength of the bolts, either 120 ksi (A325 and F1852) or 150 ksi (A490 and F2280). Level II calculates one resistance factor regardless of the bolt diameter or the bolt grade for both tension and shear whereas Level I comprises all of the data from the tension and shear tests to calculate one resistance factor.

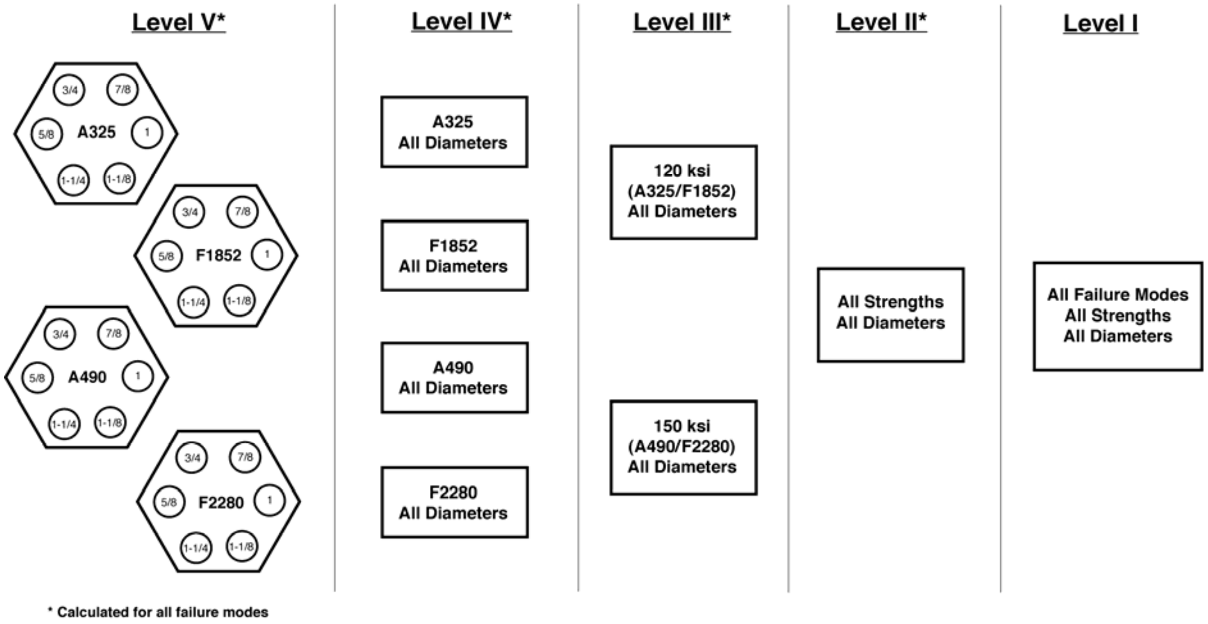


Figure 2-18: Levels of Detail Used to Calculate Resistance Factors for Tension and Shear

2.5 Determining the Number of Bolts to be Tested

Using ASTM standards and statistical analysis, the number of bolts from each lot to be tested had to be determined. According to ASTM F1789 (2005) a lot is a “quantity of product of one part number that has been processed essentially under the same conditions from the same heat treatment lot and produced from one mill heat of material and submitted for inspection at one time”. To obtain enough data to make a statistically sound recommendation of a resistance factor, approximately one hundred lots of bolts were obtained to be tested.

ASTM F1470 (2002) is a guide for determining the number of bolts which need to be tested in a random sample to determine different characteristics, in this case tensile and shear (both with the threads excluded and not excluded from the shear plane) strength. The sample size depends on the lot size. Table 2-15 (ASTM F1470 2002) shows the number of bolts to be tested from each lot for tension and shear based on the lot size.

Table 2-15: Sample Size Based on Lot Size (ASTM F1470 2002)

Lot Size	Sample Size
1 to 2	1
3 to 15	1
16 to 25	1
26 to 50	1
51 to 90	2
91 to 150	2
151 to 280	2
281 to 500	3
501 to 1200	3
1201 to 3200	3
3201 to 10,000	4
10,0001 to 35,000	4
35,001 to 150,000	5
150,001 to 500,000	6
500,001 and over	7

Based on ASTM F1470 (2002), the same sample size is required for tensile and shear strength. Assuming there are between 35,001 and 150,000 bolts per lot, five bolts per lot should be tested in tension, shear with the threads excluded and shear with the threads not excluded.

Using the U.S. Department of Defense Military Standard 105E (*NIST/SEMATECH* 2006) the same sample size was determined as based on ASTM F1470-02 conservatively assuming there are between 35,001 and 150,000 bolts in a lot. It was determined that five fasteners would need to be tested from each lot in tension and shear with threads excluded and not excluded from the shear plane for a total of fifteen fasteners from each lot.

Since one hundred lots are to be tested, or five hundred bolts in tension and five hundred bolts each in shear with threads excluded and not excluded from the shear plane, a total of 1500 bolts are to be tested to calculate resistance factors. Ten extra fasteners from each lot were to be obtained for supplemental testing in case there was unacceptable variability. The bolts to be tested ranged in size from 5/8-inch to 1-1/4-inch in diameter with lengths up to and including five inches. The one hundred lots to be tested were divided among the different diameters and between A325/F1852 and A490/F2280 bolts as shown in Table 2-16. Since A490/F2280 bolts are perceived to have inconsistent strength, they have a higher number of lots to be tested as compared to A325/F1852 bolts. The fasteners of size 3/4-inch to 1-inch in diameter have more lots to be tested due to those sizes being the most common in practice.

Table 2-16: Test Matrix

Diameter (inches)	Length (inches)	Lots of A325/F1852	Lots of A490/F2280
5/8	2-3/4 to 5	5	6
3/4	2-3/4 to 5	10	12
7/8	3 to 5	10	13
1	3 to 5	10	12
1-1/8	3-3/4 to 5	5	6
1-1/4	3-3/4 to 5	5	6
	Total	45	55

CHAPTER 3

LITERATURE REVIEW

A complete literature review was performed to obtain past data of high-strength bolts tested in direct tension and shear. Thirty-eight MS theses, PhD dissertations, reports, and journal articles were obtained. Some of the literature obtained did not pertain to this research. The theses, PhD dissertations, reports, and journal articles acquired that are relevant to the project are described in the following sections.

3.1 Large Bolted Joints (1960s)

When the A325 bolt was added to the 1954 design specification a substitution rule was in place (Foreman and Rumpf 1961). This meant that one A325 bolt would replace one A141 rivet of the same nominal size. "The basic properties of the parent materials of the high strength bolt and structural rivet suggested, from the outset, a superiority for the bolt, but, since this strength advantage had not been completely demonstrated by structural applications, the bolt has continued to be governed by the 'one for one' specification" (Foreman and Rumpf 1961).

During the 1960s tension and shear tests were performed as part of a large research project called "Large Bolted Joints Project" which was conducted at the Fritz Engineering Laboratory at Lehigh University under Dr. L. S. Beedle. The objective of this project was "to study the behavior, under static tension loads, of large plate joints connected with high strength bolts to determine if fewer bolts may be used than presently required by [the] specification" (Foreman and Rumpf 1961). The failure characteristics of bolted joints (butt joints and shingle-type joints) were the primary interest of this project (Foreman and Rumpf 1961). The bolted joints considered were fabricated from structural and high-strength steel (Foreman and Rumpf 1961). The project was "sponsored financially by the Pennsylvania Department of Highways, the Bureau of Public Roads and the American Institute of Steel Construction" (Dlugosz and Fisher

1962). The Research Council on Riveted and Bolted Structural Joints provided the technical guidance during the research.

3.1.1 John L. Rumpf (1958)

The main purpose of this research was to "determine the influence of initial clamping force upon the shear resistance of individual fasteners" (Rumpf 1958). The friction between the faying surface affects the shear resistance of a bolt, which depends on the clamping force and the coefficient of friction. Single bolts were tested with different faying surfaces and various degrees of initial tension. The faying surfaces used were mill scale with or without molycote (a lubricant).

The single bolts were tested in double shear so they will not be considered herein. However, five lots of A325 bolts were tested in tension to obtain the bolt properties. The tensile strength is shown in Table 3-1 (Rumpf 1958).

Table 3-1: Direct Tension Tests Results (Rumpf 1958)

Lot	Nominal Diameter (inches)	Mean Ultimate Load (kips)
Z	7/8	60.4
B	7/8	54.3
Y	1	73.1
A	1	74.1
G	1 1/8	91.2

3.1.2 Robert T. Foreman and John L. Rumpf (1958)

Six double lap joints with 7/8-inch A325 bolts and one double lap joint with rivets were tested to evaluate the present design specification. The design specification in the 1950s limited the "allowable bolt shear to a value equal to seventy-five percent of the allowable net tensile stress" (Foreman and Rumpf 1958). The joints were tested at various tensile-to-shear stress ratios.

Five 7/8-inch, 5-1/2-inches long, A325 bolts were tested in direct tension. It should be noted that the bolts ordered for this research were manufactured to approach the lower strength limit of the specification. A 4-inch grip between the nut and the washers under the head was used when testing the bolts. Table 3-2 (Foreman and Rumpf 1958) shows the results of the direct tension tests for the five 7/8-inch A325 bolts. A ten degree wedge washer was not used when testing as recommended by ASTM. Since strength and not ductility was being considered, there should be no reduction in the ultimate load unless the bolt head would be removed from the shank.

Table 3-2: Direct Tension Tests (Foreman and Rumpf 1958)

Bolt Number	Nominal Diameter (inches)	Ultimate Load (kips)
B45	7/8	53.2
B46	7/8	55.0
B47	7/8	56.0
B99	7/8	53.0
B100	7/8	54.2

3.1.3 Robert A. Bendigo and John L. Rumpf (1959)

As a result of increased popularity of high-strength bolts being used in structural connections, the need for accurate bolt calibration arose. This research was completed to determine the effects of direct and torqued tension calibration procedures for 7/8-inch, 1-inch, and 1-1/8-inch bolts. Only the direct tension tests will be considered herein. The effects of the grip length and thread length in the grip were also studied.

The bolts tested were A325 high-strength bolts of diameters 7/8-inch, 1-inch, and 1-1/8-inch with lengths ranging from 5-1/2-inches to 8-1/2-inches. A few of the bolts were either fully threaded or non-standard but most of the bolts tested had standard thread lengths. The results of the thirteen lots of bolts tested in direct tension are summarized in Table 3-3 (Bendigo and Rumpf 1959).

Table 3-3: Direct Tension Tests Results (Bendigo and Rumpf 1959)

Lot	Nominal Diameter (inches)	Bolt Length (inches)	Thread Length (inches)	Grip Length (inches)	Number of Bolts Tested	Mean Ultimate Load (kips)	Elongation at Failure (inches)
B	7/8	5 1/2	2	4.00	5	54.3	0.31
D	7/8	5 1/2	2	4.00	5	56.7	0.25
Z	7/8	5 1/2	2	4.00	8	60.4	0.242
Q	7/8	5 1/2	2 1/4	4.00	3	54.0	0.36
R	7/8	5 1/2	3 1/4	4.00	3	52.2	0.44
S	7/8	5 1/2	5 1/2	4.00	3	53.8	0.60
T	7/8	6 1/2	2 1/4	4.75	3	54.8	0.35
U	7/8	7	2 1/4	5.25	3	55.2	0.307
V	7/8	7 1/2	2 1/4	6.00	3	53.6	0.333
W	7/8	8 1/2	2 1/4	6.75	3	55.1	0.34
A	1	5 1/2	2 1/4	4.00	5	74.1	0.33
Y	1	5 1/2	2 1/4	4.00	5	73.0	0.38
G	1 1/8	6	2 1/2	4.00	5	91.2	0.30

It should be noted that lots Q and R do not have standard thread lengths and lot S is a fully threaded bolt. These three lots were made from the same mill heat. Figure 3-1 (Bendigo and Rumpf 1959) shows the effect of the length of thread in the grip by graphing the tension versus elongation curves for lots Q, R, and S. "At any point on this composite graph, the elongation at any load varies in some relationship to the length of thread in the grip area. Likewise, the load attained at any one elongation is related inversely to the length of thread" (Bendigo and Rumpf 1959). It can be seen from Table 3-3 (Bendigo and Rumpf 1959) that the elongation for Lot S (the fully threaded bolt) was approximately twice the elongation of Lot Q (2-1/4-inch thread length).

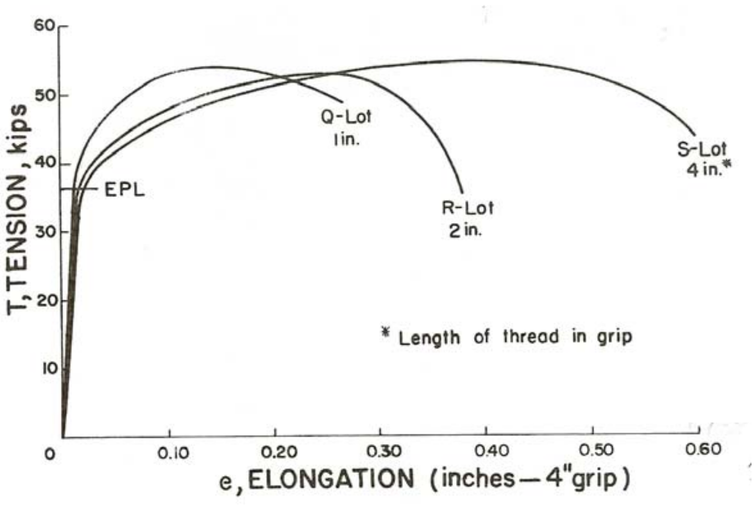


Figure 3-1: Effect of Thread Length (Bendigo and Rumpf 1959)

Lots T, U, V, and W were tested in this study to determine the effect of grip lengths and the effects of longer bolts which would be used in large bolted joints. It was concluded that "no apparent decrease in ultimate load carrying capacity and also no definite trend in elongations at rupture" (Bendigo and Rumpf 1959) resulted with the longer bolts, as can be seen in Figure 3-2 (Bendigo and Rumpf 1959).

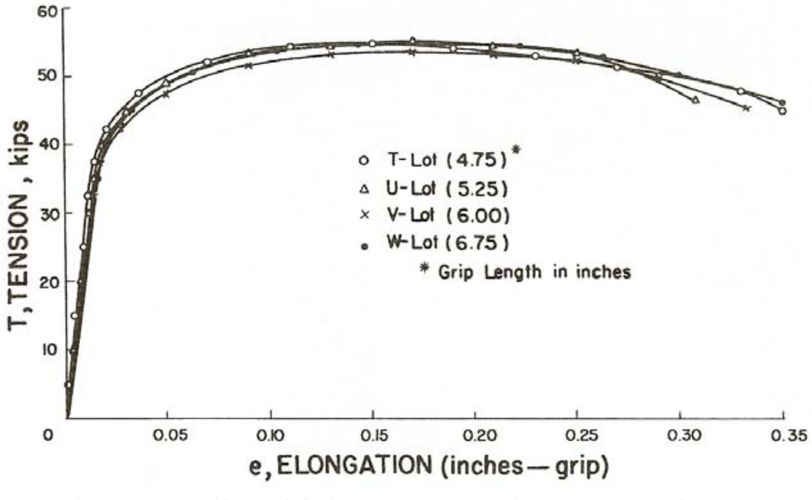


Figure 3-2: Effect of Grip Length (Bendigo and Rumpf 1959)

It was determined that the grip length had no appreciable effect on the tension or elongation characteristics of bolts. The threaded portion of the bolt behaves plastically after the bolt reaches its proof load while the shank remains elastic. Thus most of the elongation takes place in the threaded portion.

3.1.4 Robert A. Bendigo and John L. Rumpf (1960)

Twelve long butt joints with A7 steel and 7/8-inch A325 bolts were studied. Joint length was the major variable for this research. Only the material properties of the bolts used in the joints will be considered herein. There were two different parts of this research. Part (a) of the research varied the width and part (b) varied the grip.

The bolts used in the first part of this research were 7/8-inch, 5-1/2-inches long, A325 bolts with a standard 2-inch thread length. Five bolts from this lot were chosen and tested in direct tension. The bolts had an average ultimate strength equal to 56.7 kips.

The bolts used in part (b) were 7/8-inch, A325 bolts. The bolts came from the same heat-treatment but the bolt length varied. The threads were cut and had a standard length equal to 2-1/4-inches. Five bolts from each of the four lots were tested in direct tension. The results are summarized in Table 3-4 (Bendigo and Rumpf 1960).

Table 3-4: Direct Tension Tests Results (Bendigo and Rumpf 1960)

Lot	Nominal Diameter (inches)	Bolt Length (inches)	Thread Length (inches)	Number of Bolts Tested	Mean Ultimate Load (kips)
T	7/8	6 1/2	2 1/4	5	54.8
U	7/8	7	2 1/4	5	55.2
V	7/8	7 1/2	2 1/4	5	53.6
W	7/8	8 1/2	2 1/4	5	55.1

3.1.5 Roger M. Hansen and John L. Rumpf (1960)

In a bearing type connection it has been shown that the usual design assumption that all bolts carry equal shear stress at ultimate load is invalid for long joints. The original study of long bolted joints, as previously discussed in Section 3.1.4 (Bendigo and Rumpf 1960), raised four outstanding questions. This research tested four long joints to answer some of the questions.

The bolts used in the connections were 7/8-inch, A325, 9-1/2-inches long with 2-1/4-inches rolled threads. The bolts used in the research were all from the same heat treatment. At random three bolts were tested in direct tension. It was stated that the average ultimate load of the three bolts in direct tension was 53.5 kips which is 100.3% of the ASTM specified minimum (Hansen and Rumpf 1960). The standard deviation of the tension tests was not reported.

3.1.6 Robert T. Foreman and John L. Rumpf (1961)

Nine compact butt joints fabricated from structural plate and fastened with 7/8-inch, 1-inch, and 1-1/8-inch A325 bolts were tested. This research was performed to illustrate the conservatism of the 1954 specification.

Bolts were tested in direct tension and double shear to verify the bolt properties. Only the direct tension will be considered herein. Five bolts of each size were tested in direct tension and data for the load versus elongation graph was recorded. The 7/8-inch and 1-inch A325 bolts tested were 5-1/2-inches long whereas the 1-1/8-inch bolts tested were 6-inches long. The bolts used in the joints were ordered to have the minimum specified ultimate strength. The results were not published. However it was stated that the 7/8-inch bolts on average had 102% of the specified minimum ultimate strength and the 1-inch and 1-1/8-inch A325 bolts were 106% and 114% of the specified minimum ultimate strength, respectively (Foreman and Rumpf 1961).

3.1.7 Stanley E. Dlugosz and John W. Fisher (1962)

Dlugosz and Fisher tested five lots of 7/8-inch A325 bolts in direct tension and torque induced tension. Only the bolts tested in direct tension will be discussed and considered. A shorter thread length with a heavier head was being evaluated for A325 bolts during this time period. This research wanted to determine if the shorter thread length would impair the performance of an A325 bolt. The effect of the thread length under the nut was also considered.

To determine if the bolt strength had an effect on the bolt behavior, two strengths of A325 bolts were tested. Four of the lots had the specified minimum tensile strength for an A325 bolt, whereas the remaining lot had a strength twenty-five percent larger than the specified minimum tensile strength. Approximately 0.05 inches per minute was used as the speed of testing. The differences in the five lots as well as the results can be seen in Table 3-5 (Dlugosz and Fisher 1962).

Table 3-5: Direct Tension Tests (Dlugosz and Fisher 1962)

Lot	Things to Note About the Lots	Bolt Length (inches)	Percent of ASTM Specification	Thread Length Between Bottom Face of Nut & Thread Run-out (inches)	Number of Bolts Tested	Average Ultimate Load (kips)	Elongation at Failure (inches)
B	regular semi-finished	5 1/2	100%	3/4	5	54.3	0.310
8B	heavy head, short thread length	5 1/2	100%	1/8	5	55.5	0.188
				1/4	5	54.1	0.188
C	regular semi-finished	9 1/2	100%	3/4	3	53.5	0.380
E	heavy head, short thread length	5 1/2	125%	1/8	5	67.5	0.188
				1/4	4	65.2	0.188
H	heavy head, short thread length	9 1/2	100%	1/8	5	58.2	0.280

The A325 bolts which had the minimum tensile strength and heavy hex head with shorter thread lengths (lots 8B and H) failed by stripping of the threads. The remaining three lots (with the regular head and longer thread length (lots B and C), and the heavy hex bolts with twenty-five percent higher strength (lot E)) "ruptured by shearing on the transverse plane of the thread" (Dlugosz and Fisher 1962). The direct tension characteristics of Lot 8B (heavy head bolt) is compared with Lot B (regular semi-finished bolt) in Figure 3-3 (Dlugosz and Fisher 1962). The effect of the decrease in thread length under the head is apparent from Figure 3-3 (Dlugosz and Fisher 1962).

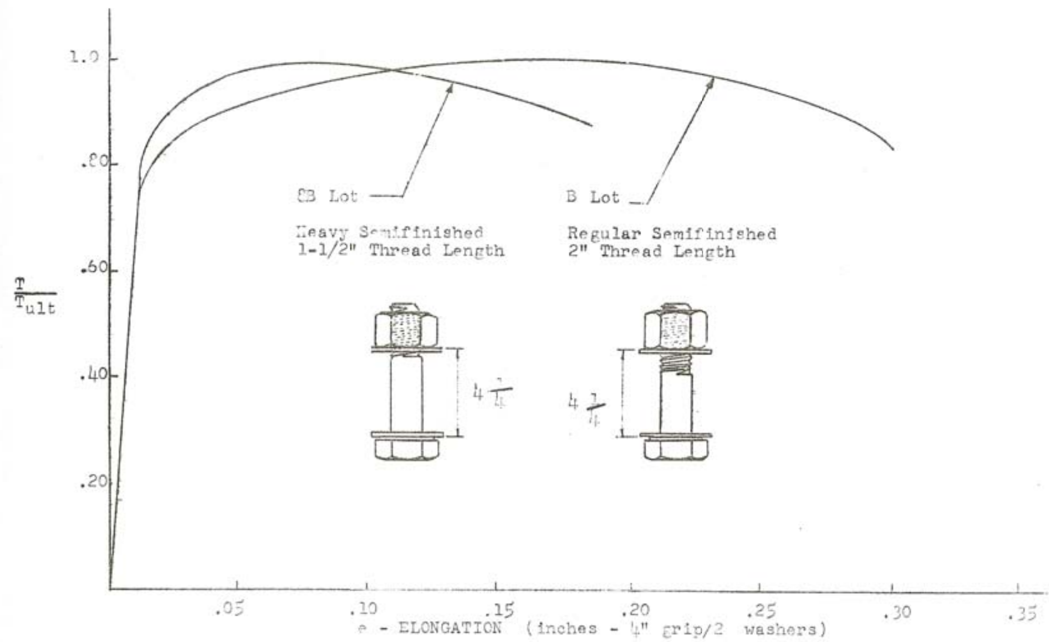


Figure 3-3: Direct Tension Calibration Comparison (Dlugosz and Fisher 1962)

3.1.8 R. A. Bendigo, R. M. Hansen, and J. L. Rumpf (1963)

Bendigo, Hansen, and Rumpf (1963) investigated sixteen double shear butt joints. This was done to determine the influence of the joint length on the ultimate strength of bearing type connections. Tests were conducted on bolted joints “in order to measure the ability of the bolts to redistribute load…” (Bendigo et al. 1963).

Anywhere from three to sixteen 7/8-inch A325 bolts were used in the butt joints. The thread lengths on the A325 bolts specified during 1963 were longer than today’s specification. Bolts from each lot were tested in direct tension to obtain tension-elongation curves. The clamping force of the bolts used in the test joints were determined from the tension-elongation curves. Table 3-6 (Bendigo et al. 1963) summarizes the tensile strength of the 7/8-inch bolts.

3.1.9 John L. Rumpf and John W. Fisher (1963)

The behavior and performance of A325 bolts, both with regular and heavy hex heads, in direct and torqued tension were studied. The heavy hex headed A325 bolts had a shorter thread length than the regular headed bolts. The bolts tested ranged in size from 7/8-inch to 1-1/8-inches in diameter. The threads were mostly rolled but a few of the bolts tested had cut threads. Only the direct tension tests will be considered herein.

The ninety A325 bolts tested in direct tension were loaded at a rate of 0.005 inches per minute. The results of the direct tension tests for the different diameters and lengths of A325 bolts are summarized in Table 3-7 (Rumpf and Fisher 1963).

Table 3-6: Direct Tension Tests (Bendigo et al. 1963)

Bolt Lot Mark	Bolt Length (inches)	Mean Tensile Strength (kips)	Std. Dev. Tensile Strength (kips)
D	5 1/2	56.9	0.55
T	6 1/2	54.8	0.94
U	7		
V	7 1/2		
W	8 1/2		
C	9 1/2	53.4	0.12
L	3 1/2	55.2	0.97

Table 3-7: Direct Tension Tests (Rumpf and Fisher 1963)

Head and Thread Type	Lot	Nominal Diameter (inches)	Bolt Length (inches)	Thread Length (inches)	Grip Length (inches)	Thread Length in Grip (inches)	Number of Bolts Tested	Mean Ultimate Load (kips)	Standard Deviation of Ultimate Load (kips)	Elongation at Failure (inches)	Standard Deviation of Elongation (kips)
Regular Head with Rolled Threads	B	7/8	5 1/2	2	4.25	0.75	5	54.3	1.22	0.31	0.047
	C	7/8	9 1/2	2 1/4	8.25	1.00	5	53.3	0.30	0.31	0.044
	D	7/8	5 1/2	2	4.25	0.75	5	56.9	0.55	0.27	0.050
	D	7/8	5 1/2	2	3.80	0.30	0	-	-	-	-
	Z	7/8	5 1/2	2	4.25	0.75	8	60.4	2.45	0.24	0.040
	A	1	5 1/2	2 1/4	4.25	1.00	5	73.7	0.96	0.36	0.030
	Y	1	5 1/2	2 1/4	4.25	1.00	5	73.1	0.94	0.39	0.033
	G	1 1/8	6	2 1/2	4.25	0.75	5	91.2	1.91	0.30	-
Regular Head with Cut Threads (from same steel and heat treatment)	Q	7/8	5 1/2	2 1/4	4.25	1.00	3	53.9	0.14	0.37	0.036
	R	7/8	5 1/2	3 1/4	4.25	2.00	3	52.2	0.09	0.38	-
	S	7/8	5 1/2	5 1/2	4.25	4.25	3	53.8	0.52	0.53	0.164
	T	7/8	6 1/2	2 1/4	5.00	0.75	3	54.8	1.04	0.35	0.050
	U	7/8	7	2 1/4	5.50	0.75	3	55.2	0.72	0.39	0.026
	V	7/8	7 1/2	2 1/4	6.25	1.00	3	53.8	0.51	0.33	0.026
	W	7/8	8 1/2	2 1/4	7.00	0.75	3	55.2	0.95	0.34	0.040
Heavy Head with Rolled Threads	H	7/8	9 1/2	1 3/4	8.125	0.375	7	58.3	1.29	-	-
	E	7/8	5 1/2	1 1/2	4.25	0.250	4	65.2	1.04	0.19	-
	E	7/8	5 1/2	1 1/2	4.125	0.125	5	67.5	1.01	0.18	-
	8A	7/8	5 1/4	1 1/2	4.00	0.250	5	59.4	1.12	0.31	-
	8A	7/8	5 1/4	1 1/2	4.50	0.750	-	-	-	-	-
	8B	7/8	5 1/2	1 1/2	4.125	0.125	5	55.6	1.00	0.19	-
	8B	7/8	5 1/2	1 1/2	4.25	0.250	5	54.1	1.60	0.19	-

It was concluded from the research that the bolts had similar elongation characteristics if the strengths were slightly above and up to 125% of the minimum specified tensile strength. It was also concluded that for both the regular and heavy headed bolts the deformation decreased when a lesser amount of exposed threads were under the nut. Figure 3-4 (Rumpf and Fisher 1963) shows the load versus elongation of bolts with different thread lengths. “The shorter length of thread under the nut of the bolt with short thread results in a decrease in the elongation capacity” (Rumpf and Fisher 1963) as shown in Figure 3-4 (Rumpf and Fisher 1963).

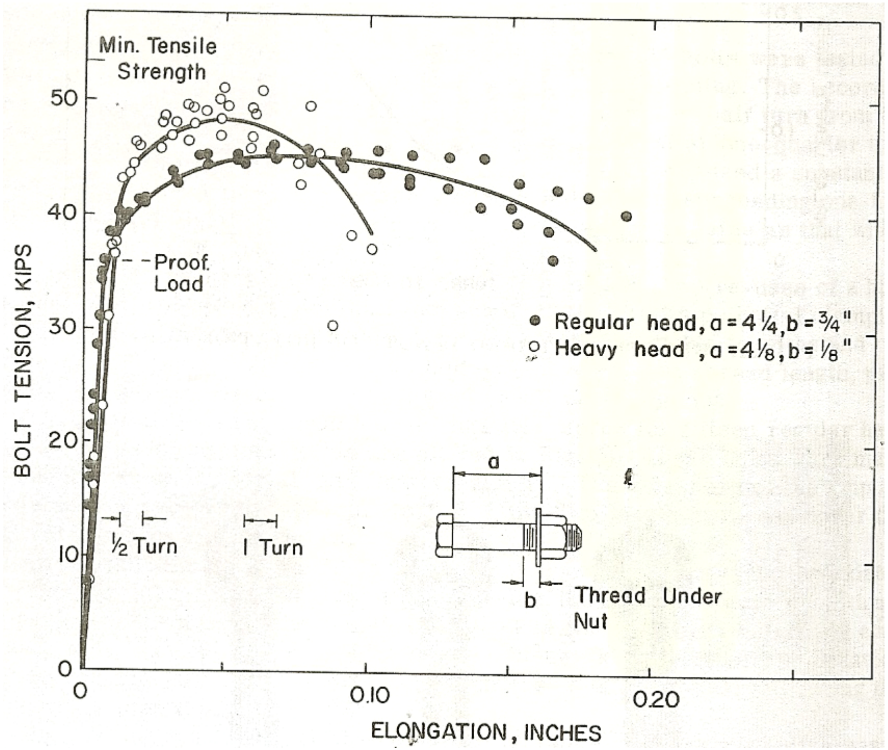


Figure 3-4: Effect of Thread Length Under the Nut (Rumpf and Fisher 1963)

3.1.10 John W. Fisher, Paul O. Ramseier, and Lynn S. Beedle (1963)

During the early 1960s the use of high-strength steel for construction was becoming more common. This research was performed “to investigate the behavior of these steels when used in connections fabricated with A325 high-strength bolts” (Fisher et al. 1963). The properties of the A325 bolts were also established during this research by testing them in direct tension, torqued tension, and double shear (in tension and compression).

The bolts tested were 7/8-inch A325 with lengths varying from 5-1/4 to 9-1/2 inches. The same procedure was used to test the bolts in direct tension as was used in Rumpf and Fisher (1963), from Section 3.1.9. The summary of the bolts tested in direct tension are given in Table 3-8 (Fisher et al. 1963).

A single A325 bolt was tested in double shear by A440 plates loaded in tension and compression. Figure 3-5 (Fisher et al. 1963) shows the shear stress versus deformation for the two different types of tests. It was determined that "the shear strength of single bolts tested in plates loaded in tension was approximately 10% less than the shear strength from the compression test. When bolts are loaded by plates in tension, the bearing condition near the end shear planes causes a prying action and results in an additional tensile component which reduces the bolt shear strength" (Fisher et al. 1963).

3.1.11 James J. Wallaert (1964)

When higher-strength bolts (A354BD and A490) are used in joints with high-strength steel, fewer bolts should be required due to the bolts having a larger tensile strength (Wallaert and Fisher 1965). A larger tensile strength should induce greater clamping force thus higher shear strength (Wallaert and Fisher 1965). Figure 3-6 (Wallaert 1964) shows shear stress due to double shear versus deformation for an A141 rivet, an A325 bolt, and an A490 bolt.

Table 3-8: Direct Tension Tests (Fisher et al. 1963)

Bolt Lot	Bolt Length (inches)	Number of Tests	Mean Ultimate Load (kips)	Std. Dev. Ultimate Load (kips)
D	5 1/2	5	56.9	0.55
8A	5 1/4	5	59.4	1.11
8B	5 1/2	5	55.5	1.12
H	9 1/2	7	58.3	1.28

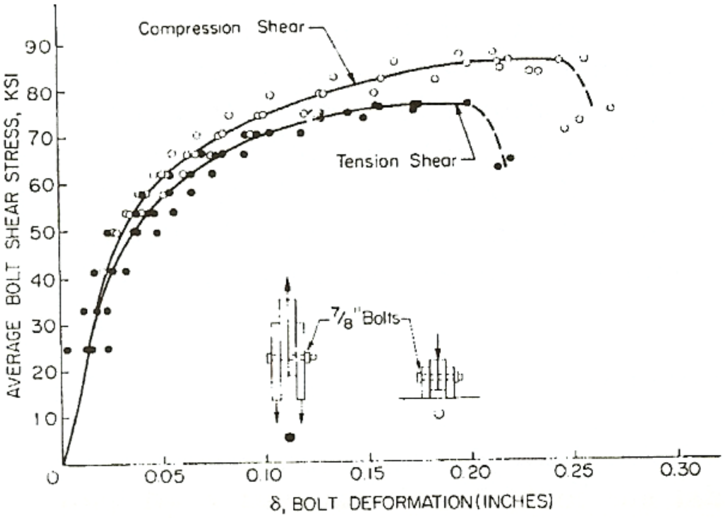


Figure 3-5: Shear-Deformation Relationship (Fisher et al. 1963)

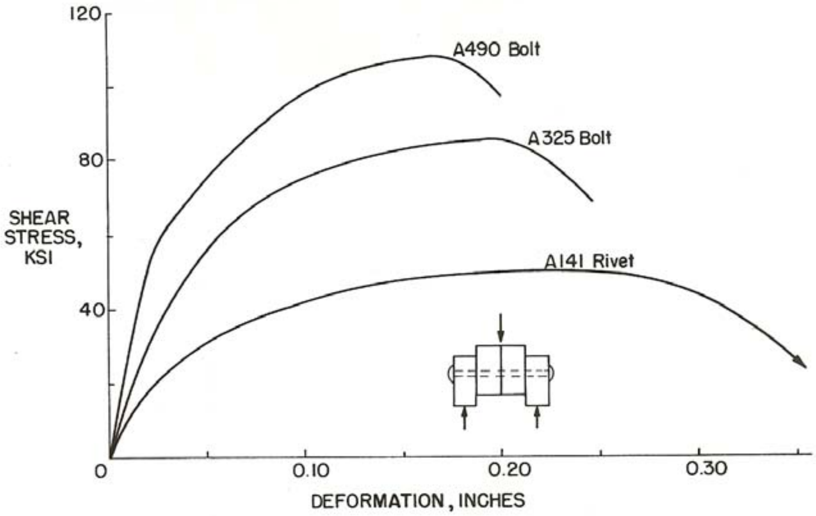


Figure 3-6: Stress-Deformation Curves for Rivets and Bolts (Wallaert 1964)

For a Master's of Science degree at Lehigh University, Wallaert studied the behavior and performance of a high-strength structural bolt in double shear. A number of variables which could affect the ultimate shear strength and the deformation at ultimate load were investigated. To establish the minimum shear strength, the bolts used for testing were deliberately ordered near the minimum tensile strength as specified by ASTM (Wallaert and Fisher 1965).

Bolts of 7/8-inch and 1-inch in diameter, of grade A325, A354 BC, A354 BD (similar to A490), and A490 were tested to determine their double shear strength through the full shank area. Some of the bolts tested had heavy heads whereas some had regular heads. Three lots of A354 BC bolts were tested, from which one of the three lots had heavy heads. Three lots of A354 BD bolts, which all had regular heads, where tested. Two lots of A490 structural bolts were tested as well. The heavy head A354 bolts “were made to conform to the size requirements specified in ASTM A325 by reheat-treating AISI 4140 alloy steel bolts obtained from a Canadian firm” (Wallaert and Fisher 1964).

Full size bolts as well as 0.505 inch diameter specimens were tested in direct tension to determine the mechanical properties. Only the results of full size bolts will be considered herein. The average bolt tensile strength was published in units of kips per square inch. The strength was determined by using the effective area as previously discussed in Section 2.2

$$A_{eff} = \frac{\pi}{4}\left(d - \frac{0.9743}{n}\right)^2 \tag{3-1}$$

as shown in Table 3-9 (Wallaert and Fisher 1965) to obtain the strength in units of kips.

Table 3-9: Direct Tension Tests (Wallaert and Fisher 1965)

Grade	Lot	Nominal Diameter (inches)	Bolt Length (inches)	Number of Bolts Tested	Bolt Tensile Strength (ksi)	Number of Threads per Inch	Mean Ultimate Load (kips)
A354BC	AC	7/8	5 1/4	3	140.8	9	65.01
	CC	7/8	5 1/2	3	134.8	9	62.24
	DC	1	5 1/2	3	137.0	8	82.99
A354BD	ED	7/8	5 1/2	3	168.3	9	77.71
	FD	1	5 1/2	3	163.8	8	99.22
	GD	7/8	9 1/2	3	163.3	9	75.40
A490	KK	7/8	5 1/2	3	168.6	9	77.85
	JJ	1	5 1/2	3	163.5	8	99.04
A325	8A	7/8	5 1/4	5	128.5	9	59.33
	8B	7/8	5 1/2	5	117.1	9	54.07
	D	7/8	5 1/2	5	123.1	9	56.84
	H	7/8	9 1/2	7	126.1	9	58.22
	Q	7/8	5 1/2	3	116.7	9	53.88
	R	7/8	5 1/2	3	113.0	9	52.18
	S	7/8	5 1/2	3	116.4	9	53.75
	T	7/8	6 1/2	3	118.6	9	54.76
	Y	1	5 1/2	3	120.6	8	73.05
	Z	7/8	5 1/2	3	130.7	9	60.35

Resistance factors will be calculated based on the tests performed on the A354 BD, since they have the same chemical and physical characteristics of A490 bolts. The results of the A354 BC bolts will not be considered when calculating resistance factors.

There were four testing jigs to test the lots of bolts in double shear. The tests were performed in a tension or compression jig made from either A440 steel or constructional alloy steel (Wallaert and Fisher 1964). The constructional alloy steel (denoted Q & T) was stronger than A440 but was less ductile. Table 3-10 (Wallaert and Fisher 1964) depicts the number of bolts tested in each jig.

Table 3-10: Testing Matrix (Wallaert and Fisher 1964)

Bolt Grade	Lot	Diameter (inches)	Head	Length (inches)	Jigs Tested				
					Compression			Tension	
					A440	Q & T	A7	A440	Q & T
A354 BC	AC	7/8	Heavy	5 1/4	3	3	-	-	-
	CC	7/8	Regular	5 1/2	3	3	-	3	3
	DC	1	Regular	5 1/2	3	3	-	3	3
A354 BD	ED	7/8	Regular	5 1/2	3	3	-	3	3
	FD	1	Regular	5 1/2	3	3	-	3	3
	GD	7/8	Regular	9 1/2	3	3	-	3	3
A490	KK	7/8	Heavy	5 1/2	3	-	-	3	-
	JJ	1	Heavy	5 1/2	-	-	-	-	3
A325	8B	7/8	Heavy	5 1/2	3	-	-	3	-
	Q	7/8	Regular	5 1/2	-	-	3	-	-
	R	7/8	Regular	5 1/2	-	-	3	-	-
	S	7/8	Regular	5 1/2	-	-	3	-	-
	T	7/8	Regular	6 1/2	-	-	3	-	-
	Y	1	Regular	5 1/2	-	-	27	-	-
	Z	7/8	Regular	5 1/2	-	-	27	-	-

Since the tests on single bolts were preformed in double shear, the results will be excluded in this research due to the complexities associated with double shear testing. However, some of the conclusions made from the research are worth noting.

It was found that the type of material used does not affect the ultimate shear strength. For one lot, the deformation of a bolt tested in the Q & T jig was nearly double the deformation from the A440 steel jig. “The test data shows that the variation in shear strength for a particular type of fastener as influenced by the type of connected material is no greater than the variation in shear strengths between the different bolt lots for a particular type of fastener. Thus, the test data indicates that the type of connected material has no influence on the ultimate shear strength" (Wallaert 1964).

Figure 3-7 (Wallaert 1964) shows the typical mean stress versus deformation curves for the two types of testing devices (tension and compression). As can be seen from Figure 3-7 (Wallaert 1964), the "ultimate shear strength of bolts tested in a tension jig is lower than when the bolt is tested in a compression jig" (Wallaert 1964).

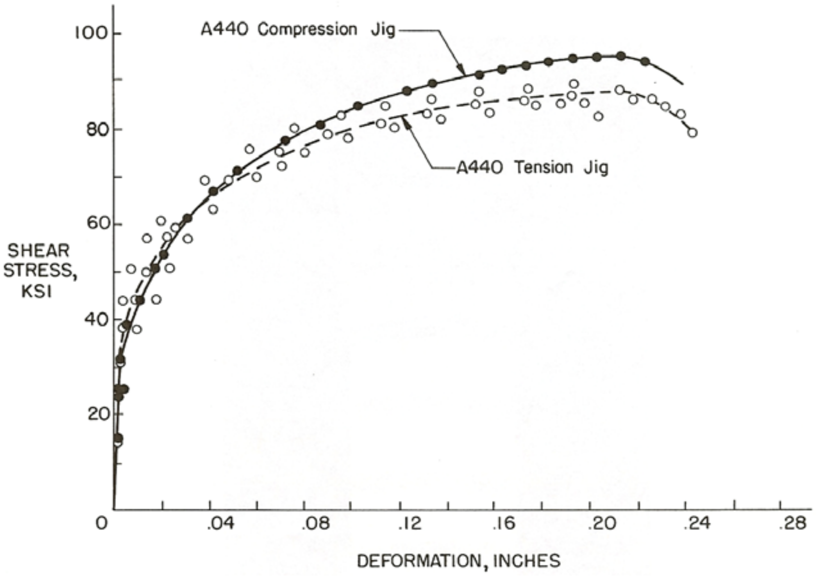


Figure 3-7: Stress-Deformation Curves for A354 Bolts in Tension

It was noticed that the tension jig gave a lower shear strength compared to the compression jig. "When considering all of the test results, the ultimate shear strength for bolts tested in the tension jigs is 6% to 13% lower when compared to the compression jig tests using A440 steel. This same trend was observed in the Q & T jig tests with the percent reduction in strength varying from 8% to 13%" (Wallaert 1964). This reduction in shear strength when bolts are tested in a tension fixture is due to lap plate prying, "a phenomena which tends to bend the lap plates of the tension jig outward" (Wallaert 1964). "Due to the uneven bearing deformations of the test bolt, the resisting force P/2 does not act at the centerline of the lap plate, but acts at a distance 'e' to the left of it. This sets up a clockwise moment M_L = P/2(e), which tends to bend the lap plate away from the main plate. However, this moment, M_L, is resisted by the counterclockwise moment M_R = ΔT(a). This is the moment which induces an additional force, ΔT, into the bolt" (Wallaert 1964). The mechanism of lap plate prying just described is shown in Figure 3-8

(Wallaert 1964). When comparing the ultimate shear strengths and deformations from the tension and compression jigs, regardless of the material, it was observed that the tension jig had more consistent results.

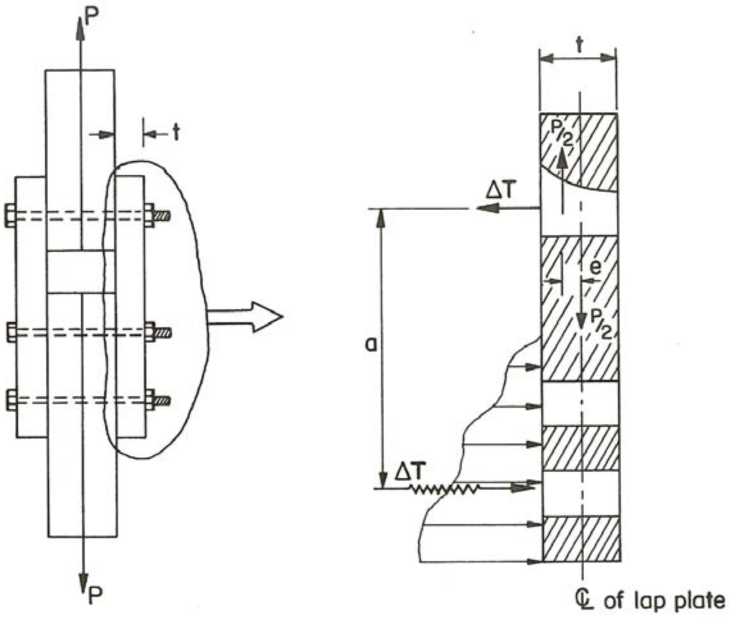


Figure 3-8: Lap Plate Prying (Wallaert 1964)

3.1.12 E. W. J. Troup and E. Chesson, Jr. (1964) Gordon Sterling and John W. Fisher (1964)

Troup and Chesson (1964) from the University of Illinois-Urbana and Sterling and Fisher (1964) from Lehigh University provided data on the behavior of A490 bolts in direct tension and torqued tension. Only the direct tension tests will be considered herein. The research was completed at two universities "to determine whether different testing procedures employed at various laboratories would contribute significantly to experimental scatter" (Troup and Chesson 1964). The A490 bolts tested were obtained by a manufacturer and then split between the two universities.

This research was approved by the Research Council on Riveted and Bolted Structural Joints in March 1963. The study was performed to provide additional data about A490 bolts for possible revisions to the Council's specifications in 1964. "The American Society for Testing and Materials acknowledged the need for a structural bolt of higher strength by developing a specification for a heavy structural bolt, comparable dimensionally to the ASTM A325 fastener but with material properties similar to the ASTM A354 grade BD bolt" (Troup and Chesson 1964).

Bolts tested of grade A490 where 7/8-inch in diameter with lengths of 5-1/2-inches and 9-1/2-inches (Sterling et al. 1965). The threads, length 1-7/16-inches, were produced by rolling between dies for the bolts with lengths equal to 5-1/2-inches whereas the 9-1/2-inch bolts had threads, length 1-3/8-inch, which were produced by machine cutting (Sterling et al. 1965).

The testing machine, measurement of elongation of the bolts, and the loading rate were different at the two universities. The University of Illinois-Urbana used a 120-kip Baldwin hydraulic testing machine, whereas a 300-kip Baldwin hydraulic testing machine was used at Lehigh University (Sterling et al. 1965). At Lehigh University extensometers were attached to the bolts directly. Lever type extensometers were used at the University of Illinois-Urbana. The bolts were tested at a head speed of about 0.05 inches per minute at the University of Illinois-Urbana, whereas at Lehigh University the speed was 0.01 inches per minute (Sterling et al. 1965).

The number of direct tension tests and results from Lehigh University and the University of Illinois-Urbana are summarized in Table 3-11 (Troup and Chesson 1964) (Sterling and Fisher 1964). As can be seen from the table, there was excellent agreement between the data from the two universities.

Table 3-11: Direct Tension Results (Troup and Chesson 1964) (Sterling and Fisher 1964)

Bolt Length (inches)	Testing Location	Nominal Grip (inches)	Thread Length in Grip (inches)	Number of Bolts Tested	Mean Ultimate Load (kips)	Standard Deviation (kips)	Mean Elongation (inches)
5 1/2	Illinois	4 1/8	1/8	5	75.9	0.45	0.13
		4 9/16	9/16	5	72.1	0.54	0.23
	Lehigh	4 1/8	1/8	5	76.0	0.54 (1.07)	0.137
		4 9/16	9/16	5	72.1	0.17 (0.57)	0.245
9 1/2	Illinois	8 1/4	1/8	6	74.6	1.57	0.15
		8 11/16	9/16	5	69.8	1.32	0.19
	Lehigh	8 1/4	1/8	5	73.2	1.59	0.12
		8 11/16	9/16	5	70.8	1.69 (1.36)	0.18

Note: The standard deviations shown in parentheses are different values reported in

In conclusion, the only result which seemed to differ considerably, approximately 10% or less, was the mean elongation at ultimate load, which is not shown in the table. It was concluded that the ultimate strength increases as the amount of thread in the grip decreases (Sterling and Fisher 1964). Figure 3-9 (Troup and Chesson 1964) and 3-10 (Troup and Chesson 1964) shows the average load versus elongation curves. From Figure 3-9 (Troup and Chesson 1964) "it can be seen that in the elastic region, a difference in the thread length in the grip (1/8 inch or 9/16 inch) has little effect. However, the ultimate load for bolts with the shorter thread length in the grip averaged about 5 percent greater than that for bolts with the longer included thread length. Also, there was a noticeable increase in ductility or total elongation observed for the tests conducted with the longer (9/16 inch) thread in the grip…" (Troup and Chesson 1964). Similar results can be seen from Figure 3-10 (Troup and Chesson 1964) which shows the average load versus elongation curves for 9-1/2-inch bolts. "The effect of shorter thread length in the grip produced about an 8 percent increase in ultimate load" (Troup and Chesson 1964) for the 9-1/2-inch long bolts, as shown in Figure 3-10 (Troup and Chesson 1964).

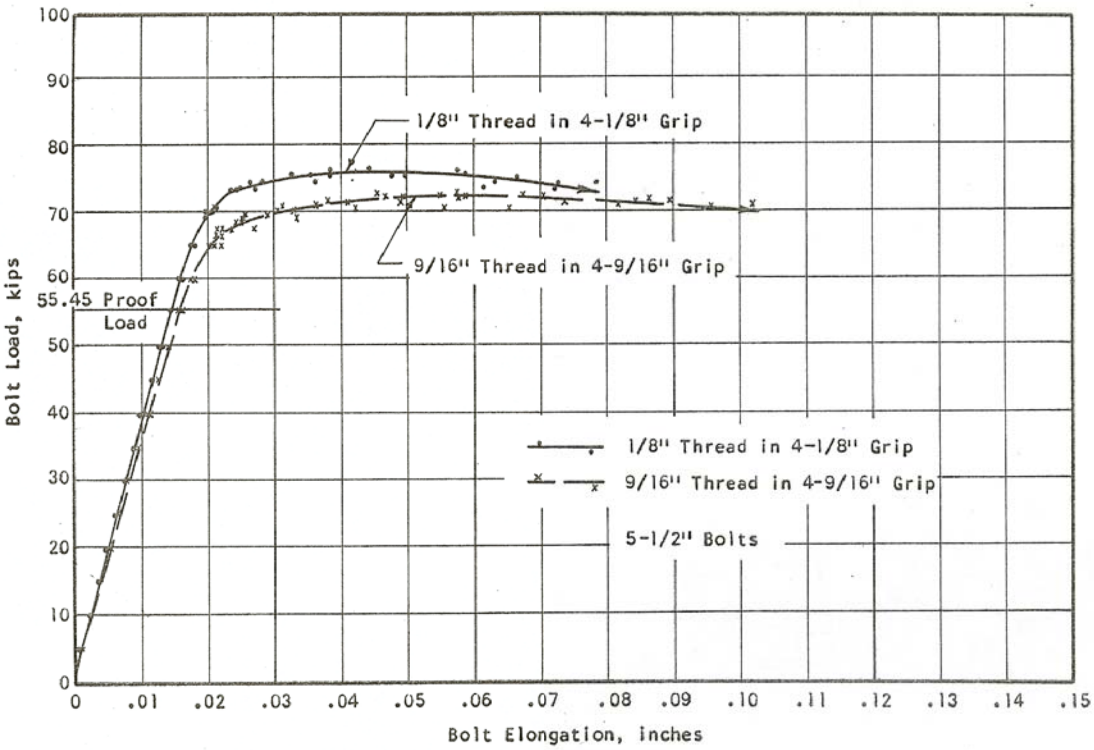


Figure 3-9: Tension versus Elongation - 7/8" x 5-1/2" A490 (Troup and Chesson 1964)

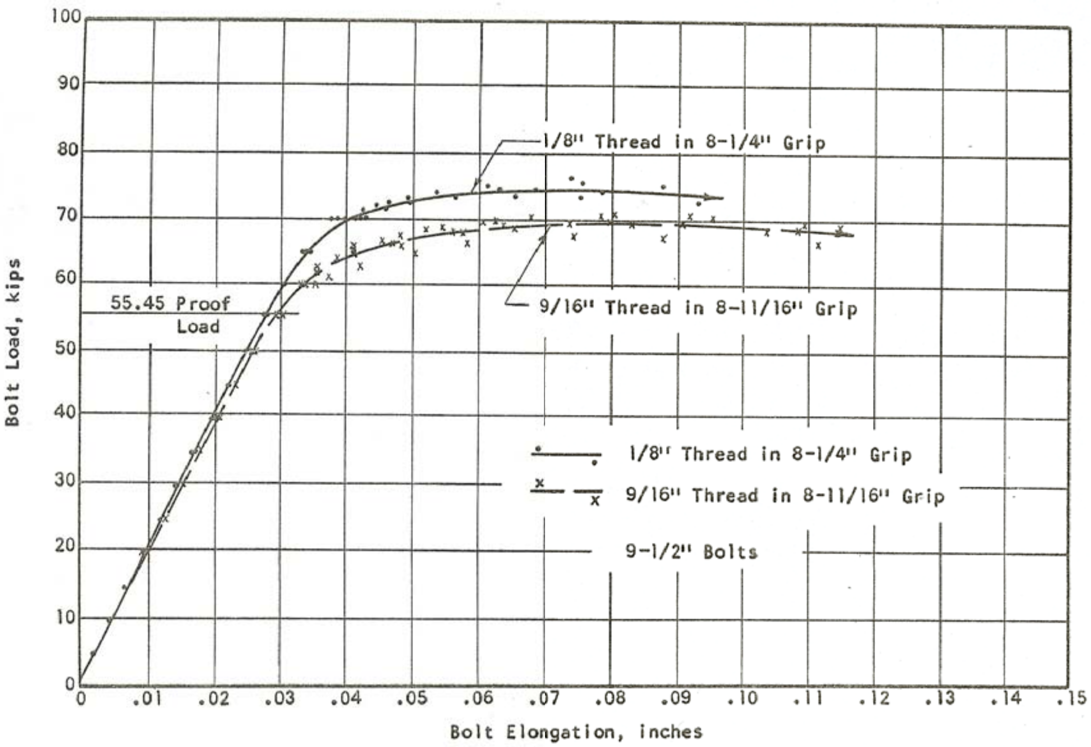


Figure 3-10: Tension versus Elongation - 7/8" x 9-1/2" A490 (Troup and Chesson 1964)

3.1.13 Richard J. Christopher (1964)

Richard J. Christopher of Lehigh University tested A354 BC, A354 BD, and A490 bolts in direct tension as part of his Master's of Science Degree in 1964. This study's main objective was to investigate the behavior and performance of alloy steel structural bolts under a variety of conditions of installation and service load (Christopher et al. 1966).

Four lots of both A354 BC and A354 BD along with eight lots of A490 bolts were tested in tension. The A490 bolts have the same chemical and physical characteristics of the A354 BD bolts but have the heavy hex head and short thread length like the A325 bolts. The bolts tested were 7/8-inch and 1-inch in diameter. Before the results are summarized it should be noted that "the A490 specification was not yet published at the time these tests were initiated and since the A354 bolt was not in general use as a structural fastener, all of the bolts used for this study were manufactured specially and because of this, exhibited a greater variation in properties, both geometric and structural, then would ordinarily be expected" (Christopher 1964). A few of these lots of bolts were tested in double shear as previously explained in Section 3.1.11 (Wallaert 1964). The results from the eighty-four direct tension tests are summarized in Table 3-12

(Christopher 1964). The lots were designated by two letters followed by numbers and letters. The bolt diameter in eighths of an inch is indicated by the first number following the double letter. The length of thread under the nut in sixteenths of an inch is the next number after the dash. Lastly, the S and L designate between short (approximately four inches) and long grip lengths (approximately 8 inches).

Table 3-12: Direct Tension Results (Christopher 1964)

Lot	Grade	Head Type	Nominal Diameter (inches)	Type of Thread	Bolt Length (inches)	Number of Bolts Tested	Mean Ultimate Load (kips)	Standard Deviation of Ultimate Load (kips)	Elongation at Failure (inches)
AC-7-2S	A354BC	Heavy Hex	7/8	Cut	5 1/4	3	72.6	1.88	0.173
AC-7-9S	A354BC	Heavy Hex	7/8	Cut	5 1/4	3	65.0	1.57	0.190
BC-8-2S	A354BC	Heavy Hex	1	Cut	5 1/4	3	91.0	2.26	0.140
BC-8-11S	A354BC	Heavy Hex	1	Cut	5 1/4	3	82.9	1.60	0.263
CC-7-12S	A354BC	Regular Hex	7/8	Rolled	5 1/2	3	62.3	0.20	0.300
DC-8-16S	A354BC	Regular Hex	1	Rolled	5 1/2	3	83.1	1.22	0.293
AD-7-2S	A490 *	Heavy Hex	7/8	Cut	5 1/4	3	83.1	2.63	0.083
AD-7-9S	A490 *	Heavy Hex	7/8	Cut	5 1/4	3	76.5	1.51	0.113
BD-8-2S	A490 *	Heavy Hex	1	Cut	5 1/4	3	102.1	1.83	0.127
BD-8-11S	A490 *	Heavy Hex	1	Cut	5 1/4	3	100.0	0.20	0.143
CD-7-2L	A490 *	Heavy Hex	7/8	Cut	9 1/4	3	82.6	1.25	0.120
CD-7-9L	A490 *	Heavy Hex	7/8	Cut	9 1/4	3	74.5	0.44	0.120
DD-8-2L	A490 *	Heavy Hex	1	Cut	9 1/4	3	105.4	0.71	0.147
DD-8-11L	A490 *	Heavy Hex	1	Cut	9 1/4	3	96.7	0.53	0.173
ED-7-12S	A354BD	Regular Hex	7/8	Rolled	5 1/2	3	77.8	0.67	0.120
FD-8-16S	A354BD	Regular Hex	1	Rolled	5 1/2	3	99.3	2.18	0.207
GD-7-12L	A354BD	Regular Hex	7/8	Cut	9 1/2	3	75.5	0.82	0.137
HD-8-16L	A354BD	Regular Hex	1	Cut	9 1/2	3	100.5	1.25	0.137
LI-7-2S	A490	Heavy Hex	7/8	Rolled	5 1/2	5	76.0	0.54	0.137
LI-7-9S	A490	Heavy Hex	7/8	Rolled	5 1/2	5	72.1	0.17	0.245
AB-7-2L	A490	Heavy Hex	7/8	Cut	9 1/2	5	73.2	1.59	0.120
AB-7-9L	A490	Heavy Hex	7/8	Cut	9 1/2	5	70.8	1.69	0.180
KK-7-3S	A490	Heavy Hex	7/8	Rolled	5 1/2	5	77.9	0.44	0.115
JJ-8-6S	A490	Heavy Hex	1	Rolled	5 1/2	5	99.2	1.57	0.189

* Made by re-heat treating Canadian bolts manufactured to AISI specification 4140 to conform to A490

From Table 3-12 (Christopher 1964) it can be seen that bolts have a higher tensile strength and lower elongation if a shorter length of threads is under the nut, than when the same lot is tested with more threads under the nut. Figure 3-11 (Christopher 1964) is the tension versus elongation graph of one lot of A490 bolts which shows the effect of thread length under the nut. "This higher strength is partially the result of a small decrease in thread depth near the thread runout which results in a somewhat larger cross sectional area. This increase in strength may also be due to the fact that failure is forced to occur over a relatively short length of thread" (Christopher 1964). When a longer thread length was under that nut the bolts normally failed on a diagonal plane whereas for the shorter length the failure was not nearly as inclined. “Because of the short length of highly stressed threaded portion, elongation capacity is reduced for short thread lengths under the nut” as can be seen in Figure 3-11 (Christopher 1964).

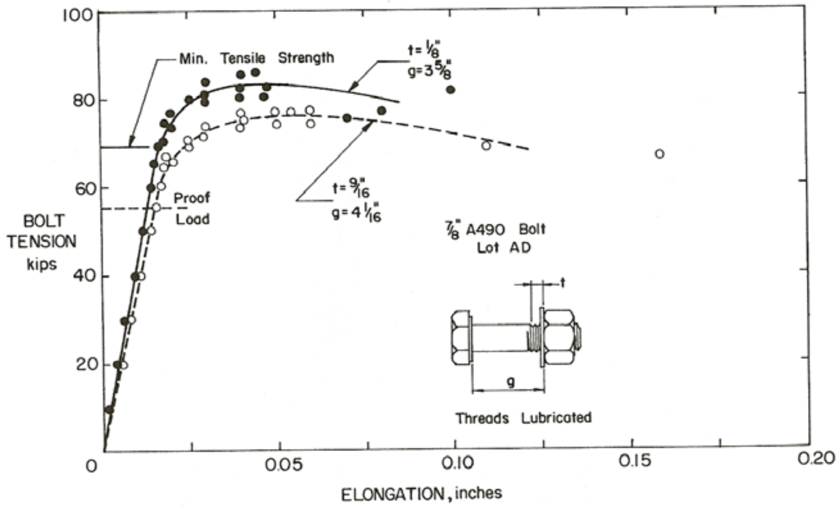


Figure 3-11: Effect of Thread Length Under Nut (Christopher 1964)

Since A354 BD bolts have the same chemical and physical characteristics of A490 bolts, resistance factors will be calculated based on the tests performed on the A354 BD and A490 bolts. The results of the A354 BC bolts will not be considered when calculating resistance factors.

3.1.14 Gordon H. Sterling and John W. Fisher (1966)

“The recent development of the ASTM A490 high-strength bolt was necessitated by the increased use of high-strength steels. Fasteners of higher strength than the A325 bolt had to be developed so that the connections could have reasonable proportions” (Sterling and Fisher 1966). Four compact joints were tested to determine the behavior of A490 bolts in butt joints of A440 steel (Sterling and Fisher 1965). The fasteners used in this research were 7/8-inch in diameter.

So that a theoretical prediction of the joint load could be made, load versus deformation curves for single A490 bolts were determined. The single 7/8-inch, A490 bolts were tested in double shear. Due to the complexity associated with double shear the results will not be considered herein.

3.1.15 Geoffrey L. Kulak and John W. Fisher (1968)

This research was carried out to examine the behavior of constructional alloy bolted butt joints. Both information on the ultimate strength and slip behavior of the butt joint were obtained. Eighteen joints were tested with A514 steel fastened by A325 or A490 bolts. Four butt joints used 1-inch A490 bolts, six used 1-1/8-inch A325 bolts, seven used 7/8-inch A490 bolts, and the last butt joint used 1-1/8-inch A490 bolts. The fasteners of the same diameter and grade came from the same lot of bolts.

Some of the bolts from each lot were tested in direct tension and torqued tension to establish the strength of the lot compared to the minimum specified value. Only the three lots of bolts tested in direct tension will be considered herein. The bolts tested and used in this research were ordered to the minimum ASTM strength requirements (Kulak 1967). Table 3-13 (Kulak and Fisher 1968) shows the results of the direct tension tests for the A490 bolts.

Table 3-13: Direct Tension Tests (Kulak and Fisher 1968)

Lot	Bolt Grade	Bolt Diameter (inches)	Grip (inches)	Tensile Strength (kips)
B	A490	7/8	4	72.2
C	A490	1 1/8	8	119.5
D	A490	7/8	4	75.4
JJ	A490	1	4	99.1

3.1.16 John W. Fisher and Geoffrey L. Kulak (1968)

Fifteen double-shear butt joints were tested in static tension to study hybrid connections. The butt joints had four to nineteen A325 or A490 bolts of diameter 7/8-inch or 1-1/8-inch. Of the fifteen butt joints, ten consisted of A514 steel plates with 1-1/8-inch A325 bolts. The other five butt joints were hybrid. Two butt joints had the main plate steel from A36 and the lap plate was from A440 connected with 7/8-inch A325 bolts. The remaining three butt joints were tested with A440 main plate steel and A514 lap plate steel connected with 7/8-inch A325 or A490 bolts.

The bolts used for the butt joints were ordered with ASTM's minimum strength requirements. Bolts from each lot were tested in direct and torqued tension and double shear. Herein only the bolts tested in tension will be considered. The results of the direct tension tests can be seen in Table 3-14 (Fisher and Kulak 1968). It should be noted that only the mean values of the tensile strength were reported in the journal article.

Table 3-14: Direct Tension Tests (Fisher and Kulak 1968)

Bolt Grade	Bolt Diameter (inches)	Grip (inches)	Tensile Strength (kips)
A325	1 1/8	4	81.4
		3 3/4	106.3
		7 1/2	104.5
	7/8	6 3/4	68.3
		4 1/2	69.3
		5 7/8	60.6
A490	7/8	5 7/8	78.1

3.2 Tension Tests

Direct tension tests which were performed and published that were not part of the "Large Bolted Joints Project" conducted at Lehigh University are summarized in this section.

3.2.1 W. H. Munse, D. T. Wright, and N. M. Newmark (1952)(1954)

Static and fatigue tests were performed on structural joints connected with high-strength bolts. This research was carried out to indicate that joints with high-strength bolts are generally superior to joints using rivets in either static or fatigue loading conditions (Munse et al. 1954).

The ultimate strength of the A325 bolts used in the joints was determined and summarized in Table 3-15 (Munse et al. 1952). The ultimate load for the 3/4-inch bolts was below the ASTM minimum strength. "Upon close analysis it was found that the 3/4-inch bolts were actually hexagon head cap screws which had an ultimate strength a little lower than required and a bolt head which was somewhat smaller than that specified" (Munse et al. 1952).

Table 3-15: Ultimate Strength (Munse et al. 1952)

Bolt Grade	Bolt Diameter (inches)	Number of Tests	Ultimate Load (pounds)
A325	3/4	7	39,900
A325	7/8	4	66,900
A325	1	10	79,200

3.2.2 T. F. Leahey and W. H. Munse (1954)

During the mid-1950s little data on high-strength bolts in direct tension was available. Five static and eighteen fatigue tests with 3/4-inch, 4-inch long, A325 bolts were performed to determine the behavior of high-strength bolts in tension.

To determine if the bolts used in the connections met ASTM requirements and to obtain the properties of the bolt material, full size bolts were tested in direct tension. As required by ASTM, a ten degree wedge washer was placed under the bolt head while testing in direct tension. Table 3-16 (Leahey and Munse 1954) summarizes the results of the direct tension tests. Round coupons were also tested but will not be considered herein.

Table 3-16: Direct Tension Results (Leahey and Munse 1954)

Bolt Grade	Bolt Diameter (inches)	Ultimate Load (pounds)
A325	3/4	46,700
		47,100
		46,800
		46,750

3.2.3 W. H. Munse, K. S. Petersen, and E. Chesson, Jr. (1961)

During the 1950s engineers wondered whether or not bolts and rivets should be permitted to carry direct tensile loads (Petersen and Munse 1956). Twenty-eight structural T-stub connections with either high-strength bolts or rivets were tested. This research was performed to demonstrate the ability of bolts and rivets to carry direct tensile loads effectively.

The 3/4-inch A325 bolts used in the research were provided by two manufacturers (Petersen and Munse 1956). Five bolts were tested in direct tension of each length and from each manufacturer. Four of the bolts were tested to failure with a ten degree wedge washer, per ASTM, and the remaining bolt was tested without the wedge washer. Table 3-17 (Munse et al. 1961) shows the results of these direct tension tests.

Table 3-17: Ultimate Strength (Munse et al. 1961)

Bolt Manufacturer	Bolt Length (inches)	Ultimate Load (pounds)	
		Wedged*	Not Wedged
Manufacturer "N"	3	45,500	45,800
	4	45,300**	45,500
	4 3/4	47,350	47,100
	5	44,150	43,800
	6	46,820	46,000
	7	44,720	44,800
Manufacturer "S"	3	44,550	46,700
	4	42,550	42,400
	4 3/4	48,520	48,300
	5	45,890	43,800
	6	45,700	44,600
	7	49,220	49,600

* average of four tests unless otherwise noted

** average of two tests

3.2.4 R. S. Nair, P. C. Birkemoe, and W. H. Munse (1974)

T-stubs are frequently used as bolted structural connections when fasteners are subjected to direct tensile loading. An increase in the tensile load on the bolts and a reduction of the connection capacity, known as prying action, is a result of deformation of the connected parts. Sixteen symmetric T-stub connections with four high-strength bolts were tested under static and fatigue loading to investigate prying action. Four single-bolt connections without prying action were also tested under static and fatigue loading for comparison.

All of the bolts used in the T-stub connections were 3/4-inch, 4-1/2-inches long, A325 or A490 bolts. The average tensile strength of three A325 bolts with a 3-1/2-inch grip length was 42.0 kips. Three A490 bolts with a 3-5/8-inch grip length were also tested in tension. It was found that the A490 bolts had an average tensile strength of 51.8 kips.

3.2.5 Scott T. Undershute and Geoffrey L. Kulak (1994)

Since tension control bolts were relatively new in the late 1990s, this research was performed to investigate the preload of tension control bolts. This was studied because the preload may vary under different conditions of weathering, aging, and thread conditions as well as from manufacturer to manufacturer. The tests were used to evaluate the reliability of tension control bolts for use in high-strength bolting. This research was also performed to establish if the F1852 (A325 tension control) bolts met the ASTM requirements by examining the behavior of the bolts in direct and torqued tension.

A total of thirteen lots of tension control bolts were obtained from five different manufacturers/suppliers from the United States, from one Japanese manufacturer/supplier, and from a Japanese company that operates in the United States (Kulak and Undershute 1998). According to the Research Council on Structural Connections 3/4-inch diameter structural bolts are most commonly used in construction making this the target diameter tested. The F1852 bolts tested in this research varied in length. Eight of the lots were 3/4-inch diameter, 2-3/4-inches long. Four lots were 3/4-inch diameter with lengths 2-1/4-inches, 2-1/2-inches, 3-inches, and 3-1/4-inches. The last lot tested was 7/8-inch diameter, 4-inches long.

The results published were not reported as ultimate tensile strength but as the ratio of the average measured ultimate tensile strength to the specified ultimate tensile strength (Undershute and Kulak 1994). These ratios for the thirteen lots are summarized in Table 3-18 (Undershute and Kulak 1994). Based on an effective area of seventy-five percent of the shank area and the ultimate stress for F1852 being 120 ksi the tensile strength in kips was determined. It was concluded that F1852 structural bolts have substantially the same material properties as A325 as would be expected.

Table 3-18: Average Tensile Strength (Undershute and Kulak 1994)

Manufacturer	Bolt Lot	Bolt Diameter (inches)	Bolt Length (inches)	Number Tested	Average Measured per Specified Tensile Strength	Specified Tensile Strength (kips)	Average Measured Tensile Strength (kips)
A	2	3/4	2 3/4	5	1.06	39.761	42.15
B	3	3/4	2 3/4	5	1.31	39.761	52.09
	4	3/4	2 3/4	5	1.31	39.761	52.09
	5	3/4	3 1/4	5	1.26	39.761	50.10
C	1	3/4	2 3/4	5	1.23	39.761	48.91
	6	3/4	2 3/4	5	1.23	39.761	48.91
	7	3/4	3	5	1.18	39.761	46.92
	8	3/4	2 1/4	5	1.22	39.761	48.51
	9	7/8	4	4	1.20	54.119	64.94
D	10	3/4	2 3/4	5	1.27	39.761	50.50
E	11	3/4	2 3/4	5	1.20	39.761	47.71
F	12	3/4	2 3/4	5	1.12	39.761	44.53
G	13	3/4	2 1/2	5	1.15	39.761	45.72

3.2.6 James A. Swanson (1999)

James A. Swanson tested forty-eight T-stubs and ten clip angles (Swanson and Leon 2000) as part of his doctoral work at Georgia Institute of Technology. During the 1994 Northridge and 1995 Kobe earthquakes, numerous fully welded moment connections failed (Swanson and Leon 2000). Swanson performed these tests to provide information about the behavior, ductility, and failure modes of T-stubs and clip angles as part of a SAC Phase II project (Swanson and Leon 2000). Structural bolts of 7/8-inch and 1-inch in diameter of grades F1852 (tension control A325) and F2280 (tension control A490) were used in various configurations (Swanson and Leon 2000).

There were several tests performed on the bolts but only the direct tension tests will be considered herein. From the lots of 7/8-inch and 1-inch F1852 and F2280 bolts, to be used in the T-stubs, fifty-five bolts were chosen for tension testing. It should be noted that the tension tests were not performed using a wedge washer as stated in ASTM F606, but a “suitable fixture”

(Swanson 1999) was used. Table 3-19 (Swanson 1999) and Table 3-20 (Swanson 1999) summarize the ultimate load and elongation for the F1852 and F2280 bolts tested in direct tension, respectively.

Table 3-19: Direct Tension Results for F1852 (Swanson 1999)

Nominal Diameter (inches)	Bolt Length (inches)	Ultimate Load (kips)	Elongation at Failure (inches)
7/8	3 1/2	65.5	0.1431
		65.1	0.1238
		67.9	0.1165
		67.0	0.1349
		71.6	0.0710
		68.4	0.1168
		70.3	0.1263
7/8	4 1/2	66.1	0.1545
		65.5	0.1587
7/8	5	69.2	0.1365
		69.5	0.1268
		72.5	0.1603
		70.1	0.0993
		77.0	0.0884
		73.1	0.0864
		71.9	0.1673
1	3 1/2	86.4	0.1416
		87.8	0.1327
		90.3	0.1347
		91.9	0.1329
		95.1	0.1334
		90.9	0.1330
1	5	86.4	0.1284
		83.6	0.1328
		88.0	0.1216
		88.4	0.1311
		96.3	0.1449
		87.7	0.1063

Table 3-20: Direct Tension Results for F2280 (Swanson 1999)

Nominal Diameter (inches)	Bolt Length (inches)	Ultimate Load (kips)	Elongation at Failure (inches)
7/8	3 1/2	80.5	0.1120
		82.4	0.1171
		87.1	0.0726
		86.8	0.0851
		90.7	0.0590
		88.0	0.0637
7/8	4 1/2	76.8	0.0926
		76.1	0.0504
7/8	5	80.4	0.0942
		83.0	0.1049
		86.1	0.0604
		85.2	0.0587
		80.0	0.1282
		79.7	0.1024
1	3 1/2	109.4	0.0968
		105.6	0.1409
		110.2	0.0900
		100.3	0.0878
		110.7	0.0775
		107.5	0.0748
1	4 1/2	102.8	0.1039
1	5	104.1	0.1347
		103.6	0.1134
		106.0	0.0935
		107.9	0.0908
		107.5	0.0951
		105.8	0.0811

Swanson stated that “on average, the ultimate strength determined from the tension tests was 8% higher than that reported on the manufacturer’s certification with a standard deviation of 4%” (1999). The average ultimate strength of the F1852 bolts, based on the manufactures certifications, was 140.0 ksi with a 3.4 ksi standard deviation. This is 16.7% higher than the specified 120 ksi for F1852 bolts. Also based on the manufactures certifications, the F2280 bolts had an average ultimate strength of 162.7 ksi with a 2.7 ksi standard deviation. Compared to the specified minimum strength for F2280 bolts of 150 ksi, this is 8.5% higher.

From Table 3-19 (Swanson 1999), for the F1852 bolts, the average elongation at failure was 5.2% with a 1.6% standard deviation. The F2280 bolts had an average elongation at failure of 3.6% with a 1.1% standard deviation, from Table 3-20 (Swanson 1999). It was concluded that F1852 bolts have a 44% higher elongation at failure than F2280 bolts.

3.2.7 Jennifer Amrine and James A. Swanson (2004)

Amrine and Swanson investigated the strength of T-stubs with prying that had bolts with different levels of pretension. It became a concern that an iron worker may unintentionally tighten some bolts in a connection while leaving some bolts untightened. A fracture of the tightened bolts could occur before the untightened bolts achieve their expected capacity which could lead to an unzipping type of failure if this situation occurred. Some of the bolts used in the T-stubs were tested in direct tension in order to establish the baseline strength of the fasteners. This was performed in order to determine if differing levels of pretension had an effect on the overall strength.

The bolts tested where 3/4-inch A325 and A490 with lengths varying from 3-1/4-inches to 3-3/4-inches. To investigate the effects of the number of threads in the bolt's grip, the A325 bolts were order in varies lengths. Table 3-21 (Amrine and Swanson 2004) and Table 3-22 (Amrine and Swanson 2004) shows the results for the A325 and A490 bolts, respectively, tested in direct tension. It can be seen from Table 3-22 (Amrine and Swanson 2004) that the ultimate load of the two lots of A490 bolts vary. After the first lot of A490 bolts were tested it was noticed that the ultimate load was lower than expected. Due to the questionable strength a different lot of A490 bolts was obtained and tested, indicated as A490-B.

Table 3-21: Direct Tension Results for A325 Bolts (Amrine and Swanson 2004)

Bolt Designation	Nominal Diameter (inches)	Bolt Length (inches)	Threads in Grip	Ultimate Load (kips)
A325-A	3/4	3 1/2	5 to 6	48.347
				45.945
				48.176
				46.881
				47.736
				47.812
				47.192
				47.340
				47.337
				46.886
A325-B	3/4	3 1/4	8 to 9	46.935
				47.743
				46.224
				46.066
				45.183
A325-C	3/4	3 3/4	1 to 2	48.025
				49.098
				46.578
				47.428
				47.289
				47.900

Table 3-22: Direct Tension Results for A490 Bolts (Amrine and Swanson 2004)

Bolt Designation	Nominal Diameter (inches)	Bolt Length (inches)	Threads in Grip	Ultimate Load (kips)
A490-A	3/4	3 1/2	5 to 6	49.341
				49.954
				48.396
				49.712
				49.384
A490-B	3/4	3 1/2	5 to 6	55.468
				54.189
				54.928
				54.351
				54.463

The strength was slightly affected by the number of threads in the grip as can be seen from the A325 tension results in Table 3-21 (Amrine and Swanson 2004). The number of threads in the grip did have a great effect on the deformation capacity. "When more threads are included in the grip of a bolt, the plastic deformation is distributed over a longer length and leads to a more ductile fastener behavior" (Amrine and Swanson 2004).

As can be seen in Table 3-22 (Amrine and Swanson 2004), the A490-A bolts presented a strength lower than the minimum specified by ASTM. According to Amrine and Swanson (2004) the A490-A bolts "demonstrated more ductility than some A325 bolts". The second lot of A490 bolts (A490-B) were obtained and tested. The strength of A490-B were above the ASTM minimum strength. A relatively slow loading rate (same loading rate which was used for the T-stub testing) was used when testing the bolts in direct tension. Amrine and Swanson (2004) believed the A490-A bolts might have met ASTM minimum strength requirements if a faster load rate was used.

3.3 Shear Tests

A published shear test that was not part of the "Large Bolted Joints Project" conducted at Lehigh University is summarized in this section.

3.3.1 Burak Karsu (1995)

Burak Karsu (1995) studied the behavior of one bolt in single shear at Virginia Polytechnic Institute and State University (a.k.a. Virginia Tech). The failure mechanisms and load deformation characteristics were evaluated in this Master's Thesis by conducting seventy tests with different configurations. "A new analytical model for the determination of load-deformation response of bolted connections was presented as well as a new Unified Design Curves approach for design purposes" (Karsu 1995).

A large variety of failure modes can occur in a bolted connection, including shear failure of the bolt or plate, bearing failure of the bolt or plate, bending failure of the bolt, transverse tension failure of the plate, tension failure of the bolt, and splitting failure of the plate. Shearing of the bolt and bearing and splitting of the plate were most common during the seventy tests performed.

Only the bolts which failed in shear will be considered, from which resistance factors will be calculated.

The seventy tests performed during this research were conducted with different plate thicknesses and bolt sizes. The plates used were A36 steel in varying thickness from 1/8-inch to 3/4-inch. The bolts ranged in size from 3/4-inch to 1-inch in diameter of grade A325. The bolts were arranged in the plates so the threads were excluded from the shear plane.

Twenty-six out of the seventy connections failed as a result of the bolt shearing. The results of these tests can be seen in Table 3-23 (Karsu 1995).

Table 3-23: Single Shear Results (Karsu 1995)

Test No.	Bolt Diameter (in)	Test Desg.	Load at Failure (kips)	Deformation at Failure (in)
7	3/4	3/8 x 3/8 x 3/4	36.3	0.53
6	3/4	3/8 x 1/2 x 3/4	36.5	0.51
9	3/4	3/8 x 5/8 x 3/4	37	0.23
10	3/4	3/8 x 3/4 x 3/4	37.53	0.21
11	3/4	3/8 x 1 x 3/4	38.5	0.47
20	3/4	1/2 x 1/2 x 3/4	35.6	0.23
21	3/4	1/2 x 5/8 x 3/4	40	0.25
22	3/4	1/2 x 1 x 3/4	37.4	0.2
23	3/4	5/8 x 5/8 x 3/4	35.3	0.24
24	3/4	5/8 x 1 x 3/4	37.8	0.16
40	7/8	1/2 x 1/2 x 7/8	49.1	0.33
41	7/8	1/2 x 3/4 x 7/8	52.3	0.42
42	7/8	1/2 x 1 x 3/4	52.4	0.32
43	7/8	3/4 x 3/4 x 7/8	49.1	0.27
44	7/8	3/4 x 1 x 7/8	52.8	0.27
45	7/8	1 x 1 x 7/8	53.9	0.2
57	1	1/2 x 1/2 x 1	57.4	0.48
58	1	1/2 x 5/8 x 1	63.1	0.52
59	1	1/2 x 3/4 x 1	63.1	0.38
60	1	1/2 x 1 x 1	58.8	0.23
61	1	5/8 x 5/8 x 1	56.2	0.19
62	1	5/8 x 3/4 x 1	66.1	0.43
63	1	5/8 x 1 x 1	60.5	0.25
64	1	3/4 x 3/4 x 1	63.1	0.2
69	3/4	1/2 x 1/2 x 3/4	35.7	0.4
71	3/4	5/8 x 5/8 x 3/4	39.6	0.32

3.4 Combined Tension and Shear Tests

Research which was performed on tension and shear strength of high-strength bolts is summarized in this section.

3.4.1 E. Chesson, Jr., N. L. Faustino, and W. H. Munse (1964)(1965)

One hundred fifteen high-strength bolts were tested in order to define the strength and behavior of one bolt subjected to various combinations of tension and shear at the University of Illinois-Urbana. The bolts being tested consisted of grades A325 and A354 BD (which has similar mechanical properties to A490) of diameters 3/4-inch and 1-inch with lengths of 3-inches, 4-inches, and 6-inches. Like other tension and shear tests previously described, the bolt grip and type of material used (factors which might affect the performance) were investigated as well. The bolt diameter and type, in addition to the location of the shear plane, were also considered (Chesson et al. 1964). There were three types of materials used for the testing (ASTM A7, ASTM A242, and quenched and tempered steel (Q&T)).

Direct tension tests were performed on three bolts from each type and size. These results are tabulated in Table 3-24 (Chesson et al. 1964). The one hundred fifteen bolts were tested in nine series (designated A through I) at various combinations of tension and shear. Herein only the direct tension and direct shear tests will be considered. Table 3-25 (Chesson et al. 1964) and Table 3-26 (Chesson et al. 1964) summarize the results of just the direct tension and shear tests, respectively. The A354 BD bolts will be used as A490 bolts when calculating resistance factors since they have the same chemical and physical characteristics.

Table 3-24: Tension Results (Chesson et al. 1964)

Grade	Nominal Diameter (inches)	Bolt Length (inches)	Mean Ultimate Load (pounds)
A354 BD	3/4	3	55,700
			56,250
			58,700
A325 Low Hardness	3/4	3	41,000
			39,700
			39,700
A325 Low Hardness	3/4	6	41,250
			40,000
			41,450
A325 High Hardness	3/4	3	47,100
			47,800
			46,200
A325 Low Hardness	1	4	69,700
			70,700
			70,200

Table 3-25: Direct Tension Results (Chesson et al. 1964)

Series	Grade (Hardness)	Nominal Diameter (inches)	Bolt Length (inches)	Grip (inches)	Ultimate Load (kips)
A	A325 (Low)	3/4	3	2.28	36.70
					37.92
					39.15
B	A325 (Low)	3/4	3	1.60	41.70
					40.85
					41.40
C	A325 (High)	3/4	3	1.60	49.00
					49.50
D	A325 (Low)	3/4	3	1.60	41.00
					40.80
E	A325 (Low)	3/4	3	1.60	40.40
					39.65
F	A354BD	3/4	3	2.25	53.40
					54.50
G	A354BD	3/4	3	1.60	55.40
					55.90
H	A325 (Low)	3/4	6	4.67	42.50
					41.85
I	A325 (Low)	1	4	2.54	68.50
					69.30

Table 3-26: Direct Shear Results (Chesson et al. 1964)

Series	Grade (Hardness)	Nominal Diameter (inches)	Bolt Length (inches)	Grip (inches)	Shear Plane of Loading	Testing Material	Ultimate Load (kips)
A	A325 (Low)	3/4	3	2.41	Threads	A7	25.38
							26.16
							27.00
B	A325 (Low)	3/4	3	1.60	Shank	A7	34.40
							35.80
							35.50
C	A325 (High)	3/4	3	1.60	Shank	A7	40.80
							40.70
D	A325 (Low)	3/4	3	1.60	Shank	A242	33.30
							34.30
E	A325 (Low)	3/4	3	1.60	Shank	Q&T	33.00
							33.00
F	A354BD	3/4	3	2.25	Threads	A242	38.50
							35.30
G	A354BD	3/4	3	1.60	Shank	Q&T	42.30
							43.50
H	A325 (Low)	3/4	6	4.67	Shank	A7	36.80
							37.60
I	A325 (Low)	1	4	2.54	Shank	A7	62.50
							59.60

To determine the relative behavior of structural bolts when the shear plane is excluded or not excluded from the threads, Series A and B (A325 bolts) and F and G (A354 BD bolts) were considered. From these series, with the load being predominantly shear, it was concluded that “the ultimate strength of bolts with the shear planes through the threads was slightly more than 80% of that for bolts with the shear planes through the shank” (Chesson et al. 1964).

To determine the effect of the material used for testing on the strength and behavior of structural bolts Series B, D, and E were analyzed. It was concluded that the strength and behavior of structural bolts are unaffected by the different materials used when testing based on Series B, D, and E.

3.4.2 K. H. Frank and J. A. Yura (1981)

Frictional forces initially provide load transfer between plate components in high-strength bolted shear connections. The friction characteristics of the contact surfaces and the high-strength clamping forces develop the frictional forces. A friction connection is one which relies on the slip resistance to transfer load. The connection becomes a bearing connection when the slip resistance is exceeded. Before 1975, the American Association of State Highway and Transportation Officials (AASHTO) prohibited friction connections to have surface coatings on the contact surfaces. This research was performed to study the slip characteristics of four primary surface coatings.

The bolts used in the research were tested in direct tension and single shear. Three lots of 7/8-inch A325 bolts were used and tested. The average ultimate tension and shear strength for each lot are summarized in Table 3-27 (Yura and Frank 1981) and Table 3-28 (Yura and Frank 1981), respectively.

Table 3-27: Direct Tension Results (Yura and Frank 1981)

Bolt Lot	Bolt Grade	Bolt Diameter (inches)	Length (inches)	Average Ultimate Load (pounds)
A	A325	7/8	5 1/2	57,600
B	A325	7/8	5 3/4	56,800
C	A325	7/8	6 3/4	64,900

Table 3-28: Direct Shear Results (Yura and Frank 1981)

Bolt Lot	Bolt Grade	Bolt Diameter (inches)	Length (inches)	Average Ultimate Shear Strength (pounds)	
				Threads Excluded	Threads Not Excluded
A	A325	7/8	5 1/2	46,000	37,100
B	A325	7/8	5 3/4	45,300	36,100
C	A325	7/8	6 3/4	49,600	41,800

It was concluded that “the average ratio of ultimate shear stress on the gross area to the ultimate direct tensile strength on the tensile stress area is 0.60…” (Yura and Frank 1981).

3.5 Summary of Tension Tests

A review of the literature has shown that the actual direct tensile strength of production fasteners exceeds the minimum requirements of the code considerably (Kulak et al. 2001). The average actual tensile strength is 18% higher than required for A325 bolts up to 1-inch in diameter with a coefficient of variation equal to 4.5% (Kulak et al. 2001). The load versus elongation relationship and the frequency distribution is shown in Figure 3-12 (Kulak et al. 2001) for A325 bolts, where the average tensile strength is given by T_u. This plot of load versus elongation is for a bolt with average strength since T/T_u equals 1.0. Also shown in this figure is T_u/T_{spec} which is the average tensile strength divided by the required strength. The minimum required strength is located 18 divided by 4.5 or 4 standard deviations from the mean as shown in Figure 3-13 (partial from Kulak et al. 2001). From standard normal probabilities with the number of standard deviations below the mean equal to 4, the probability of a bolt being below the required strength is 0.00003. This means that 3 bolts out of every 100,000 will be below the minimum required strength. For A325 bolts greater than 1-inch in diameter the actual direct tensile strength exceeds the minimum required strength by an even larger percentage.

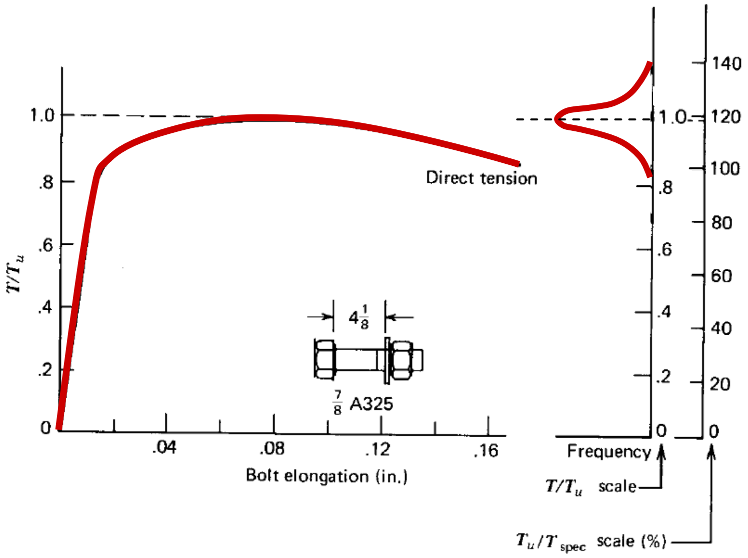


Figure 3-12: Load versus Elongation & Frequency Distribution for A325 Bolts (Kulak et al. 2001)

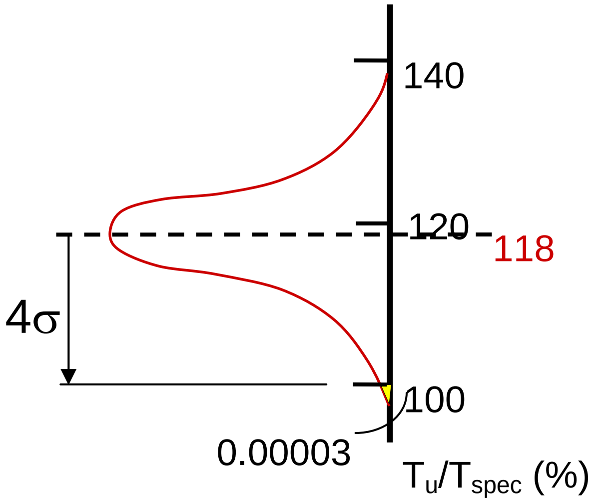


Figure 3-13: Distribution of A325 Bolts (partial from Kulak et al. 2001)

Similarly, direct tension tests on A490 bolts shows the average actual strength is 10% higher than the minimum required value, with a coefficient of variation of 3.5% (Kulak et al. 2001). Figure 3-14 (Kulak et al. 2001) shows the load versus elongation relationship and the frequency distribution for A490 bolts. The minimum required strength is located 10 divided by 3.5 or 2.857 standard deviations from the mean as shown in Figure 3-15 (partial from Kulak et al. 2001). The probability of a bolt being below the required strength as determined from standard normal probabilities is 0.0021. This means that 2 A490 bolts out of every 1,000, or 1 A490 bolt out of every 500, will be below the minimum required strength. The A490 bolts exceed the minimum tensile strength by a smaller percentage when compared to A325 bolts "because specifications require the actual strength of A490 bolts to be within the range of 150 to 170 ksi[6], whereas for A325 only a minimum strength is specified" (Kulak et al. 2001).

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[6] ASTM A490-04a states 173 ksi whereas RCSC states 170 ksi maximum tensile strength for A490 bolts.

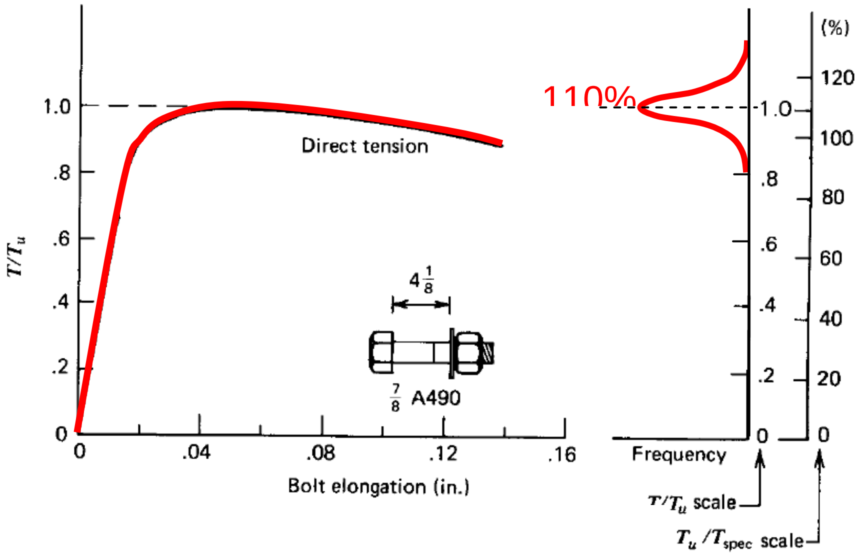


Figure 3-14: Load versus Elongation & Frequency Distribution for A490 Bolts (Kulak et al. 2001)

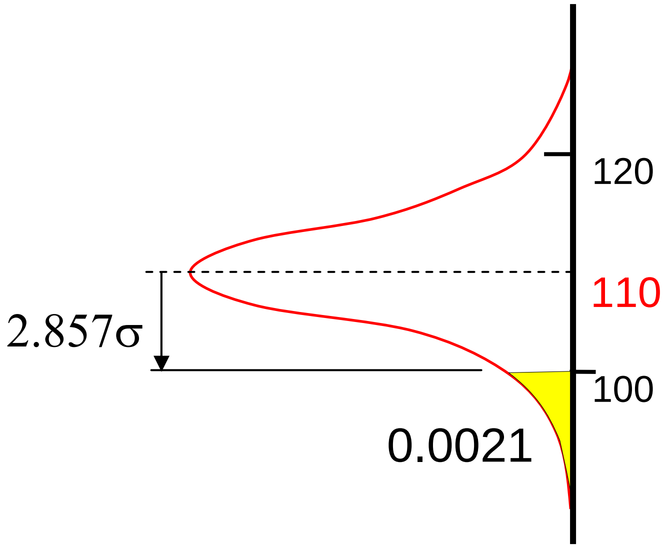


Figure 3-15: Distribution of A490 Bolts (partial from Kulak et al. 2001)

3.6 Summary of Shear Tests

Subjecting bolts to shear, induced by plates in either compression or tension, results in shear versus deformation relationships (Kulak et al. 2001). Figure 3-16 (Kulak et al. 2001) shows a typical load versus deformation from shear tests on A325 and A490 bolts. An A490 bolt has a higher shear strength and a smaller deformation compared to an A325 bolt, which is to be expected due to the increased tensile strength of A490 bolts.

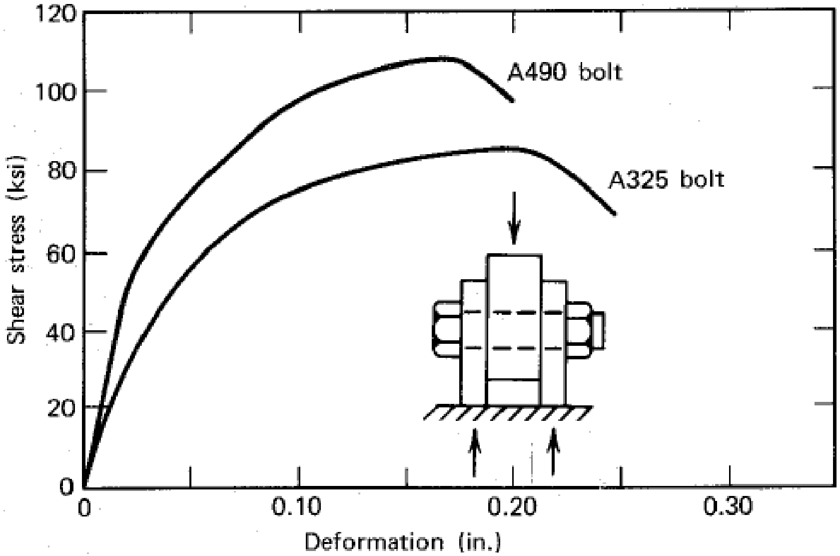


Figure 3-16: Typical Shear Load versus Deformation (Kulak et al. 2001)

A bolt can be tested in shear in a fixture subjected to either tension or compression, which may influence the shear strength (Kulak et al. 2001). Bolts from the same lot were tested in a compression and a tension jig to compare their strength and deformation capacity. The load versus deformation for the two types of jigs used is shown in Figure 3-17 (Kulak et al. 2001). It was shown that the shear strength of bolts tested in an A440 tension jig was six to thirteen percent lower than if the same lot was tested in an A440 compression jig (Kulak et al. 2001). Similarly, when bolts were tested in a constructional alloy steel tension jig the shear strength was eight to thirteen percent lower than when the bolts were tested in a constructional alloy steel compression jig (Kulak et al. 2001). It should be noted that these conclusions were based on bolts being tested in double shear. Based on the bolts tested in a tension jig, the shear strength of a single bolt is approximately 62 percent of the bolt's tensile strength, regardless of the grade (Kulak et al. 2001). This can be seen in Figure 3-18 (Kulak et al. 2001) which plots the tensile strength versus the shear strength. Likewise, the bolts tested in a compression jig result in a shear strength of approximately 68 percent of the tensile strength (Kulak et al. 2001). The phenomenon known as lap plate prying, which "tends to bend the lap plates of the tension jig outward" (Kulak et al. 2001), causes a lower shear strength of bolts. Given that bolts tested in a tension jig result in a lower shear strength, a tension jig is recommended because it produces a lower bound shear strength and the most consistent test results (Kulak et al. 2001).

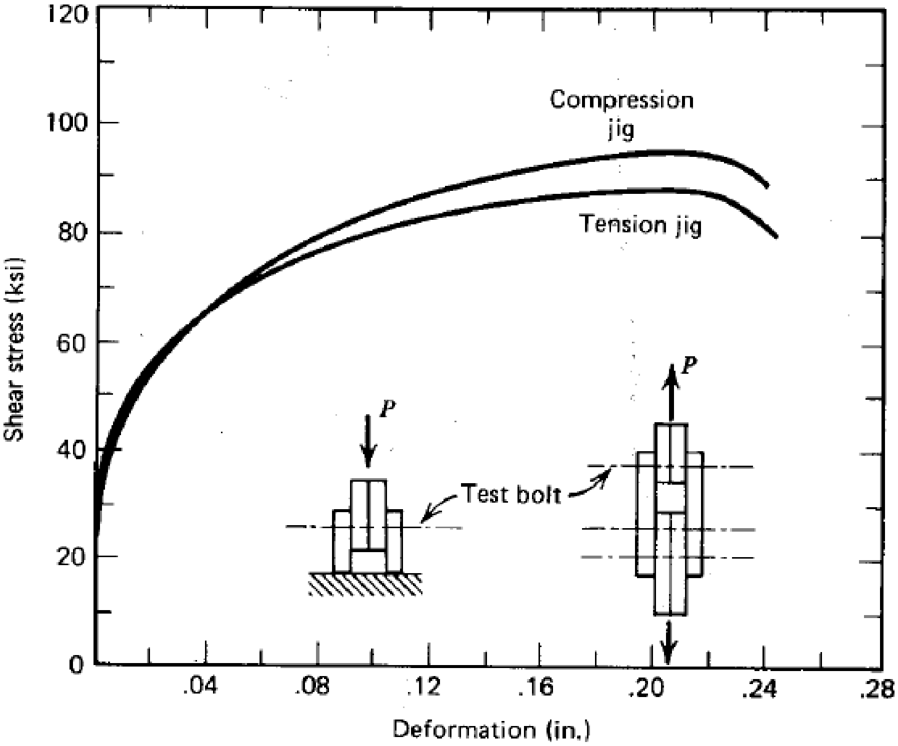


Figure 3-17: Shear Load versus Deformation for Compression and Tension Jig (Kulak et al. 2001)

3.7 Resistance Factors Based on Literature

Based on the literature summarized in Sections 3.1 through 3.4, resistance factors were calculated. Table 3-29 tabulates the total number of bolts tested, as reported in literature, which were previously discussed in Sections 3.1 through 3.4. Based on Figure 2-31 and Section 2.4.1, resistance factors were calculated in five different levels of detail from the bolts reported in literature. Method 1, based on equation (2-8), was used when calculating resistance factors as well as Method 2, which is based on equation (2-9).

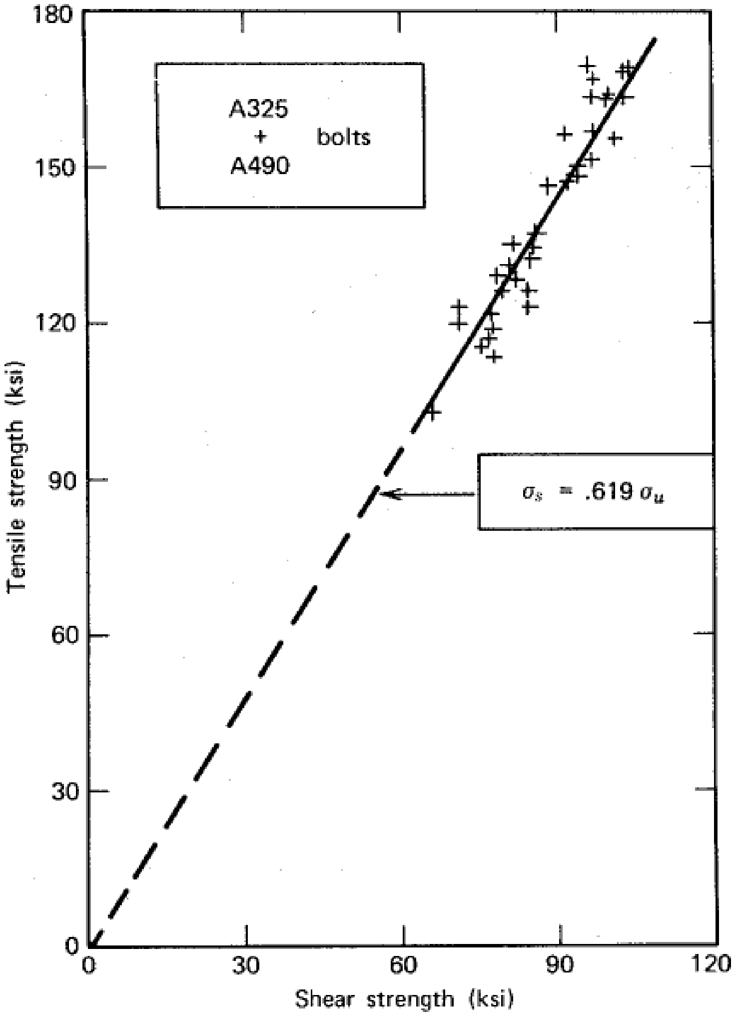


Figure 3-18: Shear Load versus Tensile Strength (Kulak et al. 2001)

Table 3-29: Number of Bolts Tested from Literature

Diameter (inches)	Tension				Shear - X		Shear - N	
	A325	F1852	A490	F2280	A325	A490	A325	A490
3/4	116	60	20	-	23	2	3	2
7/8	242 +	20	93 +	14	9	-	3	-
1	38 +	12	29 +	13	10	-	-	-
1 1/8	10 +	-	1 +	-	-	-	-	-
Total	406 +	92	143 +	27	42	2	6	2

Enough information was published in the literature to calculate Method 1 resistance factors. However some assumptions needed to be made to calculate the resistance factors based on Method 2, which depends on the cross-sectional geometry, material strength, and professional factor. Since the shank diameters were not published, the bias coefficient and the coefficient of variation for the cross-sectional geometry and the professional factor could not be calculated based on the equations in Section 2.4.1.5.

For the tension tests summarized in Sections 3.1, 3.2, and 3.4 resistance factors were calculated using Method 2 after a few assumptions were made. The bias coefficients for the cross-sectional geometry (ρ_G) and the professional factor (ρ_P) where assumed to equal 1.0 since the measured shank diameters were not provided. The coefficient of variation for the cross-sectional geometry (V_G) and the professional factor (V_P) were assumed to equal 0.05 and 0, respectively, according to Fisher et al. (1978). The bias coefficient and the coefficient of variation for the material strength were calculated based on equations (2-40) through (2-42).

Resistance factors for shear could not be calculated based on Method 2 due to the lack of published information. Based on the equations from Section 2.4.1.5.2 the bias coefficient for the material strength (ρ_M) is based on the same lot of bolts being tested in direct tension. Since this information was not published it could not be calculated. Thus the shear data from Sections 3.1, 3.3, and 3.4 had resistance factors calculated based on Method 1A only.

Resistance factors were calculated with a reliability index equal to 4.5 and 4.0 and with an adjustment factor based on a live-to-dead load ratio of 1.0 and 3.0. Sections 3.7.1 and 3.7.2 contain resistance factors with a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 1.0 and 3.0, respectively. Resistance factors based on a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 1.0 and 3.0, respectively, are tabulated in Sections 3.7.3 and 3.7.4. Section 3.7.5 summarizes Sections 3.7.1 through 3.7.4 and makes a recommendation based on the data obtained from the literature which was previously discussed in Sections 3.1 through 3.4.

3.7.1 Resistance Factors with a Reliability Index Equal to 4.5 & an Adjustment Factor Based on a L/D = 1.0

Tables 3-30 through 3-39 contain resistance factors based on a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 1. Tables 3-30 through 3-33 show the resistance factors calculated from bolts in tension, whereas Tables 3-34 through 3-38 show the resistance factors calculated from bolts in shear. Tables 3-30, 3-34 and 3-35 show the resistance factors calculated based on the diameter and grade of the bolts in tension, shear excluded, and shear not excluded, respectively (Level V). The tension and shear resistance factors based on the grade of the bolts are summarized in Tables 3-31 and 3-36, respectively (Level IV). The resistance factors based on the strength of the bolts (Level III) are shown in Tables 3-32 and 3-37 for tension and shear, respectively. Tables 3-33 and 3-38 are the resistance factors calculated from all of the data regardless of the bolt diameter or grade for tension and shear, respectively (Level II). The resistance factors from all tension and shear data (Level I) are shown in Table 3-39.

Table 3-30: Resistance Factors – Tension – Level V – β = 4.5 – L/D = 1.0

Diameter (inches)	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
3/4	A325	0.844	0.836	0.801
	F1852	0.907	0.899	0.860
	A490	0.832	0.824	0.784
7/8	A325	0.764	0.746	0.718
	F1852	0.974	0.952	0.901
	A490	0.870	0.849	0.804
	F2280	0.911	0.890	0.850
1	A325	0.826	0.803	0.754
	F1852	1.062	1.033	0.943
	A490	0.934	0.908	0.839
	F2280	0.986	0.959	0.884
1 1/8	A325	0.719	0.702	0.682
	A490	0.933	0.911	0.805
	Minimum	0.719	0.702	0.682
	Maximum	1.062	1.033	0.943

Table 3-31: Resistance Factors – Tension – Level IV – $\beta = 4.5$ – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
A325	0.775	0.754	0.728
F1852	0.932	0.922	0.879
A490	0.873	0.857	0.808
F2280	0.947	0.922	0.870
Minimum	0.775	0.754	0.728
Maximum	0.947	0.922	0.879

Table 3-32: Resistance Factors – Tension – Level III – $\beta = 4.5$ – L/D = 1.0

Strength	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
120 ksi (A325/F1852)	0.770	0.750	0.726
150 ksi (A490/F2280)	0.867	0.851	0.807
Minimum	0.770	0.750	0.726
Maximum	0.867	0.851	0.807

Table 3-33: Resistance Factors – Tension – Level II – $\beta = 4.5$ – L/D = 1.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
0.790	0.770	0.744

Table 3-34: Resistance Factors – Shear Excluded – Level V – $\beta = 4.5$ – L/D = 1.0

Diameter	Grade	Method 1A
3/4	A325	0.852
	A490	0.912
7/8	A325	0.841
1	A325	0.802
	Minimum	0.802
	Maximum	0.912

Table 3-35: Resistance Factors – Shear Not Excluded – Level V – $\beta = 4.5$ – L/D = 1.0

Diameter	Grade	Method 1A
3/4	A325	0.862
	A490	0.972
7/8	A325	0.762
	Minimum	0.762
	Maximum	0.972

Table 3-36: Resistance Factors – Shear – Level IV – β = 4.5 – L/D = 1.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.823	0.757
A490	0.912	0.972
Minimum	0.823	0.757
Maximum	0.912	0.972

Table 3-37: Resistance Factors – Shear – Level III – β = 4.5 – L/D = 1.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.823	0.757
A490	0.912	0.972
Minimum	0.823	0.757
Maximum	0.912	0.972

Table 3-38: Resistance Factors – Shear – Level II – β = 4.5 – L/D = 1.0

Method 1A	
Excluded	Not Excluded
0.822	0.775
0.815	

Table 3-39: Resistance Factors – Level I – β = 4.5 – L/D = 1.0

Tension 1A Shear 1A	Tension 1B Shear 1A
0.794	0.778

3.7.2 Resistance Factors with a Reliability Index Equal to 4.5 & an Adjustment Factor Based on a L/D = 3.0

Resistance factors based on a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 3 are shown in Tables 3-40 through 3-49. The resistance factors calculated from the bolts in tension are shown in Tables 3-40 through 3-43, whereas Tables 3-44 through 3-48 show the resistance factors calculated from the bolts in shear. Tables 3-40, 3-44 and 3-45 contain the resistance factors calculated based on the diameter and grade of the bolts (Level V) in tension, shear excluded, and shear not excluded, respectively. The tension and shear resistance factors based on the grade of the bolts (Level IV) are summarized in Tables 3-41 and 3-46, respectively. The resistance factors based on the strength of the bolts (Level III) are shown in Tables 3-42 and 3-47 for tension and shear, respectively. Tables 3-43 and 3-48 are the resistance factors calculated from all of the data regardless of the bolt diameter or grade for tension and shear, respectively (Level II). The resistance factors from all tension and shear data (Level I) are shown in Table 3-49.

Table 3-40: Resistance Factors – Tension – Level V – β = 4.5 – L/D = 3.0

Diameter (inches)	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
3/4	A325	0.827	0.819	0.785
	F1852	0.889	0.881	0.843
	A490	0.815	0.808	0.768
7/8	A325	0.748	0.731	0.704
	F1852	0.955	0.933	0.883
	A490	0.852	0.832	0.788
	F2280	0.893	0.872	0.833
1	A325	0.809	0.787	0.739
	F1852	1.041	1.012	0.924
	A490	0.915	0.890	0.822
	F2280	0.966	0.940	0.867
1 1/8	A325	0.705	0.688	0.668
	A490	0.914	0.893	0.789
	Minimum	0.705	0.688	0.668
	Maximum	1.041	1.012	0.924

Table 3-41: Resistance Factors – Tension – Level IV – $\beta = 4.5$ – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
A325	0.760	0.739	0.714
F1852	0.913	0.904	0.861
A490	0.856	0.840	0.792
F2280	0.929	0.904	0.852
Minimum	0.760	0.739	0.714
Maximum	0.929	0.904	0.861

Table 3-42: Resistance Factors – Tension – Level III – $\beta = 4.5$ – L/D = 3.0

Strength	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
120 ksi (A325/F1852)	0.755	0.735	0.712
150 ksi (A490/F2280)	0.850	0.834	0.791
Minimum	0.755	0.735	0.712
Maximum	0.850	0.834	0.791

Table 3-43: Resistance Factors – Tension – Level II – $\beta = 4.5$ – L/D = 3.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
0.774	0.755	0.729

Table 3-44: Resistance Factors – Shear Excluded – Level V – $\beta = 4.5$ – L/D = 3.0

Diameter	Grade	Method 1A
3/4	A325	0.835
	A490	0.894
7/8	A325	0.824
1	A325	0.786
	Minimum	0.786
	Maximum	0.894

Table 3-45: Resistance Factors – Shear Not Excluded – Level V – $\beta = 4.5$ – L/D = 3.0

Diameter	Grade	Method 1A
3/4	A325	0.845
	A490	0.953
7/8	A325	0.747
	Minimum	0.747
	Maximum	0.953

Table 3-46: Resistance Factors – Shear – Level IV – β = 4.5 – L/D = 3.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.806	0.742
A490	0.894	0.953
Minimum	0.806	0.742
Maximum	0.894	0.953

Table 3-47: Resistance Factors – Shear – Level III – β = 4.5 – L/D = 3.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.806	0.742
A490	0.894	0.953
Minimum	0.806	0.742
Maximum	0.894	0.953

Table 3-48: Resistance Factors – Shear – Level II – β = 4.5 – L/D = 3.0

Method 1A	
Excluded	Not Excluded
0.806	0.760
0.799	

Table 3-49: Resistance Factors – Level I – $\beta = 4.5$ – L/D = 3.0

Tension 1A Shear 1A	Tension 1B Shear 1A
0.778	0.762

3.7.3 Resistance Factors with a Reliability Index Equal to 4.0 & an Adjustment Factor Based on a L/D = 1.0

Tables 3-50 through 3-59 contain resistance factors based on a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 1. Tables 3-50 through 3-53 show the resistance factors calculated from bolts in tension, whereas Tables 3-54 through 3-58 show the resistance factors calculated from bolts in shear. Tables 3-50, 3-54, and 3-55 show the resistance factors calculated based on the diameter and grade of the bolts in tension, shear with the threads excluded from the shear plane and shear with the threads not excluded from the shear plane, respectively (Level V). The tension and shear resistance factors based on the grade of the bolts are summarized in Tables 3-51 and 3-56, respectively (Level IV). The resistance factors based on the strength of the bolts (Level III) are shown in Tables 3-52 and 3-57 for tension and shear, respectively. Tables 3-53 and 3-58 are the resistance factors calculated from all of the data regardless of the bolt diameter and grade for tension and shear, respectively (Level II). Table 3-59 shows the resistance factor calculated based on all tension and shear data (Level I).

Table 3-50: Resistance Factors – Tension – Level V – β = 4.0 – L/D = 1.0

Diameter (inches)	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
3/4	A325	0.897	0.888	0.855
	F1852	0.964	0.955	0.919
	A490	0.881	0.873	0.835
7/8	A325	0.814	0.795	0.769
	F1852	1.031	1.007	0.959
	A490	0.919	0.898	0.855
	F2280	0.967	0.944	0.907
1	A325	0.872	0.847	0.802
	F1852	1.114	1.083	0.999
	A490	0.982	0.954	0.890
	F2280	1.036	1.008	0.937
1 1/8	A325	0.772	0.754	0.734
	A490	0.975	0.952	0.853
	Minimum	0.772	0.754	0.734
	Maximum	1.114	1.083	0.999

Table 3-51: Resistance Factors – Tension – Level IV – $\beta = 4.0$ – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
A325	0.827	0.805	0.781
F1852	0.989	0.978	0.937
A490	0.923	0.905	0.859
F2280	1.001	0.974	0.925
Minimum	0.827	0.805	0.781
Maximum	1.001	0.978	0.937

Table 3-52: Resistance Factors – Tension – Level III – $\beta = 4.0$ – L/D = 1.0

Strength	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
120 ksi (A325/F1852)	0.824	0.803	0.781
150 ksi (A490/F2280)	0.918	0.901	0.859
Minimum	0.824	0.803	0.781
Maximum	0.918	0.901	0.859

Table 3-53: Resistance Factors – Tension – Level II – $\beta = 4.0$ – L/D = 1.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
0.843	0.823	0.798

Table 3-54: Resistance Factors – Shear Excluded – Level V – β = 4.0 – L/D = 1.0

Diameter	Grade	Method 1A
3/4	A325	0.904
	A490	0.952
7/8	A325	0.893
1	A325	0.850
	Minimum	0.850
	Maximum	0.952

Table 3-55: Resistance Factors – Shear Not Excluded – Level V – β = 4.0 – L/D = 1.0

Diameter	Grade	Method 1A
3/4	A325	0.901
	A490	1.016
7/8	A325	0.814
	Minimum	0.814
	Maximum	1.016

Table 3-56: Resistance Factors – Shear – Level IV – $\beta = 4.0$ – L/D = 1.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.874	0.807
A490	0.952	1.016
Minimum	0.874	0.807
Maximum	0.952	1.016

Table 3-57: Resistance Factors – Shear – Level III – $\beta = 4.0$ – L/D = 1.0

Grade	Method 1A	
	Excluded	Not Excluded
A325	0.874	0.807
A490	0.952	1.016
Minimum	0.874	0.807
Maximum	0.952	1.016

Table 3-58: Resistance Factors – Shear – Level II – $\beta = 4.0$ – L/D = 1.0

Method 1A

Excluded	Not Excluded
0.874	0.826
0.867	

Table 3-59: Resistance Factors – Level I – β = 4.0 – L/D = 1.0

Tension 1A **Shear 1A**	**Tension 1B** **Shear 1A**
0.847	0.830

3.7.4 Resistance Factors with a Reliability Index Equal to 4.0 & an Adjustment Factor Based on a L/D = 3.0

Resistance factors based on a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 3 are shown in Tables 3-60 through 3-69. The resistance factors calculated from bolts in tension are shown in Tables 3-60 through 3-63, whereas Tables 3-64 through 3-68 show the resistance factors calculated from bolts in shear. Tables 3-60, 3-64 and 3-65 contain the resistance factors calculated based on the diameter and grade of the bolts (Level V) in tension, shear excluded, and shear not excluded, respectively. The tension and shear resistance factors based on the grade of the bolts (Level IV) are summarized in Tables 3-61 and 3-66, respectively. The resistance factors based on the strength of the bolts (Level III) are shown in Tables 3-62 and 3-67 for tension and shear, respectively. Tables 3-63 and 3-68 are the resistance factors calculated from all of the data regardless of the bolt diameter and grade for tension and shear, respectively (Level II). The resistance factors from all tension and shear data (Level I) are shown in Table 3-69.

Table 3-60: Resistance Factors – Tension – Level V – $\beta = 4.0$ – L/D = 3.0

Diameter (inches)	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
3/4	A325	0.884	0.876	0.843
	F1852	0.950	0.942	0.906
	A490	0.869	0.861	0.823
7/8	A325	0.803	0.784	0.758
	F1852	1.016	0.992	0.946
	A490	0.906	0.885	0.843
	F2280	0.953	0.931	0.894
1	A325	0.859	0.835	0.790
	F1852	1.098	1.068	0.985
	A490	0.968	0.941	0.877
	F2280	1.022	0.993	0.924
1 1/8	A325	0.761	0.743	0.724
	A490	0.961	0.938	0.841
	Minimum	0.761	0.743	0.724
	Maximum	1.098	1.068	0.985

Table 3-61: Resistance Factors – Tension – Level IV – $\beta = 4.0$ – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
A325	0.815	0.794	0.770
F1852	0.975	0.964	0.923
A490	0.910	0.892	0.847
F2280	0.987	0.960	0.912
Minimum	0.815	0.794	0.770
Maximum	0.987	0.964	0.923

Table 3-62: Resistance Factors – Tension – Level III – $\beta = 4.0$ – L/D = 3.0

Strength	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
120 ksi (A325/F1852)	0.812	0.792	0.770
150 ksi (A490/F2280)	0.905	0.888	0.847
Minimum	0.812	0.792	0.770
Maximum	0.905	0.888	0.847

Table 3-63: Resistance Factors – Tension – Level II – $\beta = 4.0$ – L/D = 3.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A & 2B
0.831	0.811	0.787

Table 3-64: Resistance Factors – Shear Excluded – Level V – $\beta = 4.0$ – L/D = 3.0

Diameter	Grade	Method 1A
3/4	A325	0.891
	A490	0.939
7/8	A325	0.880
1	A325	0.838
	Minimum	0.838
	Maximum	0.939

Table 3-65: Resistance Factors – Shear Not Excluded – Level V – $\beta = 4.0$ – L/D = 3.0

Diameter	Grade	Method 1A
3/4	A325	0.888
	A490	1.001
7/8	A325	0.802
	Minimum	0.802
	Maximum	1.001

Table 3-66: Resistance Factors – Shear – Level IV – β = 4.0 – L/D = 3.0

Grade	**Method 1A**	
	Excluded	**Not Excluded**
A325	0.862	0.796
A490	0.939	1.001
Minimum	0.862	0.796
Maximum	0.939	1.001

Table 3-67: Resistance Factors – Shear – Level III – β = 4.0 – L/D = 3.0

Grade	**Method 1A**	
	Excluded	**Not Excluded**
A325	0.862	0.796
A490	0.939	1.001
Minimum	0.862	0.796
Maximum	0.939	1.001

Table 3-68: Resistance Factors – Shear – Level II – β = 4.0 – L/D = 3.0

Method 1A

Excluded	**Not Excluded**
0.861	0.814
0.855	

Table 3-69: Resistance Factors – Level I – $\beta = 4.0$ – L/D = 3.0

Tension 1A Shear 1A	Tension 1B Shear 1A
0.835	0.818

3.7.5 Conclusions

Resistance factors were calculated from the published tension and shear tests. As shown in Table 3-29, there were limited shear tests so a resistance factor based on the shear literature maybe not be statistically valid. There were ample tension results but most of the tests were performed around the 1960s and the bolts tested were specified to have ASTM minimum strength.

Tables 3-70, 3-71, and 3-72 summarize the resistance factors from Sections 3.7.1 through 3.7.4 for Level III, Level II, and Level I, respectively. Based on Table 3-72 (Level I), a resistance factor of 0.762 and 0.818, at a minimum, was calculated for a reliability index, β, equal to 4.5 and 4.0, respectively, with an adjustment factor based on a live-to-dead load ratio of 3. These minimum values were based on Method 1B for tension and 1A for shear. Method 1B for tension assumes the threaded area equals an effective area calculated from the average of the mean root and pitch diameters. However, the AISC Specification does not use this effective area but applies an approximation of 75% of the shank cross-sectional area for common size structural bolts. Therefore the resistance factor calculated from Method 1A for tension should be considered, which uses the approximate area as specified by AISC. For a reliability index, β, equal to 4.5 and 4.0, still based on a live-to-dead load ratio of three, a resistance factor of 0.778 and 0.835, respectively, was calculated based on Method 1A for tension and shear, as can be seen from Table 3-72. The current resistance factor specified in AISC is 0.75 for tension and shear, which is based on a reliability index of 4.5 and a live-to-dead load ratio of 3. However, the current AISC Specification's Commentary states that a reliability index of 4.0 can be utilized. Thus a resistance factor of 0.80 can be recommended based on the tension and shear literature which was summarized in Sections 3.1 through 3.4 with a reliability index, β, equal to 4.0 and a live-to-dead load ratio of three. Fisher et al. (1978) also recommended a resistance factor of 0.80 for high-strength bolts in tension and shear.

Table 3-70: Summary Literature Resistance Factors – Level III

		120 ksi (A325/F1852)				150 ksi (A490/F2280)			
		β = 4.0		β = 4.5		β = 4.0		β = 4.5	
		L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension	**Method 1A (0.75Ag)**	0.824	0.812	0.770	0.755	0.918	0.905	0.867	0.850
	Method 1B (A_{eff})	0.803	0.792	0.750	0.735	0.901	0.888	0.851	0.834
	Method 2A & 2B	0.781	0.770	0.726	0.712	0.859	0.847	0.807	0.791
Shear Excluded	**Method 1A**	0.874	0.862	0.823	0.806	0.952	0.939	0.912	0.894
Shear Not Excluded	**Method 1A**	0.807	0.796	0.757	0.742	1.016	1.001	0.972	0.953

Table 3-71: Summary Literature Resistance Factors – Level II

		β = 4.0		β = 4.5	
		L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension	**Method 1A (0.75Ag)**	0.843	0.831	0.790	0.774
	Method 1B (A_{eff})	0.823	0.811	0.770	0.755
	Method 2A & 2B	0.798	0.787	0.744	0.729
Shear Excluded	**Method 1A**	0.874	0.861	0.822	0.806
Shear Not Excluded	**Method 1A**	0.826	0.814	0.775	0.760

Table 3-72: Summary Literature Resistance Factors – Level I

	β = 4.0		β = 4.5	
	L/D = 1.0	**L/D = 3.0**	**L/D = 1.0**	**L/D = 3.0**
Tension 1A **Shear 1A**	0.847	0.835	0.794	0.778
Tension 1B **Shear 1A**	0.830	0.818	0.778	0.762

CHAPTER 4

TEST METHODS

To reevaluate the current resistance factor for tension and shear, fastener testing has been performed. The bolt testing consists of loading A325, F1852, A490, and F2280 bolts in direct tension and shear with both the threads excluded and not excluded from the shear plane.

This chapter describes the test methods. First the specifications for testing steel, especially fasteners, based on ASTM specifications, are discussed. A description of the equipment used to test in tension and shear follows. Lastly, this chapter includes the procedure used to test the bolts in tension and shear with the threads excluded and not excluded from the shear plane.

4.1 ASTM Specifications

The standards for testing metallic materials in tension are given by ASTM E8-04. There are certain exceptions when testing steel that are covered in ASTM A370-05 that are not discussed in ASTM E8-04. The standard test methods for the tensile and shear strengths of fasteners are given by ASTM F606-05.

4.1.1 Speed of Testing

According to ASTM E8-04, the speed of testing can be specified in a few different terms. The speed of testing can be defined by (1) the crosshead movement of the testing machine when there is no load, in inches per inch of length of reduced section per minutes, (2) the time to complete part or all of the test, in minutes or seconds, (3) rate of straining of the fastener, in inches per inch per minute, (4) rate of stressing of the bolt, in pounds per square inch per minute, and (5) rate of separation of the heads during a test, in inches per inch of length of reduced section per minute (ASTM E8-04). The speed of testing must be slow enough that the forces and strains are accurately indicated (ASTM E8-04; ASTM A370-05). Expecting the bolts to elongate more than five percent, the speed of testing shall be between 0.05 and 0.5 inch per inch of the length of reduced section per minute when determining tensile strength (ASTM E8-04; ASTM A370-05). The crosshead speed is limited to 1 inch per minute according to F606-05.

According to F606-05, the speed of testing shall be between 0.25 inch/minute and 0.5 inch/minute when testing a bolt in shear.

4.1.2 Tension Testing

Bolts are preferred to be tested full size instead of as machined test specimens (ASTM A370-05; ASTM F606-05). The following ASTM testing methods, from ASTM A370-05 and/or ASTM F606-05, apply to bolts with a minimum length of three times the nominal bolt diameter. The bolts to be tested in tension are tested in a holder with a load axially applied between the bolt head and a nut or a suitable fixture. To guarantee the full tensile strength of the bolt, it must have sufficient thread engagement in either the nut or the fixture. The nut or fixture must be assembled on the fastener leaving four complete threads exposed, or unengaged, between the grips for a heavy hex structural bolt, as can be seen in Figure 4-1 (ASTM F606-05). To obtain four complete threads unengaged, the nut or fixture must be screwed onto the fastener until the thread runout and then unscrewed four full turns (ASTM F606-05).

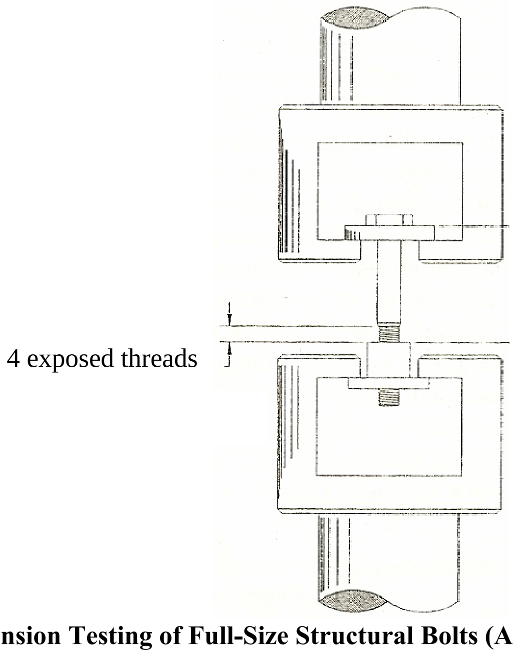


Figure 4-1: Tension Testing of Full-Size Structural Bolts (ASTM F606-05)

Tension tests are performed using a wedge washer. The purpose of using a wedge washer is to obtain the tensile strength while demonstrating the quality of the bolt head and the ductility of the fastener while an eccentric tensile load is applied. The wedge washer according to ASTM F606 can be seen in Figure 4-2 (ASTM F606-05; ASTM A370-05). The wedge washer should have a minimum Rockwell Hardness C Scale (HRC) of 45 (ASTM F606-05). The reference thickness, T (the thickness at the thin side of the hole) in Figure 4-2 (ASTM F606-05; ASTM A370-05), shall be a minimum of one half the nominal bolt diameter (ASTM F606-05). For bolt diameters between 1/4-inch and 1-inch the wedge shall have an angle, W in Figure 4-2 (ASTM F606-05; ASTM A370-05), of ten degrees (ASTM F606-05). A wedge washer with an angle, W, of six degrees should be used for bolt diameters larger than 1-inch (ASTM F606-05). Table 4-1 (ASTM F606-05) provides the hole clearance, c, in Figure 4-2 (ASTM F606-05; ASTM A370-05), in the wedge washer over the nominal size of the bolt and the required radius of the top and bottom edges of the hole, R, in Figure 4-2 (ASTM F606-05; ASTM A370-05). The minimum outside dimension of the wedge washer shall be such that no corner of the hexagonal bolt head is loaded (ASTM F606-05).

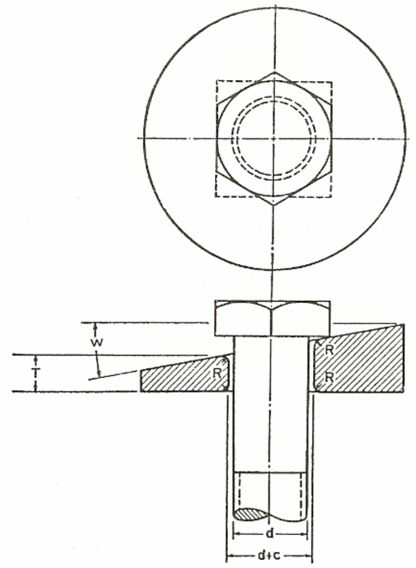


Figure 4-2: Wedge Washer (ASTM F606-05; ASTM A370-05)

Table 4-1: Wedge Washer (ASTM F606-05)

Nominal Bolt Size	Clearance in Hole (inches)	Radius on Corners of Hole (inches)
1/4" to 1/2"	0.030	0.030
9/16" to 3/4"	0.050	0.060
7/8" to 1"	0.060	0.060
1-1/8" to 1-1/4"	0.060	0.125
1-3/8" to 1-1/2"	0.094	0.125
1-3/4" to 2"	0.094	0.225
2-1/4" to 3"	0.125	0.256

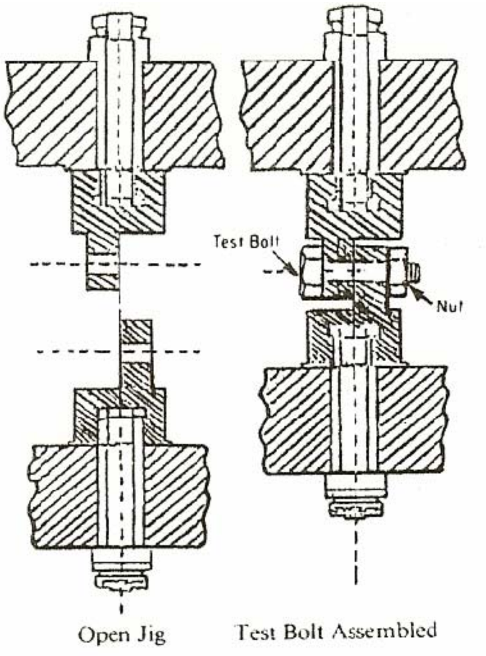
The bolt head should be positioned on the wedge washer to ensure that during testing no corner of the hexagonal head is in bearing. This means that a side of the hexagonal head (not a corner) should be aligned with the direction of the uniform thickness of the wedge washer, as shown in Figure 4-3.

Figure 4-3: Improper and Proper Installation of a Wedge Washer

The structural bolt shall be tested in tension until fracture. The fracture must occur in the body or threaded section of the bolt and not at the connection between the shank and the head.

4.1.3 Shear Testing

Shear testing is performed to determine the failure load when a transverse load is applied along the axis of the bolt. ASTM F606-05 provides the test methods for single shear testing. The shear test may be performed in either a tension or compression single shear fixture. Hardened steel of sufficient thickness shall be used for the shear fixture to prevent bearing failure (ASTM F606-05). The hole for the bolt should be 1/16-inch larger than the nominal diameter of the fastener. A chamfer of 0.010 inch should be provided on the holes to eliminate the sharp edges. A suitable shear fixture or a nut on the test bolt finger tight shall be used to prevent the shear fixture from separating during testing. An example of a shear fixture to be used in tension is shown in Figure 4-4 (ASTM F606-05).



Open Jig Test Bolt Assembled

Figure 4-4: Shear Fixture Example (Tension Type) (ASTM F606-05)

A testing machine that is capable of applying load at a controllable rate shall be used when testing a bolt in shear. To ensure the load will be transmitted in a straight line transversely through the bolt, care shall be taken when installing the fastener. The load shall be applied to the bolt until fracture occurs.

4.2 Equipment

Besides the testing machine, other equipment was used when testing the bolts in tension and shear. Data was collected so the fasteners' stiffness and ductility could be evaluated. This was done by instrumenting the bolts to obtain a plot of force versus elongation, which is more significant than a stress versus strain diagram of the bolt metal. In tension, the force versus elongation plot depicts more of the bolts characteristics since the behavior of a fastener is governed by its threaded part when subjected to an axial load (Kulak et al. 2001).

4.2.1 Testing Machine and Data Acquisition System

The tension and shear testing were carried out using a 400-kip Tinius-Olsen Closed-Loop 400 Super L Hydraulic Universal Testing Machine in displacement control. The crosshead displacement was different for tension and shear testing. The Tinius-Olsen can be seen in Figure 4-5.

Figure 4-5: Tinius-Olsen Universal Testing Machine

Data was recorded using an OPTIM Electronics MEGADAC 3415AC data acquisition system with Optim's DOS-based Test Control Software (TCS) for Windows Version 3.2 (2000). The OPTIM and laptop running TCS can be seen in Figure 4-6. The OPTIM employs a 16-bit ADC 3016 analog to digital converter. The ADC 3016 allows a post gain to be applied to the input channels, which is software selected on a channel by channel basis. The data acquisition system recorded at a rate of twenty scans per second. Load and crosshead displacement were outputted via a proportional voltage signal from the Tinius-Olsen controller to the Optim data system.

Figure 4-6: OPTIM Electronics MEGADAC with Laptop

4.2.2 Tension Testing Equipment

As described in Section 4.1, tension testing requires a holder, wedge washer, and nut or suitable fixture. The Tinius-Olsen has two different slotted bolt holders for tension testing depending on the bolt size. For bolts 1-inch in diameter and less, a small slotted bolt holder was used, which is capable of handling a maximum load of 125 kips. For bolts larger than 1-inch in diameter a larger slotted bolt holder was used which can hold up to 300 kips. The small and large tension slotted bolt holders are shown in Figure 4-7. The wedge washers, Figure 4-8, for each bolt size fit into the corresponding holder. Lastly a fixture, for each bolt size, was used instead of a nut, as can be seen in Figure 4-9.

Figure 4-7: Small and Large Tension Slotted Bolt Holder

Figure 4-8: Tension Wedge Washers

Figure 4-9: Tension Fixtures

The relative crosshead displacement was monitored by using independent Linear Variable Differential Transformers (LVDTs). The reason for using LVDTs was to eliminate the elastic compliance of the Universal Testing Machine from the measured data. The tension set-up to obtain the elongation/crosshead displacement used three LVDTs, as shown in Figure 4-10. The two LVDTs resting on the steel fixture measured the displacement of the bottom bolt fixture relative to the lower cross head. The data obtained from these two LVDTs were averaged due to the rotation of the bolt as a result of the wedge washer. The third LVDT was located in an apparatus with a lever arm, as seen in Figure 4-11. For the first sixty-six lots of bolts tested in tension, the end of the lever arm rested on the bolt head, as can be seen in Figure 4-12. However, since the bolt head bends due to the wedge washer, the elongation of the bolt was slightly incorrect. Instead of the force versus elongation curve being straight in the elastic range it was slightly curved since the wedge washer bends the head of the bolt. For the remaining tension tests the lever arm of the third LVDT rested on a small angle which was attached to the tension fixture, as seen in Figure 4-13. This was a more successful way of measuring the elongation of the tension bolts. The average displacement of the two LVDTs was added to the third LVDT displacement which resulted in the elongation of the fastener.

Figure 4-10: LVDT Set-Up for Tension

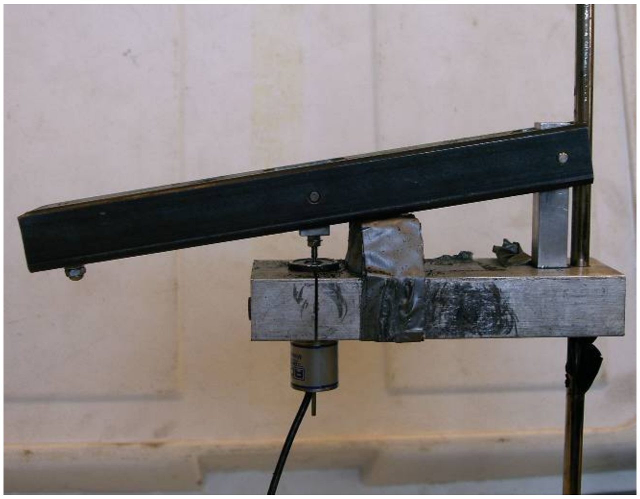


Figure 4-11: Third LVDT for Tension Testing

Figure 4-12: Third LVDT's Lever Arm on Bolt Head

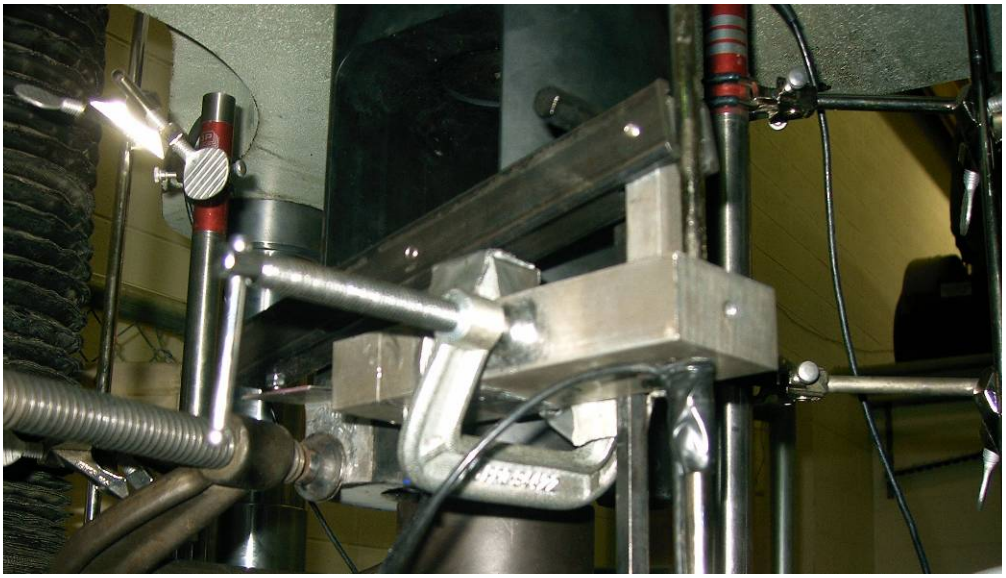


Figure 4-13: Angle with Third LVDT

4.2.3 Shear Testing Equipment

The shear strength of bolts tested in tension results in approximately 8% to 13% lower shear strength when compared to bolts tested in a compression shear fixture (Kulak et al. 2001). This is observed due to a "phenomenon that tends to bend the lap plates of the tension jig outward" (Kulak et al. 2001), known as lap plate prying. Even though this phenomenon occurs, the tension jig is preferred because it produces a conservative (lower) shear strength and has more consistent test results when compared to the compression jig (Kulak et al. 2001). The shear tests thus were performed in tension.

The shear tests were conducted according to ASTM F606-05 using a fabricated shear fixture as shown in Figure 4-14 and Figure 4-15. Tolerances of +/- 0.010 inch were allowed unless specified otherwise. Big and small inserts, to be described later, were used to accommodate the six different bolt diameters. As required in ASTM F606-05, a 0.010 inch chamfer was provided on the holes to eliminate sharp edges.

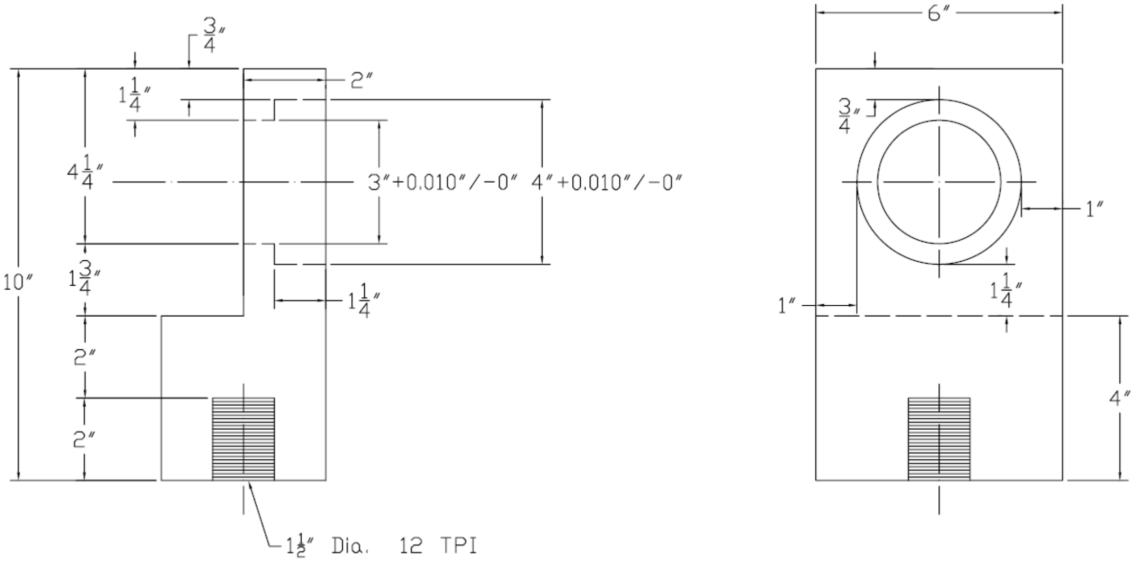


Figure 4-14: Fabricated Shear Fixture

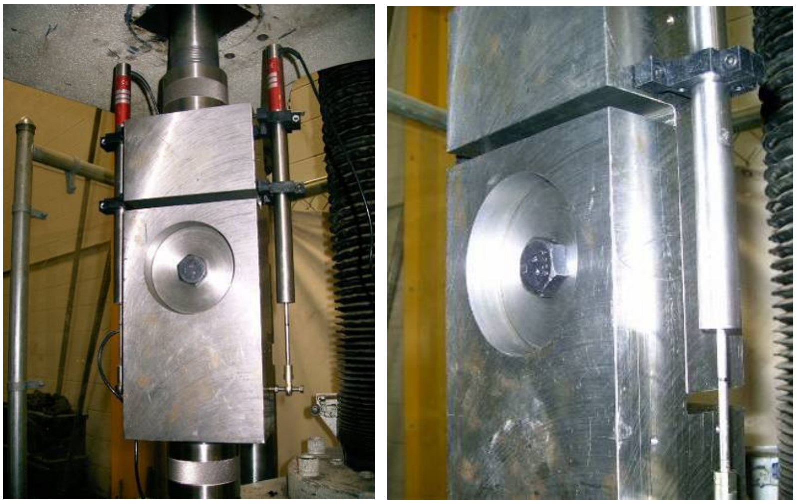


Figure 4-15: Shear Fixture

After testing a few bolts in shear a number of problems were encountered. Since the bolts are harder than the steel used to test them, the material in the fixture experienced bearing deformations. Heat-treating the shear inserts was investigated since this would increase the life of the inserts. Since the goal was to test isolated fasteners, it was thought that heat-treated inserts would provide a more conservative set of results (i.e. lower measured strengths with the hardened inserts versus unhardened inserts). ASTM F606-05 states that the fixture shall be made from hardened steel to prevent bearing failure, however, after consulting members of the RCSC Advisory Panel, it was advised not to use heat-treated steel for the inserts because it was not a realistic representation of a bolted connection.

The solution to this problem was to use three sizes of big inserts, which accommodate small inserts for each bolt size that was tested in shear. The three big inserts used can be seen in Figures 4-16, 4-17, and 4-18. Figures 4-16, 4-17, and 4-18 also show big inserts after testing. The small inserts eventually caused damage to the big inserts. The big inserts were made from D2 tool steel to provide a longer life but their usage depended on the bolt size and grade of the bolts being tested. D2 tool steel has a tensile strength of approximately 275 ksi, a yield strength of approximately 215 ksi, and a Rockwell hardness of C56 (McMaster-Carr 2007). To make the shear testing realistic, small inserts were made from 1045 steel, which has an average tensile strength of 92 ksi, an average yield strength of 57 ksi, and an average Brinell Hardness of 185 (McMaster-Carr 2007). The small inserts were rotated after each tested bolt so a clean surface without bearing deformations was used for each test. Due to the bearing failures, four hundred small inserts were made to test the bolts in shear. A pair of small inserts normally lasted about ten bolts before the hole became too deformed and new inserts needed to be used. A typical insert before and after testing can be seen in Figure 4-19.

Figure 4-16: Big Insert for 5/8” and 3/4" Bolts

Figure 4-17: Big Insert for 7/8” and 1" Bolts

Figure 4-18: Big Inserts for 1-1/8" and 1-1/4” Bolts

Figure 4-19: Typical Insert Before and After Testing

The phenomenon known as lap plate prying caused some problems with the big inserts. When the shear fixtures separated the big inserts would rotate causing damage. To prevent the shear fixtures from separating during testing four 3/4-inch steel pins were added to the shear fixture as shown in Figures 4-20 and 4-21. According to Wallaert (1964), a modified tension jig which eliminates lap plate prying results in shear strengths of bolts closer to the shear strength of a bolt tested in a compression jig.

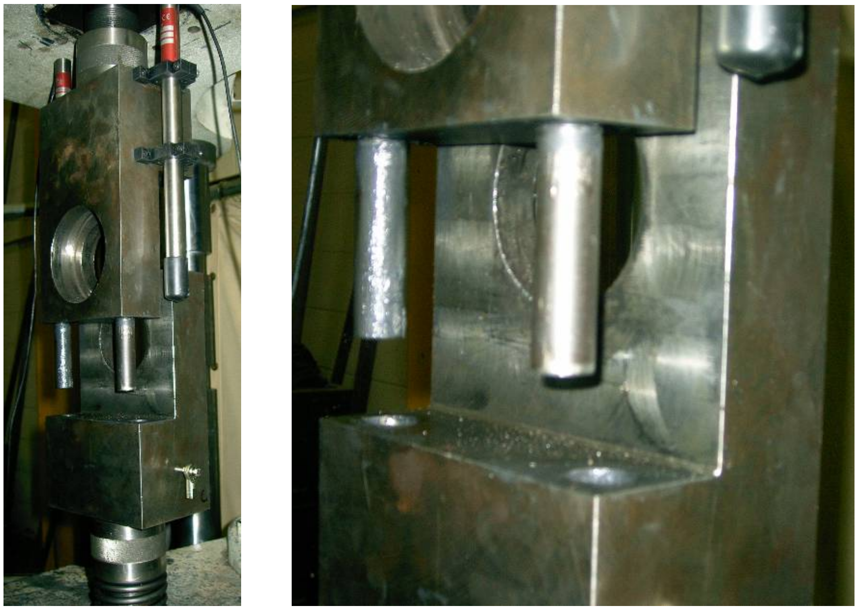


Figure 4-20: Shear Fixture with Modified Pins

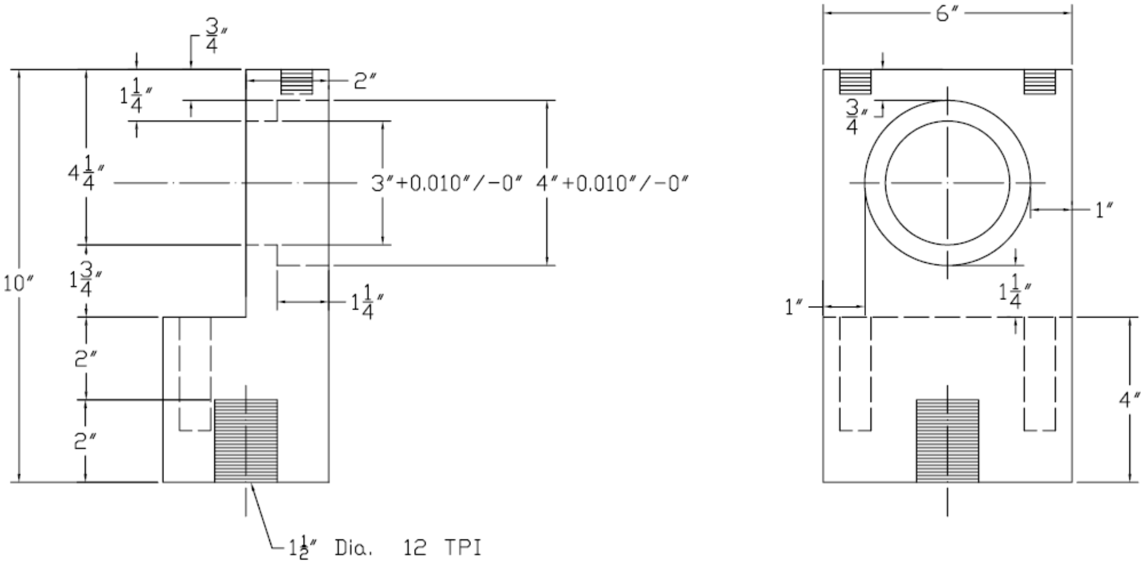


Figure 4-21: Modified Shear Fixture

The shear set-up used only two Linear Variable Differential Transformers (LVDTs). The reason for using LVDTs was to eliminate the elastic compliance of the Universal Testing Machine from the measured data. Figure 4-22 shows the shear set-up with two LVDTs, where they were attached to the sides of the shear fixture and measured displacement.

Figure 4-22: Shear Fixture Set-Up

4.3 Procedure

This section describes the process used to determine the speed of testing for tension and shear, as well as the procedure for testing. The head of each bolt was punched with a letter and number to distinguish the provenience and the lot number of the bolts.

4.3.1 Determining the Speed of Testing

4.3.1.1 Tension

To determine the speed of testing to be used in tension, two 3/4-inch diameter bolts, 3-3/4-inches long, of both A325 and A490 were tested at four different strain rates, varying from 0.01 inch/inch/minute to 0.25 inch/inch/minute. The load rate programmed into the Tinius-Olsen Machine was determined by multiplying the strain rate by the length of the reduced section, or the bolt length. After the numerous tests, it was determined that the strength of the bolt did not depend greatly on the strain rate. Table 4-2 shows the results of the A325 and A490 bolts tested at the four different strain rates. A constant strain rate of 0.15 inch/inch/minute was used for all tension tests. This rate was chosen so that the crosshead speed for the longest bolts tested (five inches) would not exceed 1 inch/minute.

Table 4-2: Determining Load Rate for Tension

Strain Rate (in/in/min)	Load Rate (in/min)	Tension Load (pounds)	
		A325	A490
0.01	0.0375	49,629	51,345
		49,914	52,415
0.05	0.1875	49,899	52,520
		50,152	52,985
0.15	0.5625	49,831	52,340
		50,307	52,704
		-	52,952
0.25	0.9375	49,791	51,968
		49,899	53,587
Average (pounds)		49,928	52,535
Standard Deviation (pounds)		212	642
Standard Deviation (percent)		0.42	1.22

4.3.1.2 Shear

The two extreme load rates, 0.25 inch/minute and 0.5 inch/minute, were evaluated on two 3/4-inch diameter A325 bolts with the threads excluded and not excluded from the shear plane to determine the load rate for testing in shear. The results of the bolts tested at the two extreme load rates are shown in Table 4-3. The load rate was determined not to be a great factor on the strength of the fastener so a load rate of 0.5 inch/minute was used for all bolts tested in shear.

Table 4-3: Determining Load Rate for Shear

Load Rate (in/min)	Shear Load (pounds)	
	X	N
0.25	42,060	27,721
0.50	42,344	29,245
Average (pounds)	42,202	28,483
Standard Deviation (pounds)	201	1078
Standard Deviation (percent)	0.48	3.78

4.3.2 Tension Testing

Before a bolt could be tested in tension, the diameter of the bolt shank was measured at five locations and recorded. The wedge washer was first placed around the bolt and then to ensure four threads were exposed it was screwed completely into the corresponding fixture. A mark was made on the bolt and then the bolt was unthreaded four complete turns as shown in Figure 4-23. The wedge washer was placed in the holder and positioned to assure that no corner of the hexagonal head was loaded. After making sure all of the LVDTs where in their proper locations, the tension test could begin. Using TCS, the three LVDTs were balanced so the starting position of the test would equal zero displacement. The bolt was then loaded until fracture occurred. The maximum load was recorded from the Tinius-Olsen machine to be used in the calculations for resistance factors. The OPTIM recorded the load from the Tinius-Olsen for the force versus deformation plot. After the bolt fracture, the elongated length was measured and recorded so the elongation of the fastener could be determined.

Figure 4-23: Four Complete Threads Exposed

4.3.3 Shear Testing

As with the tension testing, before a bolt could be tested in shear the diameter of the bolt shank was measured at five locations and recorded. Spacers were used to position the bolt so the threads would be excluded or not excluded from the shear plane, as shown in Figure 4-24. The bolt was installed in the shear fixture with a nut, finger tightened, to hold the bolt in place while it was loaded. The two LVDTs were balanced using TCS before the shear test could begin. The bolt was then loaded until it failed in shear. The maximum load was again recorded from the Tinius-Olsen machine to be used in the resistance factor calculations as like with tension. The OPTIM recorded the load from the Tinius-Olsen for the force versus displacement plot. Before the next shear test was performed the small inserts were rotated so the bearing deformation would not affect the next test and the maximum use of the inserts would be achieved.

Figure 4-24: Spacers Used to Get X and N Shear Conditions

4.3.4 Thread Length

Besides the tensile and shear strength of A325, F1852, A490, and F2280 bolts being determined, the thread lengths were also considered. It was noticed that the thread lengths on the bolts varied from the dimensions in the AISC Manual (2005). This could cause problems when designing bolts in shear for a connection. If a bolt was designed with the threads excluded from the shear plane but the thread length was longer than specified in the Manual the bolt might actually fail at a lower strength if the threads are not excluded from the shear plane. The thread length of one bolt was measured from each lot so the actual thread length could be compared to the nominal length.

CHAPTER 5

PRESENTATION OF DATA

The data and resistance factors from the 1533 bolts tested in tension and shear are summarized in this chapter. The one hundred lots of A325, F1852, A490, and F2280 high-strength structural bolts obtained from manufactures and suppliers are discussed in the first section of this chapter. The thread length was measured and is reported in Section 5.2. The results of the bolts tested in tension, shear excluded, and shear not excluded are presented in Section 5.3. The elongation of the A325, F1852, A490, and F2280 bolts is discussed in Section 5.4. The primary objective of this research (recalibrating the current resistance factor) is included in Section 5.5. Lastly, recommendations based on the 1533 structural bolts tested are found in Section 5.6.

5.1 Bolts Obtained/Tested

As previously discussed in Section 2.5, the one hundred lots tested were divided between A325/F1852 and A490/F2280 high-strength bolts with diameters ranging from 5/8-inch to 1-1/8-inches. The bolts were obtained from seven different manufacturers or distributors, who will not be identified by name. Roughly half of the bolts were sought from United States manufacturers by donations. The remaining bolts were purchased through local distributors. Purchasing half of the needed bolts limited the possibility of preferential selection by the manufacturers. Obtaining the fasteners in this matter should have led to a statistically sound sample. The bolts were punched with a letter and a number. The letter corresponded to the distributor or manufacturer where the bolt was obtained and the number distinguished the lot of the bolt. More A490/F2280 bolts were tested compared to A325/F1852 due to the perceived inconsistent strength of A490/F2280 high-strength structural bolts and the smaller amount of data available from past research. Table 5-1 shows the number of lots obtained and tested based on the grade of structural bolts (A325, F1852, A490, or F2280). Table 5-2 shows the breakdown of the lots obtained based on the bolt diameter and grade.

Table 5-1: Bolts Obtained/Tested by Grade

Grade	Number of Lots	Diameter (inches)	Length (inches)
A325	40	5/8 to 1-1/4	2.75 to 5
F1852	5	5/8 to 1-1/8	2.75 to 4.5
A490	45	5/8 to 1-1/4	2.75 to 5
F2280	10	3/4 to 1-1/8	3.25 to 4.25

Table 5-2: Bolts Obtained/Tested by Diameter and Grade

Diameter (inches)	Grade	Number of Lots	Length (inches)
5/8	A325	4	2.75 to 4.5
	F1852	1	2.75
	A490	6	3 to 5
3/4	A325	10	2.75 to 5
	F1852	1	3.75
	A490	9	2.75 to 5
	F2280	3	3.5 to 4
7/8	A325	9	3 to 5
	F1852	1	3.5
	A490	10	3 to 5
	F2280	3	3.25 to 4.25
1	A325	9	3 to 5
	F1852	1	3.25
	A490	9	3 to 5
	F2280	3	3.5 to 3.75
1 1/8	A325	4	4 to 4.5
	F1852	1	4.5
	A490	5	3.75 to 5
	F2280	1	4.25
1 1/4	A325	4	4.5 to 5
	A490	6	3.5 to 5

5.2 Thread Length

Due to the tolerances which are allowed on the thread length of bolts, the thread length of one bolt per lot was measured. The measured thread length was compared to the AISC Manual (2005). The percent error found in the thread lengths based on bolt diameter is summarized in Table 5-3. Figure 5-1 shows the frequency distribution of the percent error.

As can be seen from Table 5-3, the average percent error in the thread lengths is less than five percent for 5/8-inch, 3/4-inch, and 7/8-inch bolts. However as the bolt diameter increases the percent error in the thread length also increases to as much as 7.41 %for 1-1/4-inch bolts. The average error in the thread length was found to be 4.82 % with a standard deviation of 0.02513. The minimum and maximum error in the thread length based on the one hundred lots measured was -1.34 % (meaning the thread length is shorter than reported in AISC's Manual) and 10.38 %, respectively. This could cause some potential problems if the design shear plane is close to the thread run-out since this location varies between bolts.

Table 5-3: Percent Error of Bolt Thread Length by Diameter

Diameter	Grade	Total Lots Tested	Average (St. Dev.)	Minimum & Maximum
5/8	A325/F1852	5	4.38% (0.02328)	1.00% 6.60%
	A490	6	3.07% (0.02511)	3.67% 2.41%
	All Grades	11	3.67% (0.02407)	-0.24% 6.96%
3/4	A325/F1852	11	4.89% (0.01740)	1.09% 6.98%
	A490/F2280	12	4.26% (0.01644)	1.53% 6.22%
	All Grades	23	4.56% (0.01682)	1.09% 6.98%
7/8	A325/F1852	10	3.61% (0.02500)	-0.10% 8.03%
	A490/F2280	13	3.93% (0.02761)	-0.37% 8.60%
	All Grades	23	3.79% (0.02596)	-0.37% 8.60%
1	A325/F1852	10	4.89% (0.02458)	-1.34% 7.57%
	A490/F2280	12	5.12% (0.02619)	1.34% 9.63%
	All Grades	22	5.02% (0.02490)	-1.34% 9.63%
1 1/8	A325/F1852	5	6.25% (0.01883)	3.80% 7.90%
	A490/F2280	6	5.60% (0.02919)	0.12% 7.93%
	All Grades	11	5.89% (0.02407)	0.12% 7.93%
1 1/4	A325	4	6.56% (0.02686)	4.10% 10.38%
	A490	6	7.97% (0.02075)	5.00% 10.30%
	All Grades	10	7.41% (0.02309)	4.10% 10.38%
All Diameters	All Grades	100	4.82% (0.02513)	-1.34% 10.38%

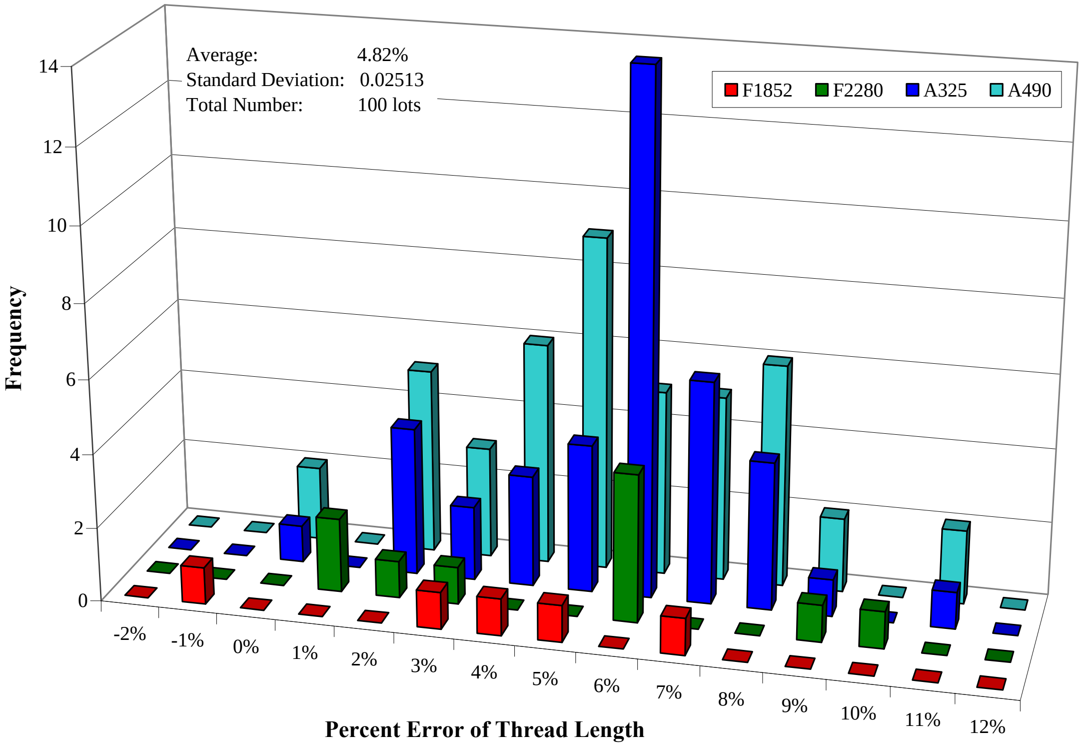


Figure 5-1: Frequency Distribution of Percent Error for Bolt Thread Length

5.3 Results of Bolts Tested

One hundred lots of bolts were tested in tension and shear with the threads excluded and not excluded from the shear plane. A few high strength bolts which failed in tension, shear with the threads excluded, and shear with the threads not excluded can be seen in Figures 5-2, 5-3, and 5-4. These figures show the typical failures.


Figure 5-2: Typical Bolts Failed in Tension


Figure 5-3: Typical Bolts Failed in Shear with the Threads Excluded

Figure 5-4: Typical Bolts Failed in Shear with the Threads Not Excluded

Appendix A tabulates the failure loads of the fifteen bolts tested per lot in tension and shear. The appendix also contains the load versus elongation curves for the direct tension tests and the load versus displacement curves for the shear with the threads excluded and not excluded. A sample load versus elongation curve and load versus displacement curve for a 7/8-inch diameter A490 bolt, 5-inches long can be seen in Section 5.3.1.

A few comparisons were made from the 1533 A325, F1852, A490, and F2280 high-strength bolts tested in tension and shear with the threads excluded and not excluded from the shear plane. The comparisons can be seen in Section 5.3.2.

5.3.1 Sample Load versus Elongation/Displacement Curves

The load versus elongation and load versus displacement curves for the one hundred lots can be found in Appendix A. For Lot C15, these curves can be seen in Figures 5-5 and 5-6 as a sample. Lot C15 is a 7/8-inch A490 bolt, 5 inches long. Note that the bolt extension measurement is impaired by the use of the wedge washer in the test setup. The bolt head will force the bolt to rotate to adapt to the washer surface, and therefore the LVDT that measures the bolt head displacement reads smaller elongations that the actual values during the rotation. After yielding, the bolt straightens and the LVDT takes accurate readings.

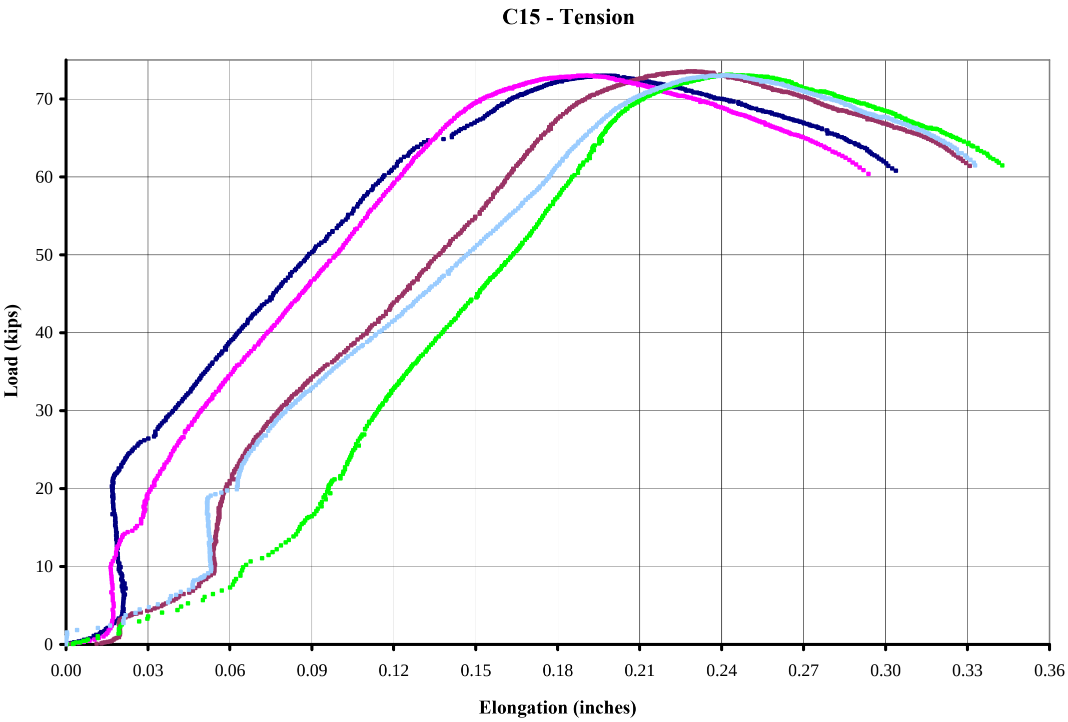


Figure 5-5: Load versus Elongation for Lot C15

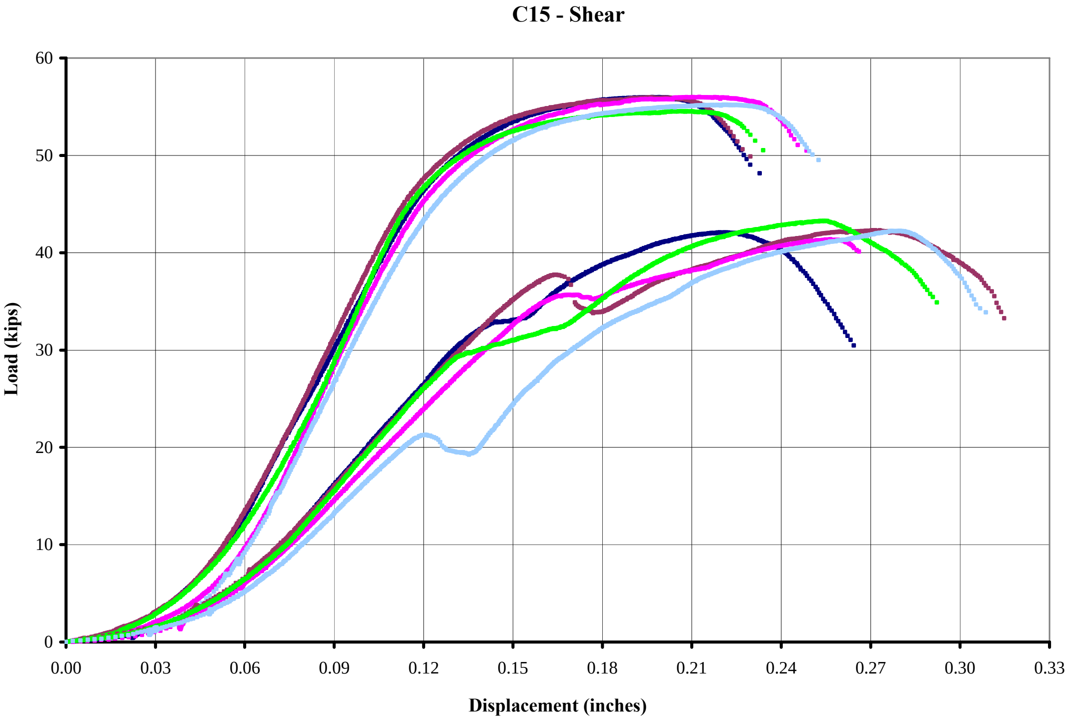


Figure 5-6: Load versus Displacement for Lot C15

5.3.2 Comparisons

Comparisons of the 1533 high-strength bolts tested in tension and shear with the threads excluded and not excluded from the shear plane were made. Section 5.3.2.1 compares the experimental tensile strength to the material data sheets of the one hundred lots tested. The tensile strength of the 515 bolts tested in direct tension was compared to the ASTM limits and is discussed in Section 5.3.2.2. Section 5.3.2.3 compares the experimental strength to the nominal strength for tension and shear with the threads excluded and not excluded from the shear plane. Lastly, the ratios of the shear strength with the threads excluded to the tensile strength and the shear strength with the threads not excluded to the shear strength with the threads excluded were compared and are summarized in Section 5.3.2.4.

5.3.2.1 Experimental Tensile Strength to Material Data Sheets

The one hundred lots of high-strength bolts tested in direct tension were compared to the material data sheets which were obtained from the manufacturer or distributor. The ratio of the experimental tensile strength to the value obtained from the material data sheet was evaluated for all lots. Figure 5-7 is the frequency distribution of the experimental tensile strength to the material data sheets for the four grades of bolts. It should be noted that only seventy-nine out of the one hundred material data sheets were available for comparison.

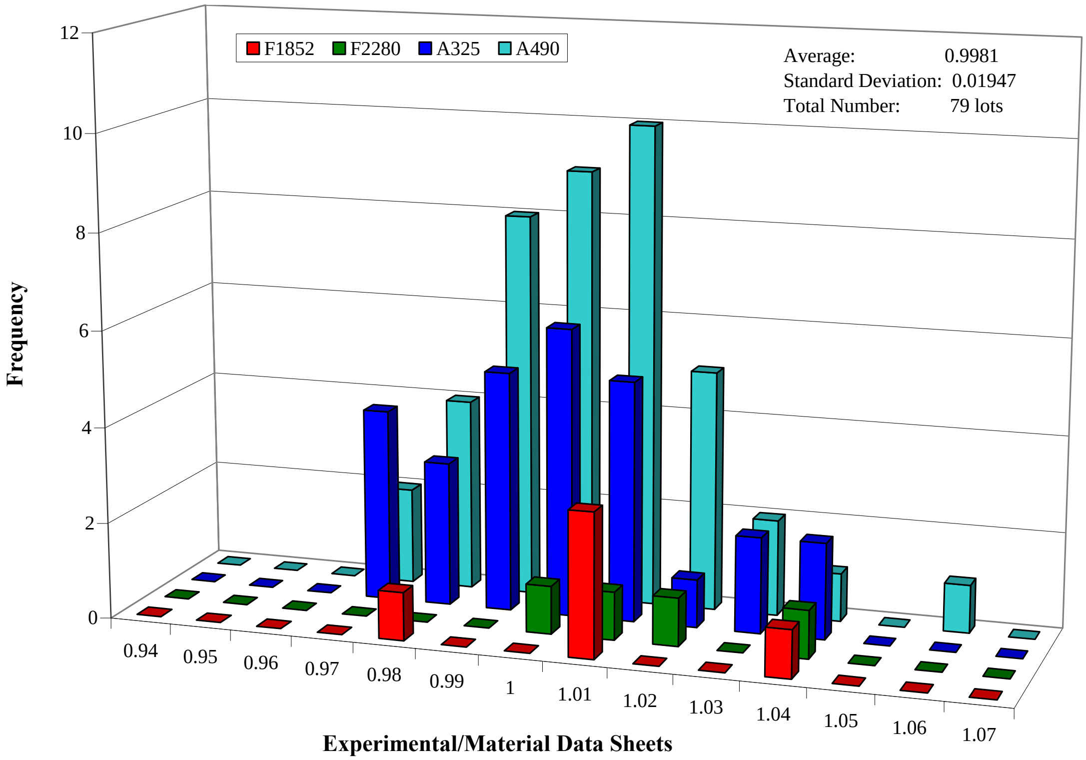


Figure 5-7: Frequency Distribution of Strength to Data Sheets

As can be seen from Figure 5-7, the experimental tensile strength was on average 99.8 percent of the strength given by the manufacturer's material data sheets. This means that the experimental tensile strength obtained from the direct tension testing is approximately equal to the tensile strength reported by the manufacturers.

To further examine this ratio, the frequency distributions for each of the four grades based on the diameter are shown in Figures 5-8 through 5-11.

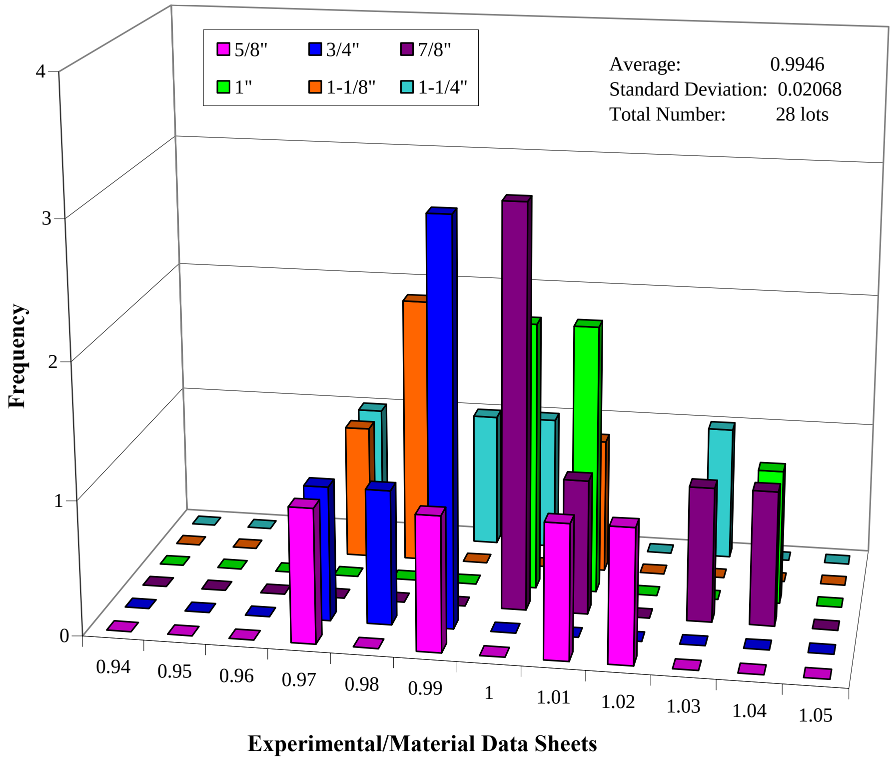


Figure 5-8: Frequency Distribution of Strength to Data Sheets for A325 Bolts

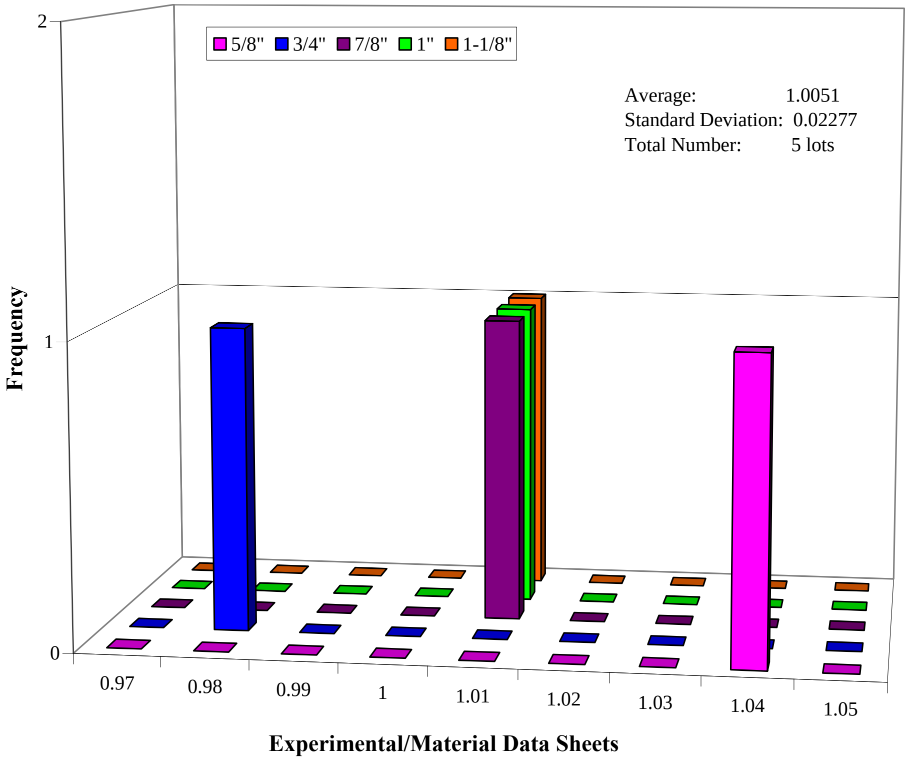


Figure 5-9: Frequency Distribution of Strength to Data Sheets for F1852 Bolts

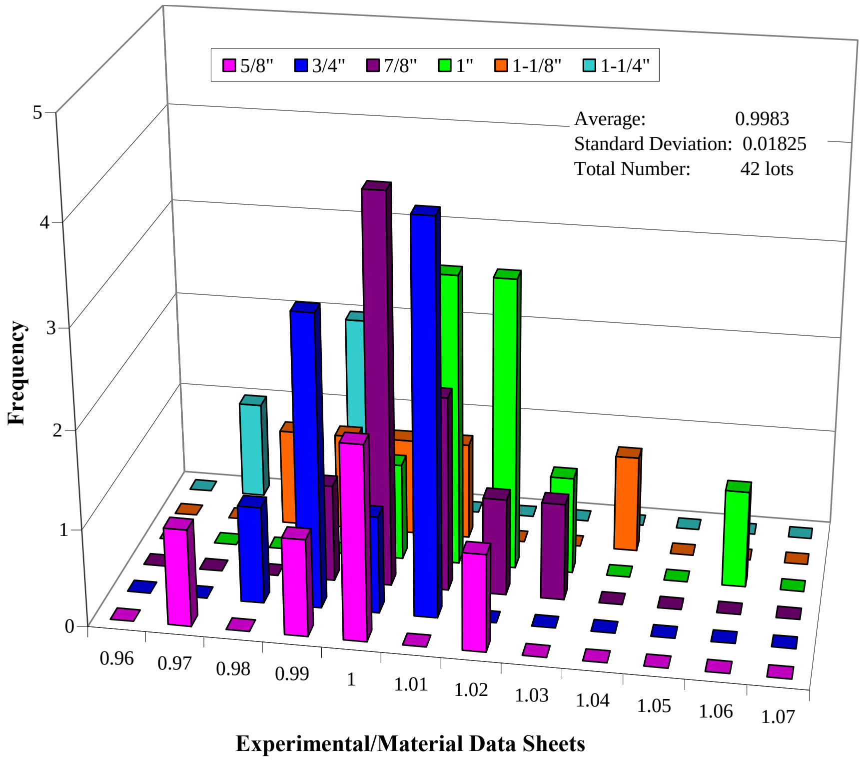


Figure 5-10: Frequency Distribution of Strength to Data Sheets for A490 Bolts

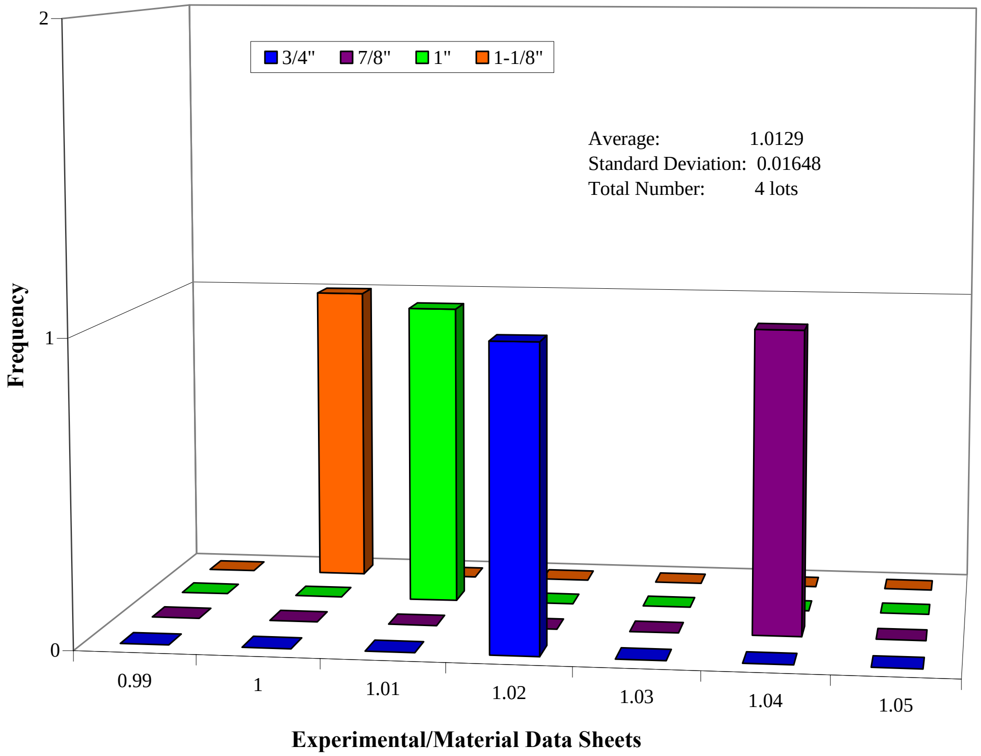


Figure 5-11: Frequency Distribution of Strength to Data Sheets for F2280 Bolts

Tables 5-4 and 5-5 summarize Figures 5-7 through 5-11. Based on the seventy-nine material data sheets, Table 5-4 summarizes the tensile strength from the material data sheets and the ratio based on the bolt grades, whereas Table 5-5 is based on the bolt diameters.

Table 5-4: Summarizing Material Data Sheets Based on Bolt Grade

		From Material Data Sheets						Strength Ratio - Experimental to Material Data Sheets			
Grade	Lots of Bolts	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number of Lots Greater than 170 ksi Tensile Strength	Number of Lots Greater than 173 ksi Tensile Strength	Average	Standard Deviation	Minimum	Maximum
A325	28	143.10	7.441	125.11	154.30	Not Applicable		0.9946	0.02068	0.9610	1.0350
F1852	5	148.03	6.583	136.94	152.69	Not Applicable		1.0051	0.02277	0.9729	1.0369
A325 F1852	33	143.85	7.441	125.11	154.30	Not Applicable		0.9962	0.02098	0.9610	1.0369
A490	42	164.21	4.144	155.34	170.96	2	0	0.9983	0.01825	0.9621	1.0507
F2280	4	167.00	2.245	165.19	170.16	1	0	1.0129	0.01648	0.9943	1.0337
A490 F2280	46	164.45	4.076	155.34	170.96	3	0	0.9995	0.01841	0.9621	1.0507
All Grades	79	N/A	N/A	N/A	N/A	3	0	0.9981	0.01947	0.9610	1.0507

Table 5-5: Summarizing Material Data Sheets Based on Bolt Diameters

			From Material Data Sheets						Strength Ratio - Experimental to Material Data Sheets			
Diameter (inches)	Grade	Lots of Bolts	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number of Lots Greater than 170 ksi Tensile Strength	Number of Lots Greater than 173 ksi Tensile Strength	Average	Standard Deviation	Minimum	Maximum
5/8	A325/F1852	5	142.45	3.814	138.88	147.12	Not Applicable		1.0020	0.02881	0.9614	1.0369
	A490	5	165.36	4.777	158.34	169.93	0	0	0.9904	0.01966	0.9621	1.0145
3/4	A325/F1852	6	151.37	2.213	148.46	154.30	Not Applicable		0.9792	0.00946	0.9638	0.9899
	A490/F2280	10	164.58	4.575	155.34	170.96	1	0	0.9952	0.01413	0.9722	1.0159
7/8	A325/F1852	7	148.75	3.485	143.63	152.69	Not Applicable		1.0078	0.01575	0.9928	1.0349
	A490/F2280	10	163.80	3.636	159.28	169.50	0	0	1.0057	0.01541	0.9890	1.0337
1	A325/F1852	6	146.12	3.277	141.52	151.05	Not Applicable		1.0073	0.01429	0.9946	1.0350
	A490/F2280	10	163.11	3.645	158.22	169.03	0	0	1.0139	0.01555	0.9966	1.0507
1 1/8	A325/F1852	5	135.82	2.109	133.36	138.83	Not Applicable		0.9839	0.01757	0.9628	1.0025
	A490/F2280	6	163.82	4.754	158.04	170.16	1	0	0.9980	0.01944	0.9747	1.0328
1 1/4	A325	4	132.38	7.031	125.11	139.33	Not Applicable		0.9926	0.02708	0.9610	1.0271
	A490	5	168.01	2.463	165.00	170.26	1	0	0.9780	0.00907	0.9674	0.9884
All Diameters	A325/F1852	33	143.85	7.441	125.11	154.30	Not Applicable		0.9962	0.02098	0.9610	1.0369
	A490/F2280	46	164.45	4.076	155.34	170.96	3	0	0.9995	0.01841	0.9621	1.0507

As can be seen from Table 5-4, the ratio of the experimental tensile strength to the material data sheet is never less than 0.961 and never more than 1.051 for all grades of bolts. Based on the tensile strength from the seventy-nine material data sheets none of the A490 or F2280 lots had a strength greater than 173 ksi as specified by ASTM. This will be discussed further based on the bolts tested in the next Section.

5.3.2.2 Tensile Strength Compared to ASTM and RCSC

ASTM A325 (ASTM A325-04b) and F1852 (ASTM F1852-05) specify a minimum tensile strength of 120 ksi for bolts less than or equal to 1-inch in diameter and 105 ksi for bolts greater than 1-inch in diameter. However ASTM A490 (ASTM A490-04a) and F2280 (ASTM F2280-06) bolts are specified to have a minimum tensile strength of 150 ksi as well as a maximum tensile strength of 173 ksi per ASTM or 170 ksi per RCSC. Therefore the tensile strength of the 515 bolts tested in direct tension was compared to ASTM and RCSC limits. The tensile strength was calculated by the failure tensile load divided by the effective area as given by equation (2-3). Figures 5-12 through 5-19 show the frequency distribution of the tensile strength for the four grades of bolts. Figures 5-12, 5-14, 5-16, and 5-18 show the frequency distribution for each bolt tested in direct tension for A325, F1852, A490, and F2280 bolts, respectively. On the other hand, Figures 5-13, 5-15, 5-17, and 5-19 show the frequency distribution of the average tensile strength for each lot of bolts tested in direct tension.

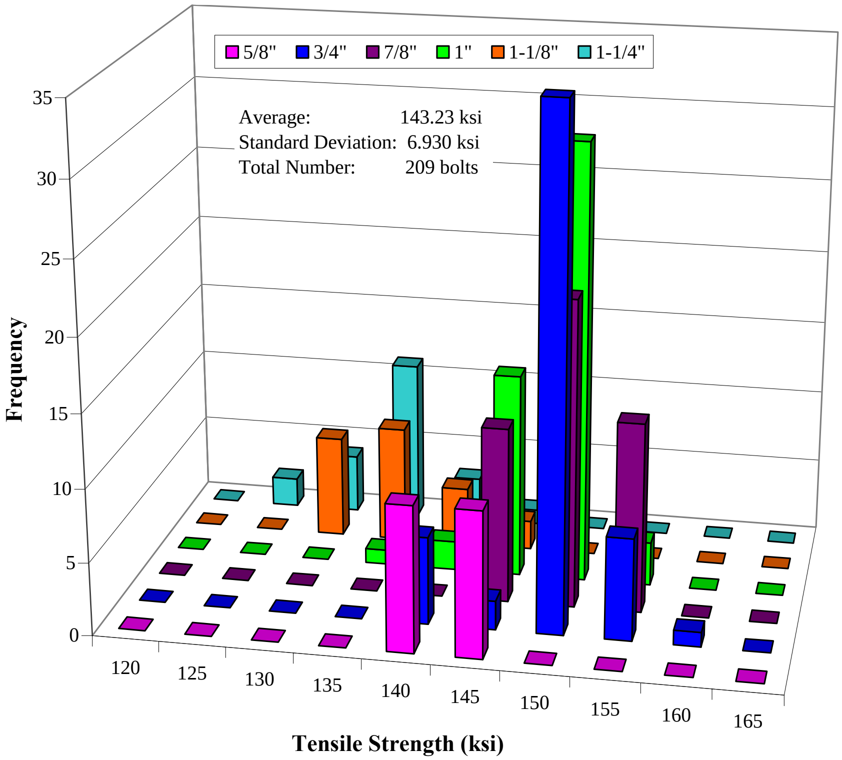


Figure 5-12: Frequency Distribution of Tensile Strength for A325 Bolts

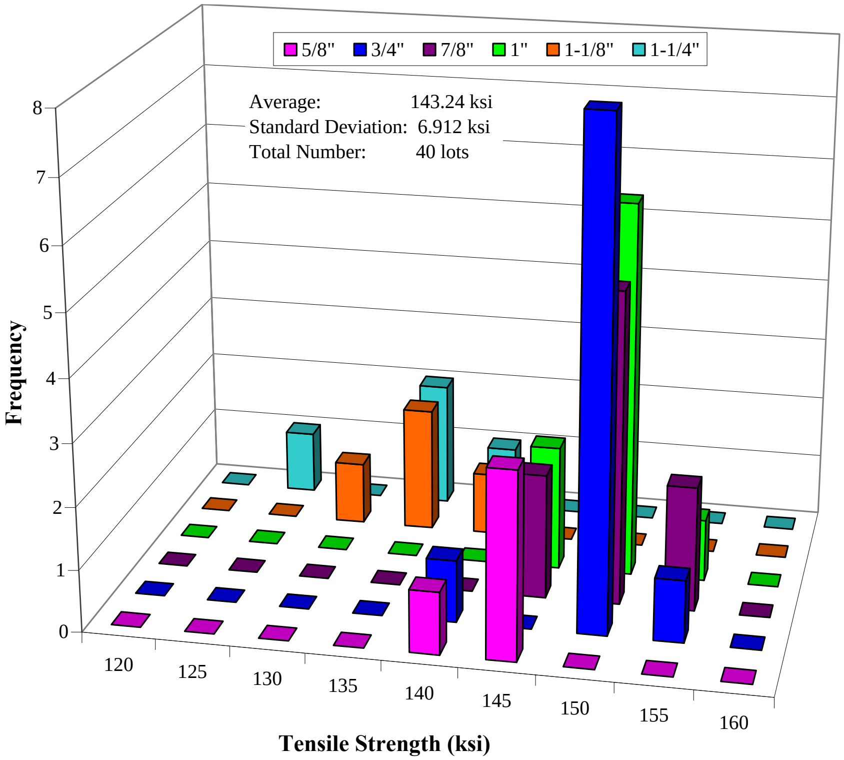


Figure 5-13: Frequency Distribution of Average Tensile Strength for Lots of A325 Bolts

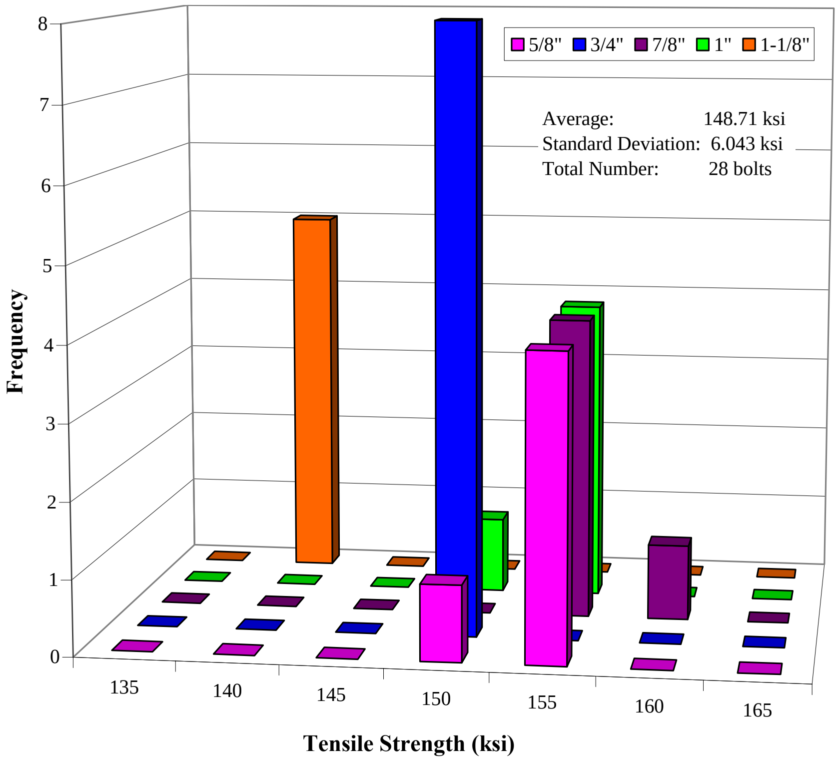


Figure 5-14: Frequency Distribution of Tensile Strength for F1852 Bolts

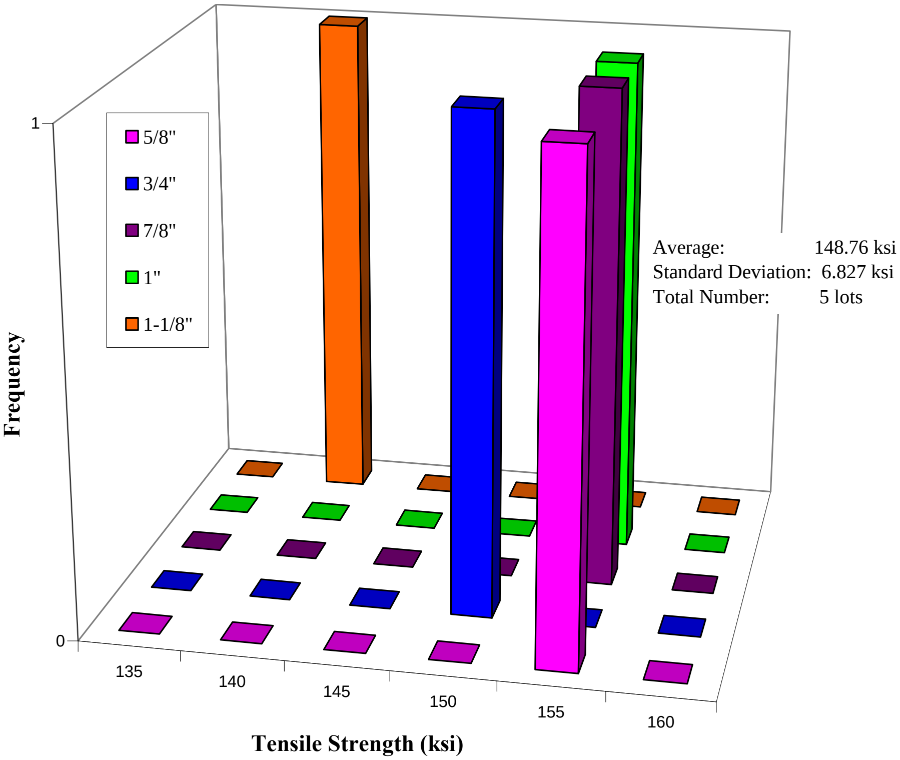
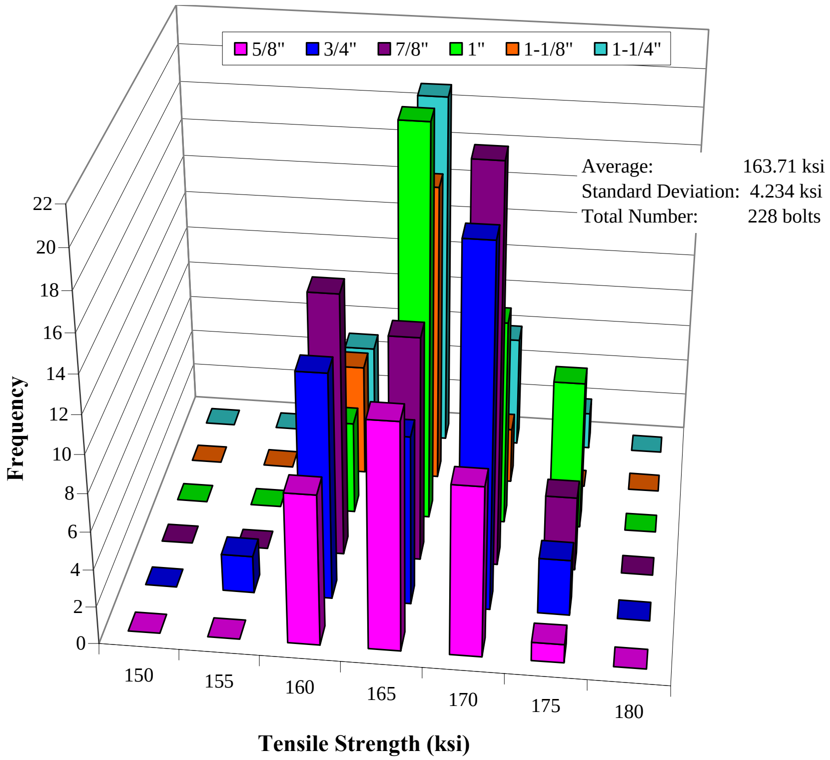
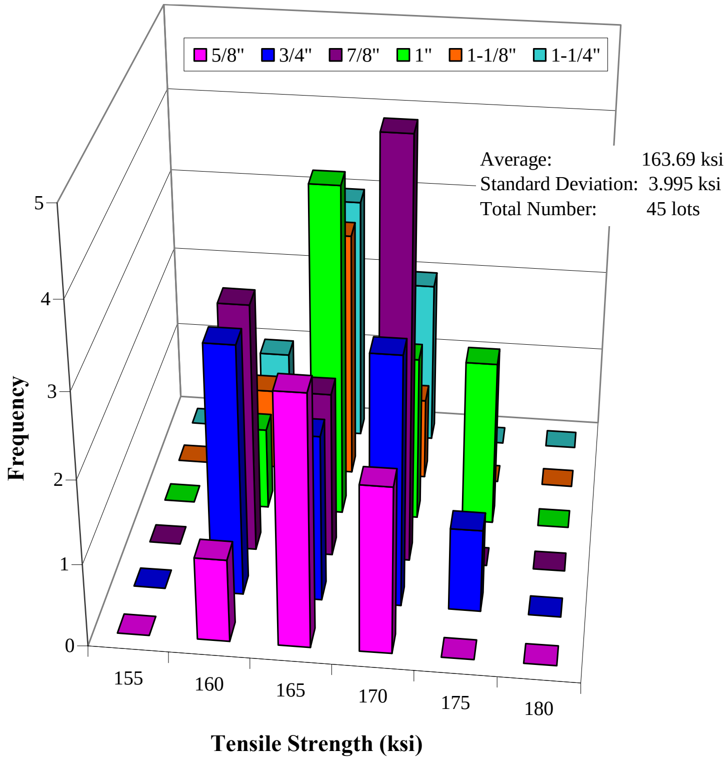


Figure 5-15: Frequency Distribution of Average Tensile Strength for Lots of F1852 Bolts



Average: 163.71 ksi
Standard Deviation: 4.234 ksi
Total Number: 228 bolts

Figure 5-16: Frequency Distribution of Tensile Strength for A490 Bolts



Average: 163.69 ksi
Standard Deviation: 3.995 ksi
Total Number: 45 lots

Figure 5-17: Frequency Distribution of Average Tensile Strength for Lots of A490 Bolts

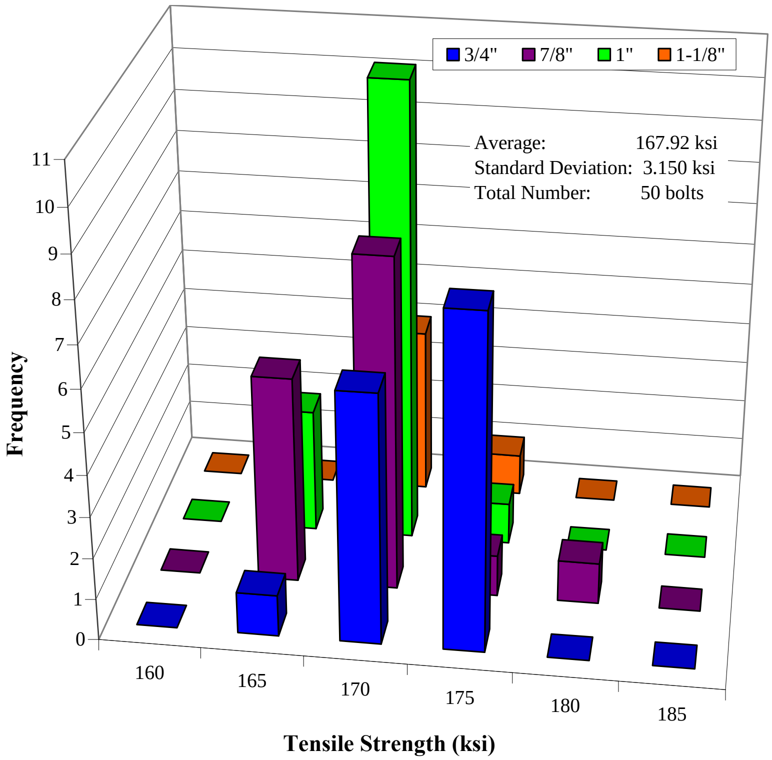


Figure 5-18: Frequency Distribution of Tensile Strength for F2280 Bolts

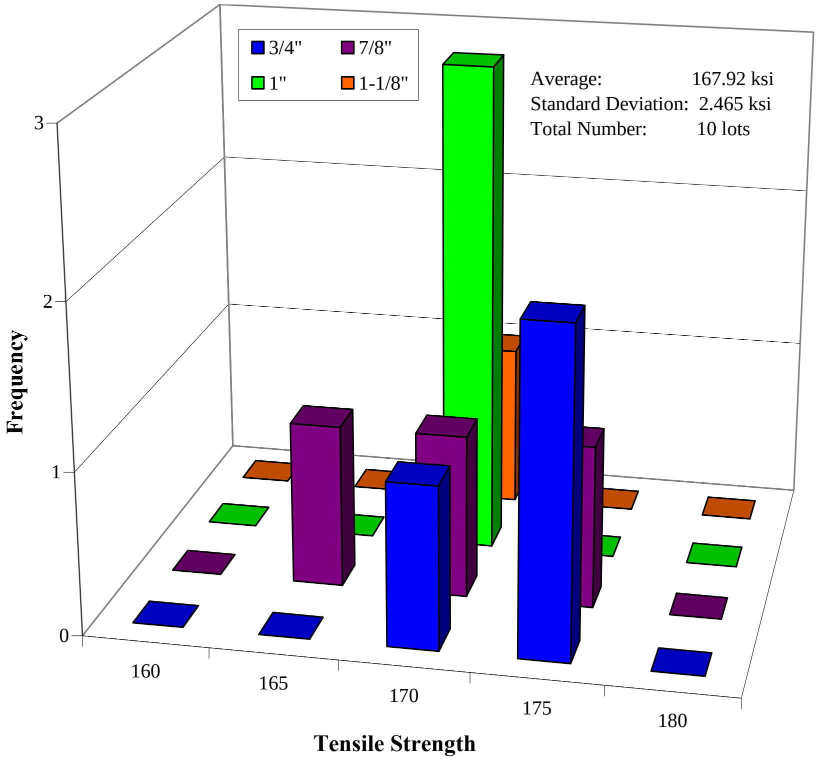


Figure 5-19: Frequency Distribution of Average Tensile Strength for Lots of F2280 Bolts

From Figures 5-12 through 5-15 it can be seen that the A325 and F1852 bolts are never below the ASTM minimum tensile strength of 120 ksi. The average tensile strength, for A325 and F1852 bolts is between approximately 143 ksi and 149 ksi. Since there is no maximum tensile strength specified by ASTM or RCSC some of the A325 and F1852 bolts have a strength in accordance with A490 or F2280 bolts since the tensile strength was found to be greater than 150 ksi.

The A490 and F2280 bolts' tensile strength is never below the specified ASTM minimum of 150 ksi, as can be seen in Figures 5-16 through 5-19. On average for the A490 and F2280 bolts the tensile strength is between approximately 164 and 168 ksi. Also from Figures 5-16 through 5-19 it can be seen that some bolts or lots exceed RCSC's maximum tensile strength of 170 ksi.

Figures 5-12, 5-14, 5-16, and 5-18 are summarized in Table 5-6 based on the 515 bolts tested in direct tension. Table 5-7 summarizes Figures 5-13, 5-15, 5-17, and 5-19 based on the one hundred lots of bolts tested in direct tension. These tables summarize the tensile strength based on the bolt grade.

Table 5-6: Tensile Strength of Bolts Tested Based on Grade

Grade	Bolts Tested in Tension	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number (and percentage) of Bolts Greater than 150 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 170 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 173 ksi Tensile Strength	
A325	209	143.23	6.930	121.55	156.28	24	11.48%	Not Applicable			
F1852	28	148.71	6.043	135.46	156.09	13	46.43%	Not Applicable			
A325 F1852	237	143.88	7.046	121.55	156.28	37	15.61%	Not Applicable			
A490	228	163.71	4.234	152.06	173.06	Not Applicable		18	7.89%	1	0.44%
F2280	50	167.92	3.150	161.78	179.79	Not Applicable		12	24.00%	2	4.00%
A490 F2280	278	164.46	4.367	152.06	179.79	Not Applicable		30	10.79%	3	1.08%

Table 5-7: Tensile Strength of Lots Tested Based on Grade

Grade	Lots Tested in Tension	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number (and percentage) of Bolts Greater than 150 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 170 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 173 ksi Tensile Strength	
A325	40	143.24	6.912	124.24	152.57	4	10.00%	Not Applicable			
F1852	5	148.76	6.827	137.17	154.09	3	60.00%	Not Applicable			
A325 F1852	45	143.86	7.047	124.24	154.09	7	15.56%	Not Applicable			
A490	45	163.69	3.995	155.34	170.64	Not Applicable		3	6.67%	0	0.00%
F2280	10	167.92	2.465	163.90	171.20	Not Applicable		3	30.00%	0	0.00%
A490 F2280	55	164.46	4.089	155.34	171.20	Not Applicable		6	10.91%	0	0.00%

To further compare the tensile strength to ASTM and RCSC Specifications, it was examined based on the diameter of the bolt. Tables 5-8 and 5-9 summarize the tensile strength for the 515 bolts tested and the one hundred lots tested, respectively, based on the diameter.

Table 5-8: Tensile Strength of Bolts Tested Based on Diameter

Diameter (inches)	Grade	Bolts Tested in Tension	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number (and percentage) of Bolts Greater than 150 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 170 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 173 ksi Tensile Strength	
5/8	A325/F1852	25	142.73	5.284	137.70	154.00	4	16.00%	Not Applicable			
	A490	30	163.19	4.331	158.40	170.74	Not Applicable		1	3.33%	0	0.00%
3/4	A325/F1852	59	147.14	3.697	137.32	156.28	8	13.56%	Not Applicable			
	A490/F2280	60	164.91	5.423	152.06	172.10	Not Applicable		11	18.33%	0	0.00%
7/8	A325/F1852	51	148.59	3.405	142.18	156.09	18	35.29%	Not Applicable			
	A490/F2280	66	164.74	4.475	155.11	179.79	Not Applicable		6	9.09%	1	1.52%
1	A325/F1852	55	146.05	3.632	134.68	153.32	7	12.73%	Not Applicable			
	A490/F2280	60	165.39	3.507	158.22	171.78	Not Applicable		9	15.00%	0	0.00%
1 1/8	A325/F1852	26	133.87	4.287	125.89	141.15	0	0.00%	Not Applicable			
	A490/F2280	30	163.46	3.663	156.81	173.51	Not Applicable		1	3.33%	1	3.33%
1 1/4	A325	21	131.35	5.253	121.55	140.61	0	0.00%	Not Applicable			
	A490	32	163.46	3.628	156.50	173.06	Not Applicable		2	6.25%	1	3.13%
All Diameters	A325/F1852	237	143.88	7.046	121.55	156.28	37	15.61%	Not Applicable			
	A490/F2280	278	164.46	4.367	152.06	179.79	Not Applicable		30	10.79%	3	1.08%

Table 5-9: Tensile Strength of Lots Tested Based on Diameter

Diameter (inches)	Grade	Lots Tested in Tension	Average (ksi)	Standard Deviation (ksi)	Minimum (ksi)	Maximum (ksi)	Number (and percentage) of Bolts Greater than 150 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 170 ksi Tensile Strength		Number (and percentage) of Bolts Greater than 173 ksi Tensile Strength	
5/8	A325/F1852	5	142.73	5.579	138.68	152.55	1	20.00%	Not Applicable			
	A490	6	163.19	4.584	159.74	169.71	Not Applicable		0	0.00%	0	0.00%
3/4	A325/F1852	11	147.23	3.476	138.63	152.57	1	9.09%	Not Applicable			
	A490/F2280	12	164.91	5.366	155.34	170.60	Not Applicable		3	25.00%	0	0.00%
7/8	A325/F1852	10	148.57	3.372	143.94	154.09	3	30.00%	Not Applicable			
	A490/F2280	13	164.73	4.242	158.38	171.20	Not Applicable		1	7.69%	0	0.00%
1	A325/F1852	10	146.10	3.543	140.65	151.77	2	20.00%	Not Applicable			
	A490/F2280	12	165.39	3.351	159.82	170.64	Not Applicable		2	16.67%	0	0.00%
1 1/8	A325/F1852	5	133.66	4.410	128.39	139.18	0	0.00%	Not Applicable			
	A490/F2280	6	163.46	3.704	158.21	169.18	Not Applicable		0	0.00%	0	0.00%
1 1/4	A325	4	131.32	5.572	124.24	137.84	0	0.00%	Not Applicable			
	A490	6	163.40	2.712	158.92	166.65	Not Applicable		0	0.00%	0	0.00%
All Diameters	A325/F1852	45	143.86	7.047	124.24	154.09	7	15.56%	Not Applicable			
	A490/F2280	55	164.46	4.089	155.34	171.20	Not Applicable		6	10.91%	0	0.00%

Some comments can be made about Tables 5-6 through 5-9. First, considering the A325 and F1852 bolts, the average tensile strength of the 237 bolts tested was 143.88 ksi with a standard deviation of 7.046 ksi which can be seen from Tables 5-6 and 5-8. The minimum and maximum tensile strength of the A325 and F1852 bolts tested was 121.55 ksi and 156.28 ksi, respectively. Considering the average tensile strength of the forty-five A325 and F1852 lots, the average tensile strength was 143.86 ksi with a standard deviation of 7.047 ksi, which can be seen from Tables 5-7 and 5-9. The minimum and maximum average tensile strength of the A325 and F1852 lots was 124.24 ksi and 154.09 ksi, respectively. It was found that of the 237 A325 and F1852 bolts tested in direct tension, none of the bolts had a strength less than the minimum tensile strength specified by ASTM. There were thirty-seven out of 237 A325 and F1852 bolts tested in direct tension (15.61%) that had a tensile strength greater than 150 ksi, as can be seen from Tables 5-6 and 5-8. Taking into consideration the average tensile strength of the bolts tested per lot, from Tables 5-7 and 5-9, there were seven A325 and F1852 lots out of forty-five (15.56%) that had an average tensile strength greater than 150 ksi. This is interesting to note, even though ASTM and RCSC do not put a limit on the maximum tensile strength. The seven lots of A325 and F1852 bolts, which had an average tensile strength greater than 150 ksi, could qualify as an A490 or F2280 bolt based on the tensile strength but not based on material composition. From Tables 5-8 and 5-9, it can be seen that the bolts which had a tensile strength greater than 150 ksi were 1-inch in diameter or less. According to ASTM A325 (2004) and F1852 (2005), the minimum tensile stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter. After testing the 237 A325 and F1852 bolts it can be concluded that the tensile strength was always greater than 120 ksi regardless of the bolt diameter.

The average tensile strength of the 278 A490 and F2280 bolts tested was 164.46 ksi with a standard deviation of 4.367 ksi, as can be seen from Tables 5-6 and 5-8. The minimum and maximum tensile strength of the A490 and F2280 bolts tested was 152.06 ksi and 179.79 ksi, respectively. Considering the average tensile strength of the fifty-five A490 and F2280 lots, the average tensile strength was 164.46 ksi with a standard deviation of 4.089 ksi as can be seen from Tables 5-7 and 5-9. The minimum and maximum average tensile strength of the A490 and F2280 lots was 155.34 ksi and 171.20 ksi, respectively. None of the 278 A490 and F2280 bolts tested in direct tension had a strength less than the minimum tensile strength of 150 ksi specified by ASTM. As stated previously ASTM A490 (2004) and F2280 (2006) specify a maximum tensile strength of 173 ksi and RCSC specifies a maximum of 170 ksi. There were thirty out of 278 A490 and F2280 bolts tested in direct tension (10.79%) that had a tensile strength greater than the specified RCSC maximum (170 ksi), as can be seen from Tables 5-6 and 5-8. However, only three of the 278 A490 and F2280 bolts (1.08%) had a tensile strength greater than 173 ksi as specified by ASTM. Taking into consideration the average tensile strength of the bolts tested per lot, from Tables 5-7 and 5-9, there were six A490 and F2280 lots out of fifty-five (10.91%) that had an average tensile strength greater than 170 ksi which is the specified maximum according to RCSC. On the other hand, no A490 or F2280 lots had an average tensile strength greater than ASTM's maximum tensile strength of 173 ksi. Therefore, depending on the maximum tensile strength (either ASTM's 173 ksi or RCSC's 170 ksi) and if individual or average tensile strengths are being taken into account, the A490 and F2280 bolts either did or did not meet the specifications. Even though some of the A490 and F2280 bolts did not meet some of the specifications, again depending on which is being considered, these bolts were still included in the data analysis and the resistance factor calculations because the manufacturers would have sold these bolts to fabricators and erectors just like they were provided for this research.

5.3.2.3 Experimental to Nominal Strength

The experimental failure load for bolts tested in direct tension, shear with the threads excluded, and shear with the threads not excluded were compared to the predicted failure load given by AISC equations. Sections 5.3.2.3.1 and 5.3.2.3.2 cover the experimental failure load to the nominal for the bolts tested in direct tension. Section 5.3.2.3.1 uses the nominal tensile load based on the approximation as specified by AISC whereas Section 5.3.2.3.2 is based on the effective area. The experimental failure load for the bolts tested in shear, with the threads excluded and not excluded from the shear plane, compared to the nominal strength is summarized in Sections 5.3.2.3.3 and 5.3.2.3.4, respectively. Section 5.3.2.3.5 summarizes all of the experimental versus nominal strength values for the three failure modes.

Tensile Strength – Based on Approximation

Figures 5-20 and 5-21 show the frequency distributions of the experimental strength to the nominal AISC strength for the direct tension tests of A325/F1852 and A490/F2280 bolts, respectively. The nominal tensile strength was calculated from equation (2-4) from Section 2.2. Repeating, for convenience, the nominal tensile strength is given by

$$R_n = \left(0.75F_u\right)A_b = \left(0.75\right)F_u\left(\frac{\pi d^2}{4}\right) \tag{5-1}$$

where F_u is the tensile strength of the bolt material which equals 120 ksi[7] for A325 and F1852 bolts and equals 150 ksi for A490 and F2280 bolts. The diameter is given by d in equation (5-1).

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[7] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

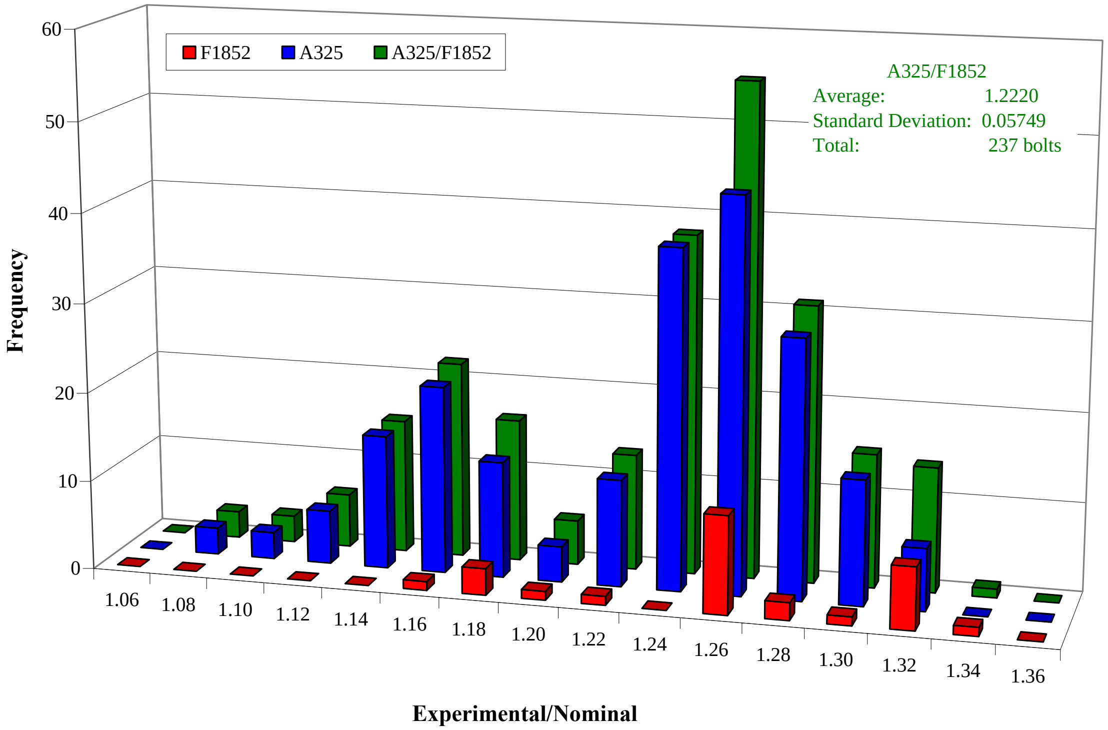

Figure 5-20: Frequency Distribution of Experimental/Nominal (AISC) for Tension of A325/F1852 Bolts

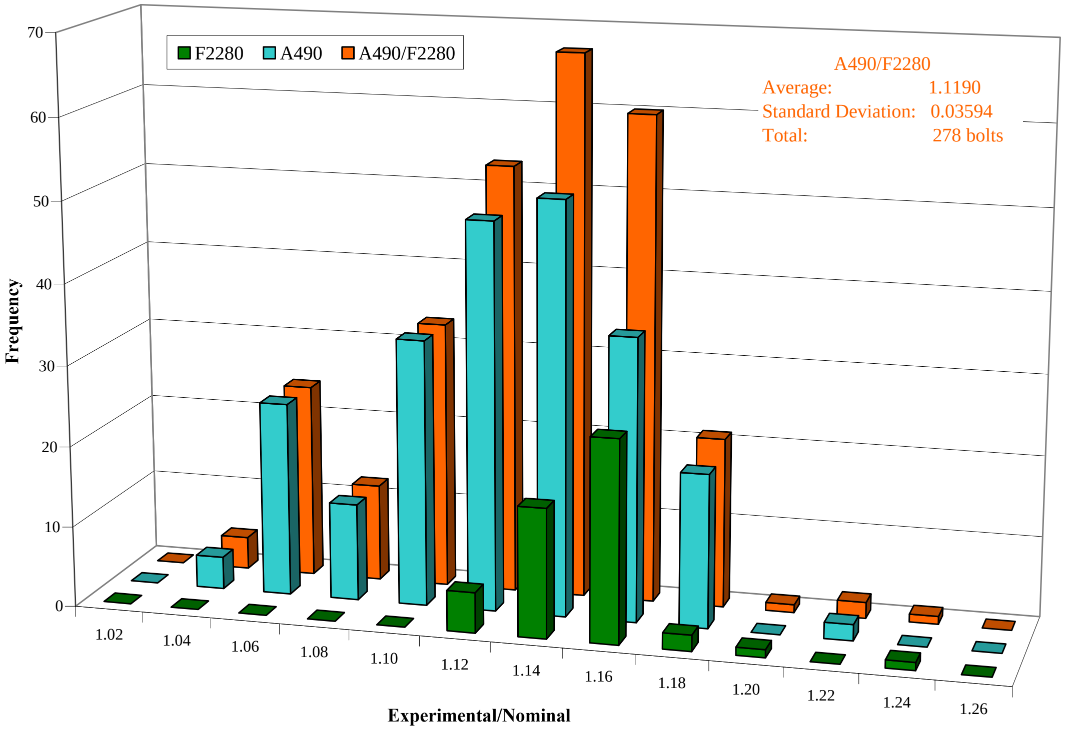

Figure 5-21: Frequency Distribution of Experimental/Nominal (AISC) for Tension of A490/F2280 Bolts

From Figures 5-20 and 5-21 the average ratio of the experimental tensile strength to the nominal equals 1.222 and 1.119 for A325/F1852 and A490/F2280 bolts, respectively. This means that, on average, the tensile strength for the A325 and F1852 bolts tested was 22% greater than the nominal tensile strength calculated based on AISC. The A490 and F2280 bolts tested had a tensile strength 12% larger on average compared to the nominal tensile strength according to AISC.

The frequency distribution of the experimental to nominal tensile strength for the A325 and F1852 bolts, from Figure 5-20, seems to show two distinct bell curves. One bell curve occurs from a ratio of 1.08 to 1.20 and the second bell curve occurs from a ratio of 1.20 to 1.34. Figures 5-22 and 5-23 show the frequency distributions based on the bolt diameter for A325 and F1852 bolts, respectively, to see if any conclusion may be drawn on the reason for the two bell curves in Figure 5-20.

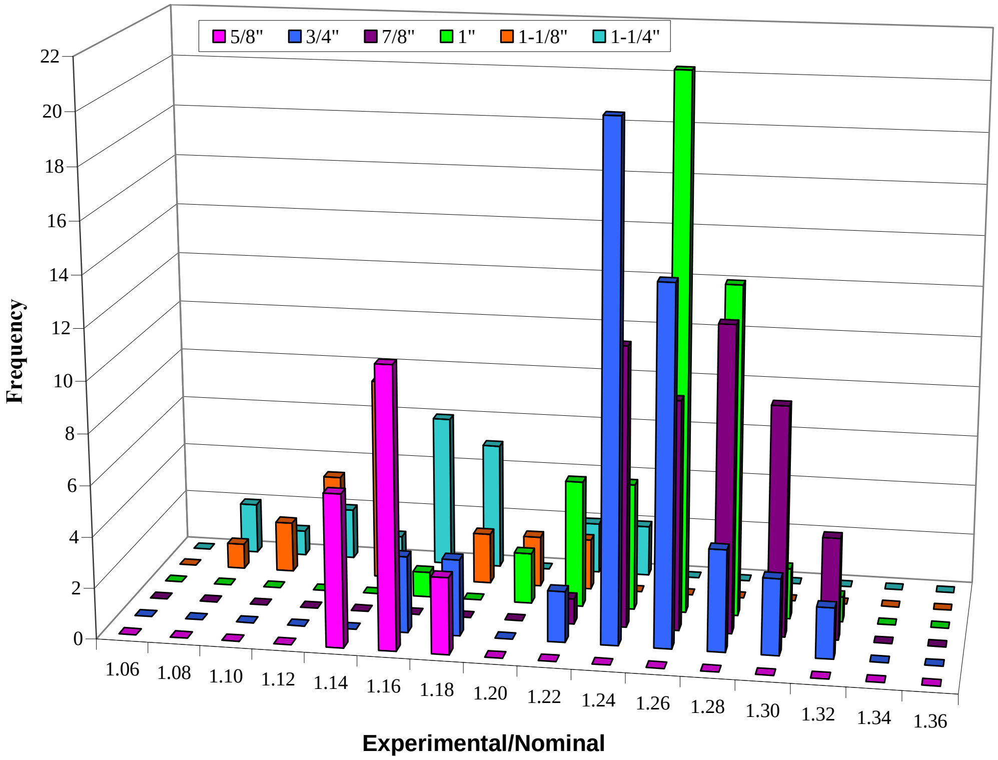

Figure 5-22: Frequency Distribution of Experimental/Nominal (AISC) for Tension of A325 Bolts

The experimental to nominal tensile strength (based on AISC) frequency distribution for A325 bolts based on bolt diameter, Figure 5-22, shows that all of the 5/8-inch bolts and more than 80% of the 1-1/8-inch and 1-1/4-inch A325 bolts make up the first bell curve (from a ratio of 1.08 to 1.20) in Figure 5-20. Less than 12% of the 3/4-inch and about two percent of the 1-inch bolts also contribute to this first peak. The second bell curve is comprised of all of the 7/8-inch bolts and the remaining 3/4-inch, 1-inch, 1-1/8-inch, and 1-1/4-inch A325 bolts.

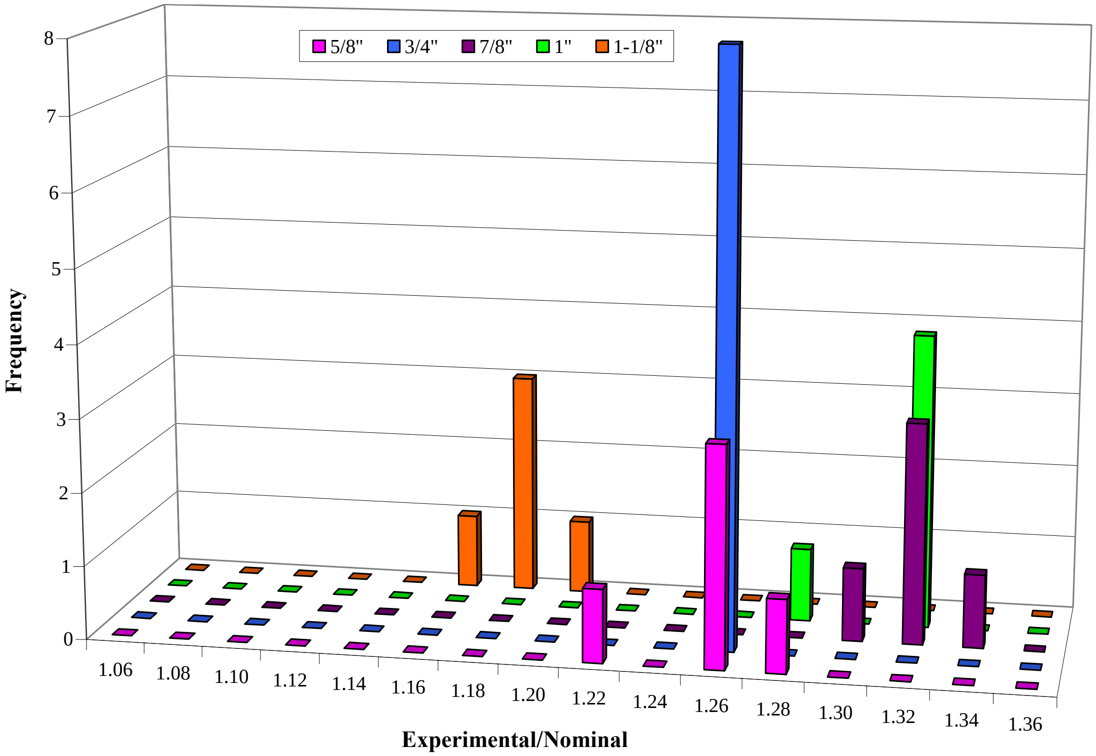

Figure 5-23: Frequency Distribution of Experimental/Nominal (AISC) for Tension of F1852 Bolts

From Figure 5-23, which shows the frequency distribution of the experimental to nominal tensile strength (based on AISC) for F1852 bolts, it can be seen that all of the 1-1/8-inch bolts contribute to the first peak (from a ratio of 1.08 to 1.20) in Figure 5-20 and all of the 5/8-inch, 3/4-inch, 7/8-inch, and 1-inch F1852 bolts are part of the second peak.

Unlike the A325 and F1852 bolts, Figure 5-21, for the A490 and F2280 high-strength bolts, shows a single bell curve. However, for completeness, Figures 5-24 and 5-25 show the frequency distributions for A490 and F2280 bolts, respectively, based on bolt diameter.

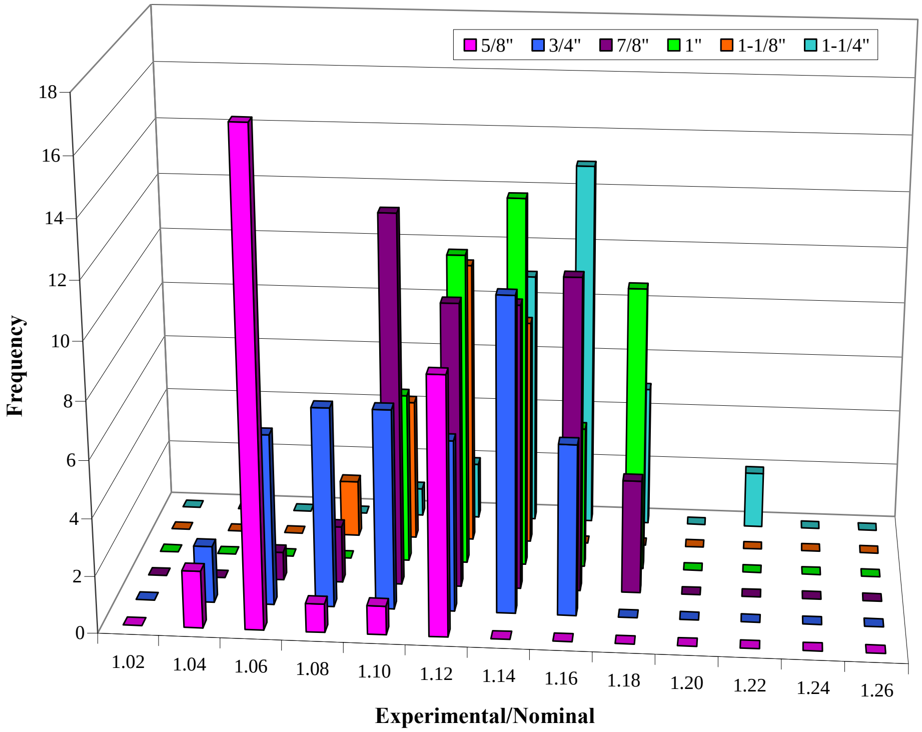

Figure 5-24: Frequency Distribution of Experimental/Nominal (AISC) for Tension of A490 Bolts

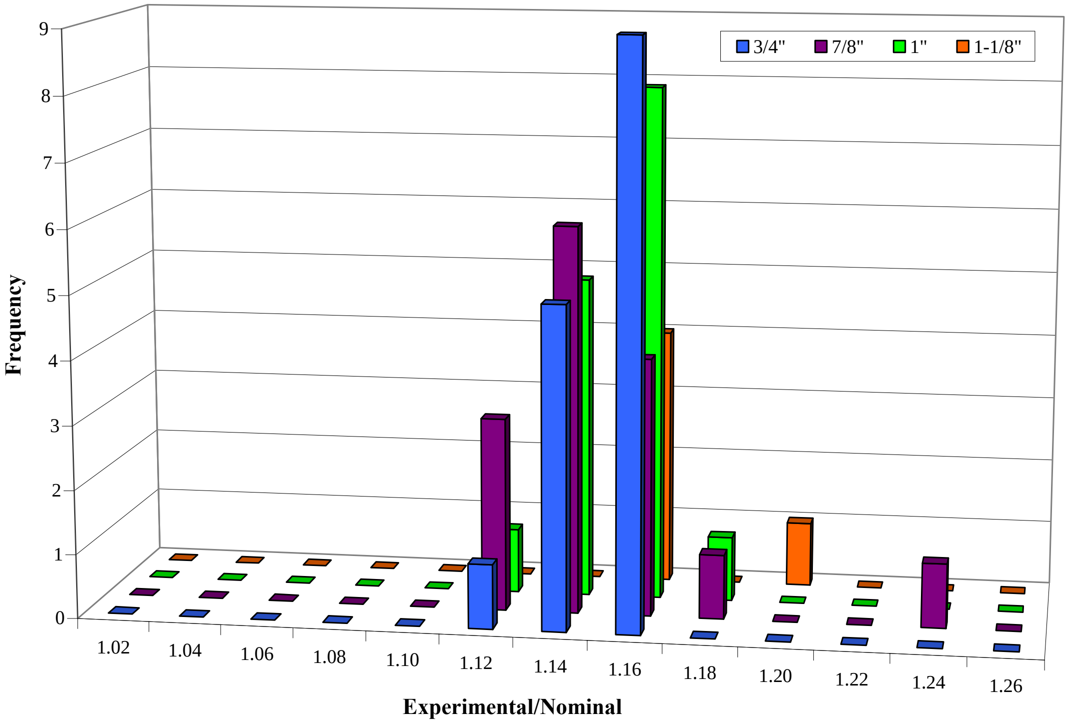

Figure 5-25: Frequency Distribution of Experimental/Nominal (AISC) for Tension of F2280 Bolts

Tensile Strength – Based on Effective Area

The frequency distributions of the experimental strength to the nominal strength calculated based on the effective area of A325/F1852 and A490/F2280 bolts are shown in Figures 5-26 and 5-27, respectively. The nominal tensile strength was calculated using the effective area from equation (2-3) from Section 2.2. The nominal tensile strength based on the effective area is given by

$$R_n = F_u A_{eff} = F_u \left[\frac{\pi}{4} \left(d - \frac{0.9743}{n} \right)^2 \right] \tag{5-2}$$

where F_u is the tensile strength of the bolt material which equals 120 ksi[8] for A325 and F1852 bolts and equals 150 ksi for A490 and F2280 bolts. The number of threads per inch and the diameter is given by n and d, respectively.

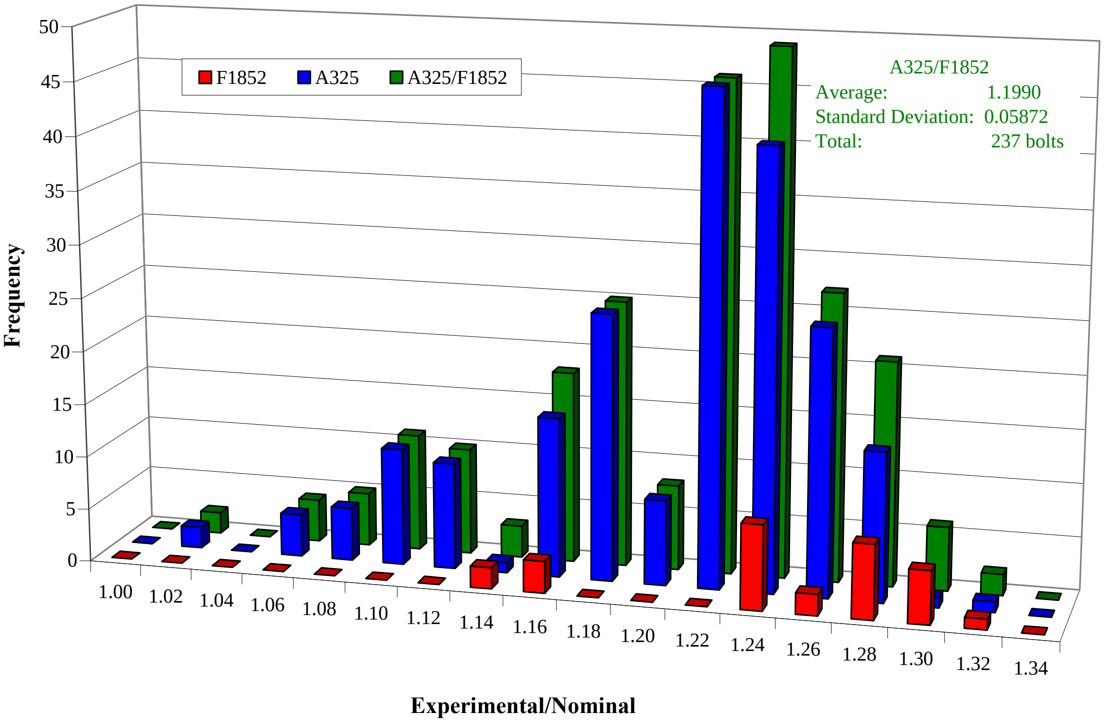

Figure 5-26: Frequency Distribution of Experimental/Nominal (Eff Area) for Tension of A325/F1852 Bolts

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[8] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

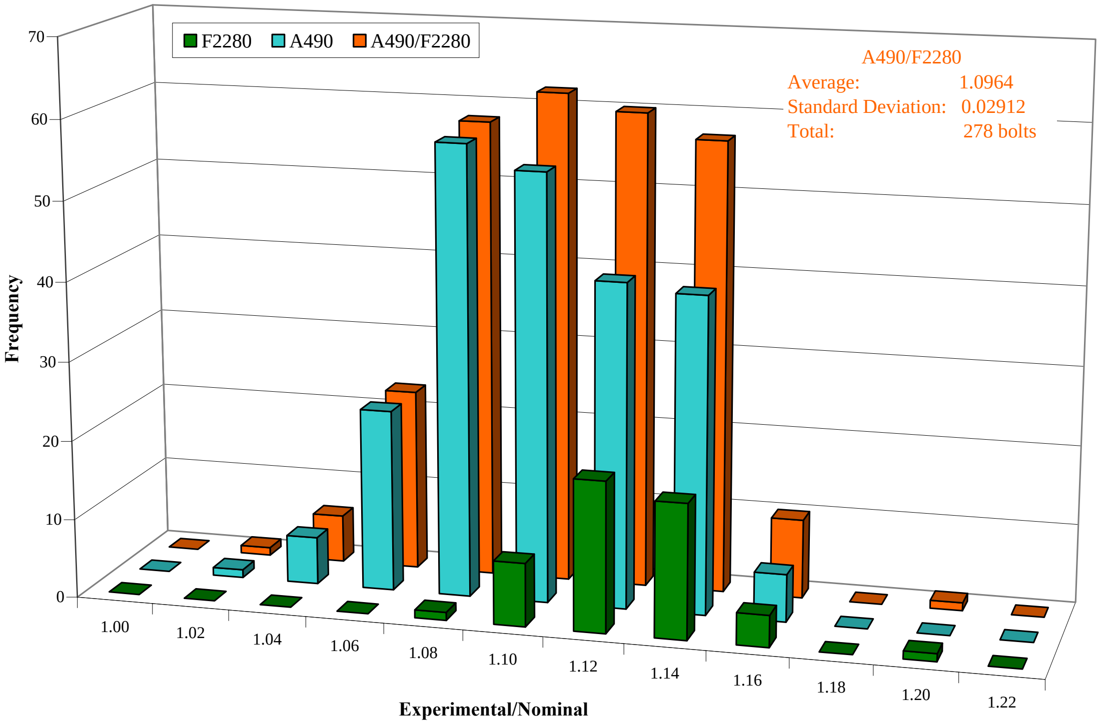

Figure 5-27: Frequency Distribution of Experimental/Nominal (Eff Area) for Tension of A490/F2280 Bolts

The average ratios of the experimental tensile strength to the nominal strength based on the effective area equal 1.199 and 1.096 for A325/F1852 and A490/F2280 bolts, respectively, as can be seen from Figures 5-26 and 5-27. Thus, on average, the tensile strength for the A325 and F1852 bolts tested is 20% greater than the nominal tensile strength calculated based on the effective area of the threaded section. The A490 and F2280 bolts tested had on average a tensile strength 10% larger compared to the nominal tensile strength based on the effective area.

From Figure 5-26, the frequency distribution of the experimental to nominal tensile strength (based on the effective area) for the A325 and F1852 bolts, seems to show three peaks. The peaks occur from a ratio of 1.02 to 1.14, from 1.14 to 1.20, and from 1.20 to 1.32. Consequently, the frequency distribution based on the bolt diameter for A325 and F1852 bolts was plotted to see if any conclusion could be drawn. These can be seen in Figures 5-28 and 5-29 for A325 and F1852 bolts, respectively.

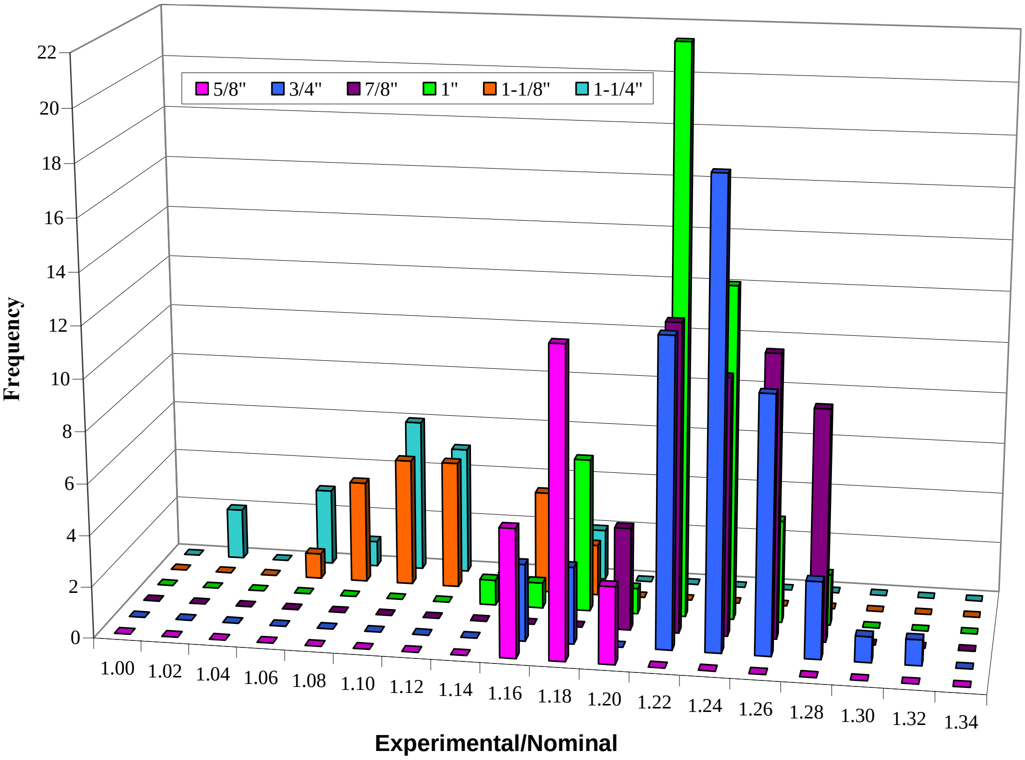

Figure 5-28: Frequency Distribution of Experimental/Nominal (Effective Area) for Tension of A325 Bolts

About 71% of the 1-1/8-inch, 81% of the 1-1/4-inch, and 2% of the 1-inch A325 bolts contribute to the first peak (from a ratio of 1.02 to 1.14) of the experimental to nominal tensile strength (based on the effective area) frequency distribution as can be seen from Figure 5-28. The second peak (from a ratio of 1.14 to 1.20) contains all of the 5/8-inch, 12% of the 3/4-inch, 9% of the 7/8-inch, 16% of the 1-inch, and the remaining 1-1/8-inch and 1-1/4-inch A325 bolts. 88% of the 3/4-inch, 91% of the 7/8-inch, and 82% of the 1-inch A325 bolts contribute to the third peak (from a ratio of 1.20 to 1.32).

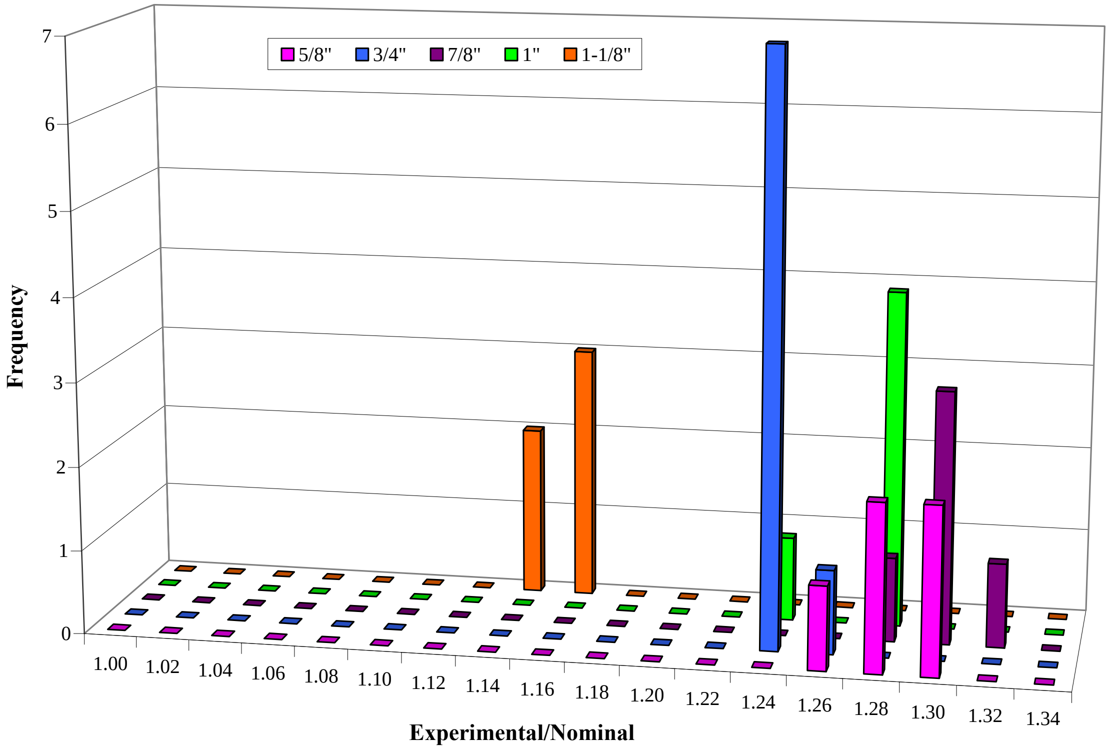

Figure 5-29: Frequency Distribution of Experimental/Nominal (Effective Area) for Tension of F1852 Bolts

Forty percent of the 1-1/8-inch F1852 bolts contribute to the first peak (from a ratio of 1.02 to 1.14) of the frequency distribution of the experimental to nominal tensile strength (based on the effective area) as can be seen from Figure 5-29. The second peak (from a ratio of 1.14 to 1.20) contains the remaining 60%of the 1-1/8-inch F1852 bolts. All of the 5/8-inch, 3/4-inch, 7/8-inch, and 1-inch F1852 bolts contribute to the last peak (from a ratio of 1.20 to 1.32).

Figure 5-27, the frequency distribution for the A490 and F2280 bolts, shows a single bell curve, compared to Figure 5-26, for the A325 and F1852 bolts. For completeness, however, Figures 5-30 and 5-31 show the frequency distributions of experimental to the nominal tensile strength, based on the bolt diameter, for the A490 and F2280 bolts, respectively.

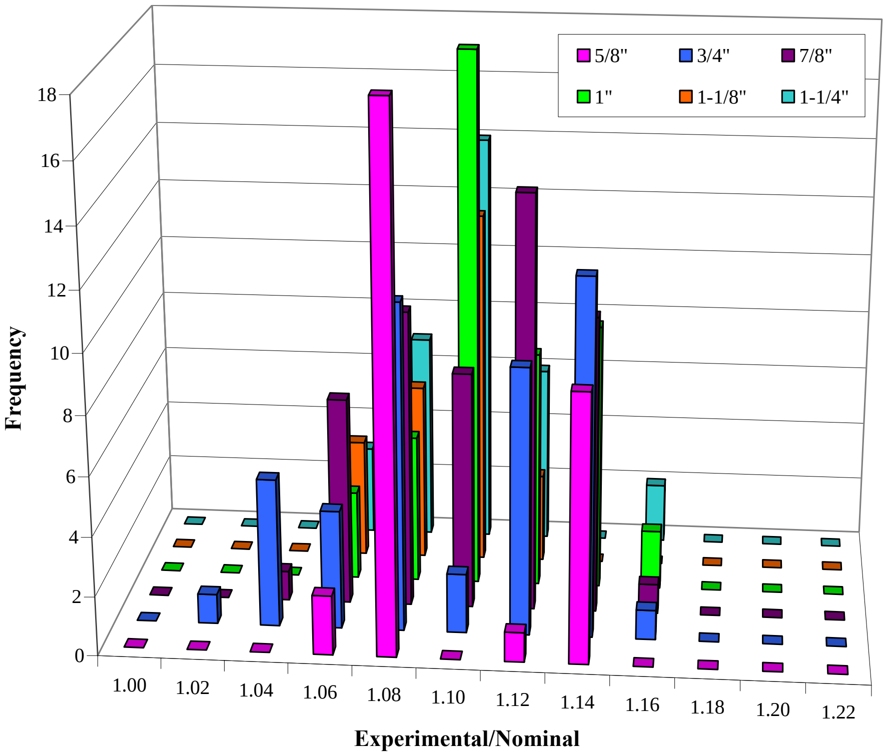

Figure 5-30: Frequency Distribution of Experimental/Nominal (Effective Area) for Tension of A490 Bolts

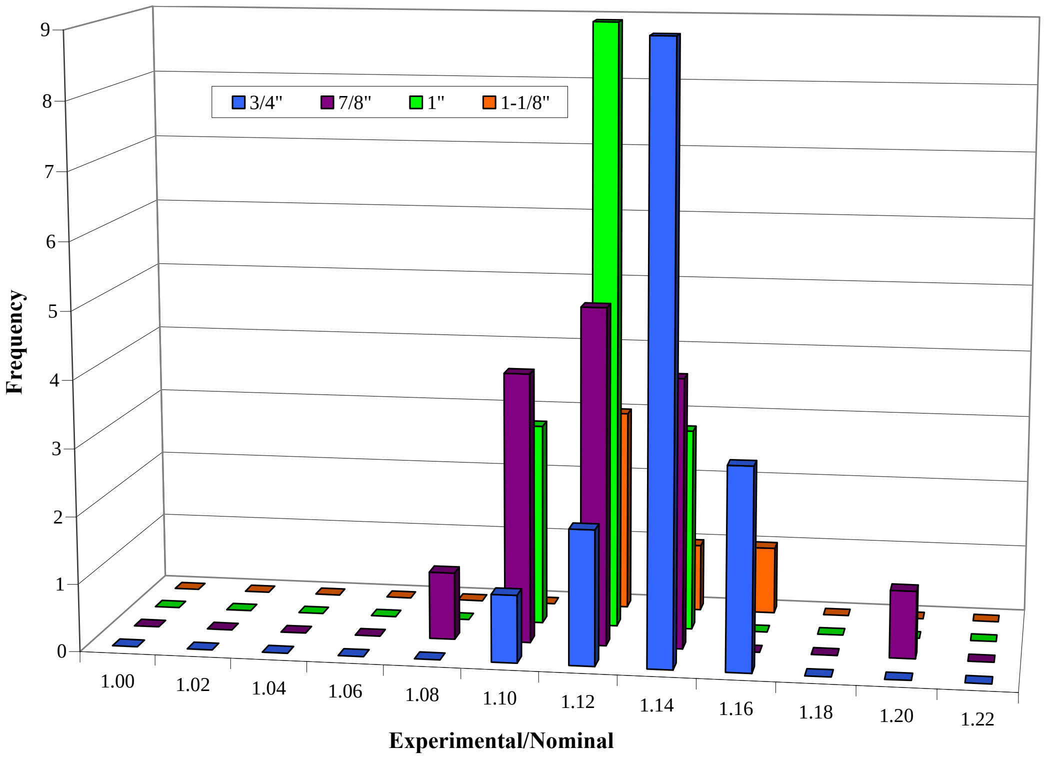

Figure 5-31: Frequency Distribution of Experimental/Nominal (Effective Area) for Tension of F2280 Bolts

Shear Strength with the Threads Excluded

The frequency distributions of the experimental strength to the nominal strength for shear with threads excluded from the shear plane for A325/F1852 and A490/F2280 bolts are shown in Figures 5-32 and 5-33, respectively. From Section 2.3, equation (2-6), the nominal strength for bolts with the threads excluded from the shear plane is given by

$$R_n \approx 0.62 F_u A_b = 0.62 F_u \left(\frac{\pi d^2}{4} \right) \tag{5-3}$$

where d is the bolt diameter. The strength of the bolt material, F_u, equals 120 ksi[9] for A325 and F1852 bolts and equals 150 ksi for A490 and F2280 bolts.

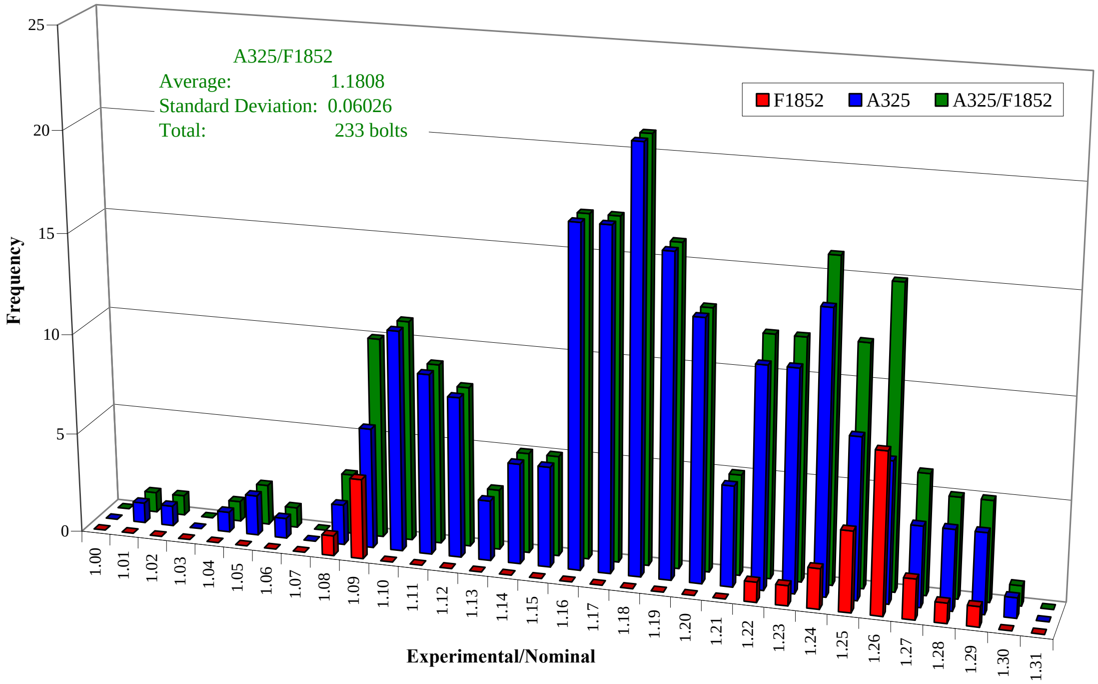

Figure 5-32: Frequency Distribution of Experimental/Nominal for Shear Excluded of A325/F1852 Bolts

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[9] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

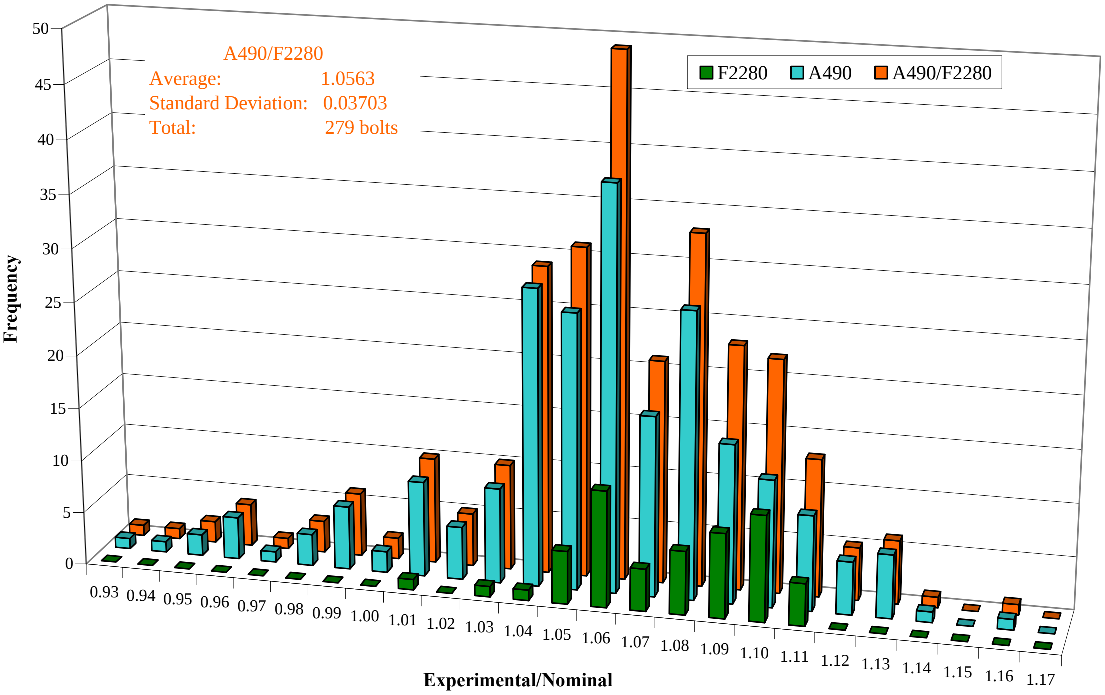

Figure 5-33: Frequency Distribution of Experimental/Nominal for Shear Excluded of A490/F2280 Bolts

The average ratios of the experimental shear strength with the threads excluded from the shear plane to the nominal equal 1.181 and 1.056 with a standard deviation of 0.06026 and 0.03703 for A325/F1852 and A490/F2280, respectively, as shown in Figures 5-32 and 5-33. On average, the shear strength with the threads excluded from the shear plane had an 18% greater strength compared to the specified AISC value for the 233 tested A325 and F1852 high-strength bolts. Similarly, on average, a 6%greater strength was encountered compared to AISC's specified shear strength with the threads excluded from the shear plane for the 279 A490 and F2280 bolts tested. These averages are slightly lower than the average for the same bolts tested in direct tension.

From Figure 5-32, for A325 and F1852 bolts, the frequency distribution of the experimental to nominal shear strength with the threads excluded from the shear plane seems to show four bell curves. One bell curve occurs from a ratio of 1.01 to 1.06, the second bell curve occurs from a ratio of 1.08 to 1.13, the third occurs from 1.13 to 1.21, and the last bell curve occurs from a ratio of 1.21 to 1.30. To see if any conclusions may be drawn based on the bolt diameter, Figures 5-34 and 5-35 show the frequency distributions based on the bolt diameter for A325 and F1852 bolts, respectively.

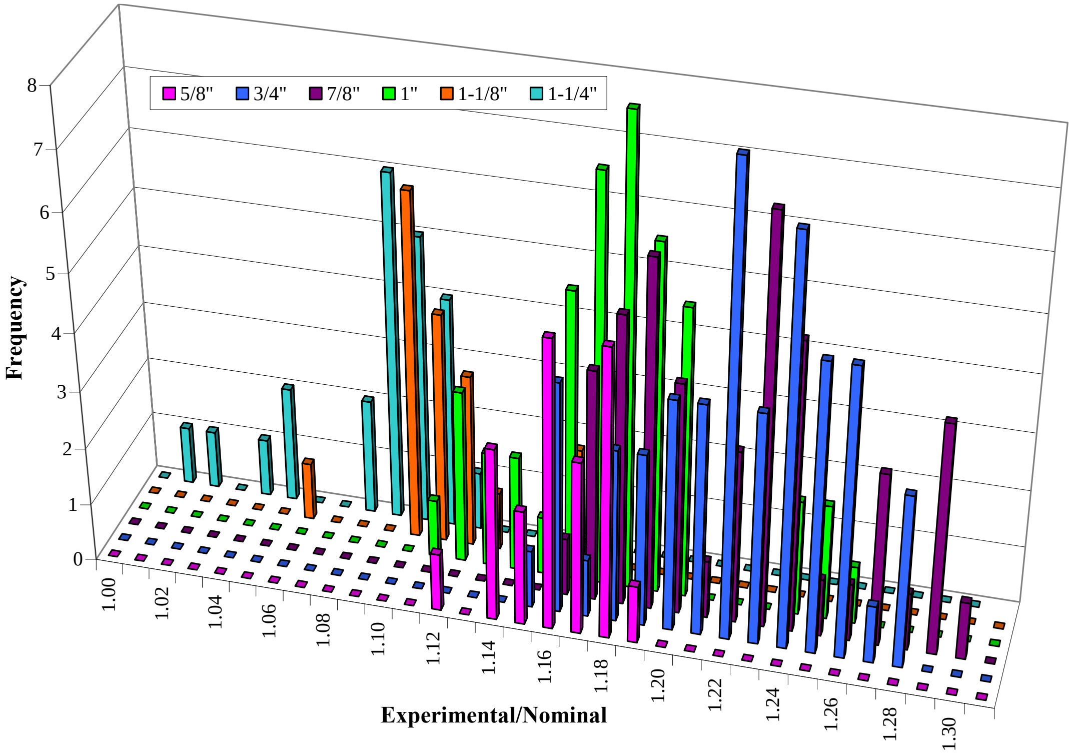

Figure 5-34: Frequency Distribution of Experimental/Nominal for Shear Excluded of A325 Bolts

Five percent of the 1-1/8-inch and about 22% of the 1-1/4-inch A325 bolts make up the first bell curve (from a ratio of 1.01 to 1.06) in Figure 5-34 of the frequency distribution of the experimental to nominal shear strength with the threads excluded. The second peak (from a ratio of 1.08 to 1.13) in Figure 5-34 consists of 5% of the 5/8-inch, about 13% of the 1-inch, 70% of the 1-1/8-inch, and about 78%of the 1-1/4-inch A325 bolts. From Figure 5-34 the third peak (from a ratio of 1.13 to 1.21) is made up of 95% of the 5/8-inch, about 38% of the 3/4-inch, about 45% of the 7/8-inch, about 76% of the 1-inch, and 25% of the 1-1/8-inch A325 bolts. The last peak, from a ratio of 1.21 to 1.30, consists of about 62% of the 3/4-inch, about 55% of the 7/8-inch, and about 11% of the 1-inch A325 bolts.

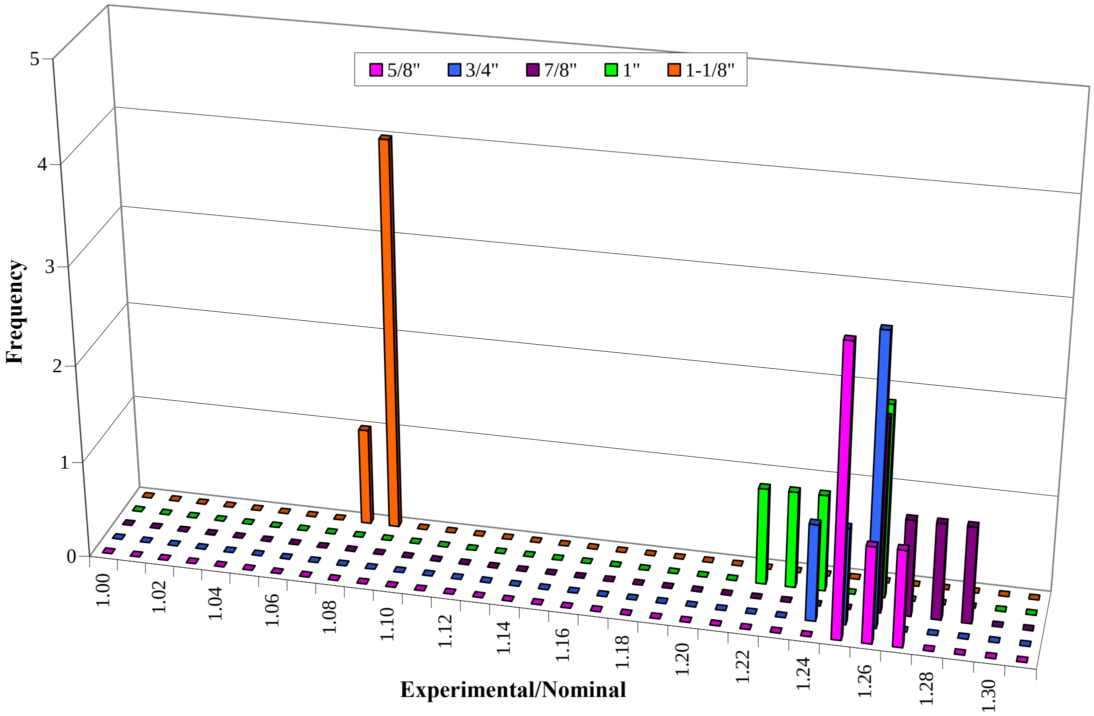

Figure 5-35: Frequency Distribution of Experimental/Nominal for Shear Excluded of F1852 Bolts

As can be seen from Figure 5-35, none of the F1852 bolts contribute to the first (from a ratio of 1.01 to 1.06) or third (from a ratio of 1.13 to 1.21) peaks of Figure 5-32. All of the 1-1/8-inch F1852 bolts are part of the second peak (from a ratio of 1.08 to 1.13) and all of the 5/8-inch, 3/4-inch, 7/8-inch, and 1-inch F1852 bolts contribute to the last peak (from a ratio of 1.21 to 1.30) as can be seen in Figure 5-35, the frequency distribution of the experimental to nominal shear strength with the threads excluded.

Even though the frequency distribution of the experimental to nominal shear strength with the threads excluded from the shear plane for A490 and F2280 bolts, Figure 5-33, shows a single bell curve, the frequency distributions for the A490 and F2280 bolts based on the bolt diameter are shown in Figures 5-36 and 5-37, respectively, for completeness.

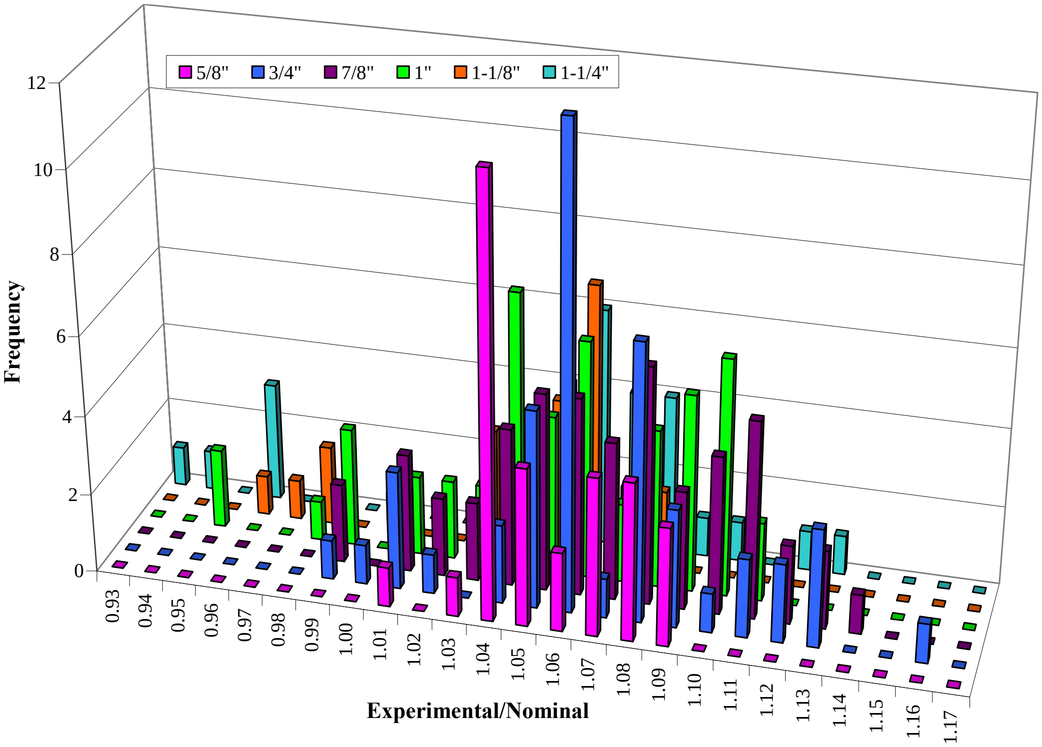

Figure 5-36: Frequency Distribution of Experimental/Nominal for Shear Excluded of A490 Bolts

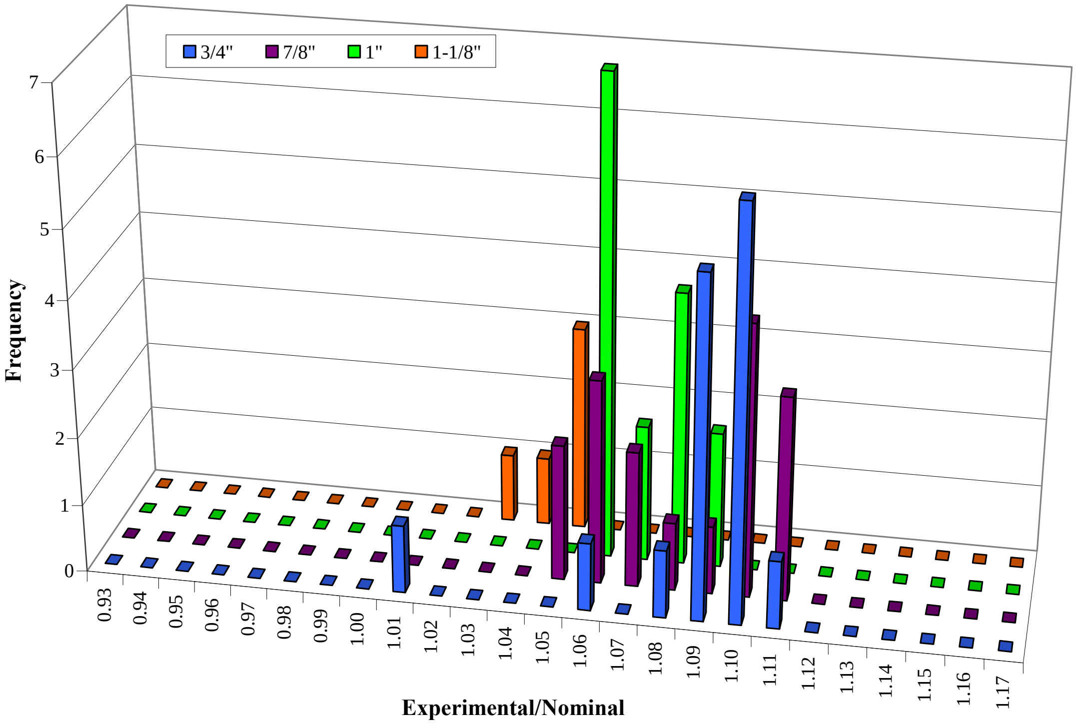

Figure 5-37: Frequency Distribution of Experimental/Nominal for Shear Excluded of F2280 Bolts

Shear Strength with the Threads Not Excluded

Figures 5-38 and 5-39 show the frequency distributions of the experimental to the nominal strength for shear with the threads not excluded from the shear plane for A325/F1852 and A490/F2280 bolts, respectively. The nominal shear strength with the threads not excluded from the shear plane was calculated from equation (2-5) from Section 2.3, which is repeated here for convenience

$$R_n = 0.5F_u A_b = 0.5F_u\left(\frac{\pi d^2}{4}\right) \tag{5-4}$$

The bolt material strength, F_u, equals 120 ksi[10] for A325 and F1852 bolts and equals 150 ksi for A490 and F2280 bolts. The diameter is given by d in equation (5-4).

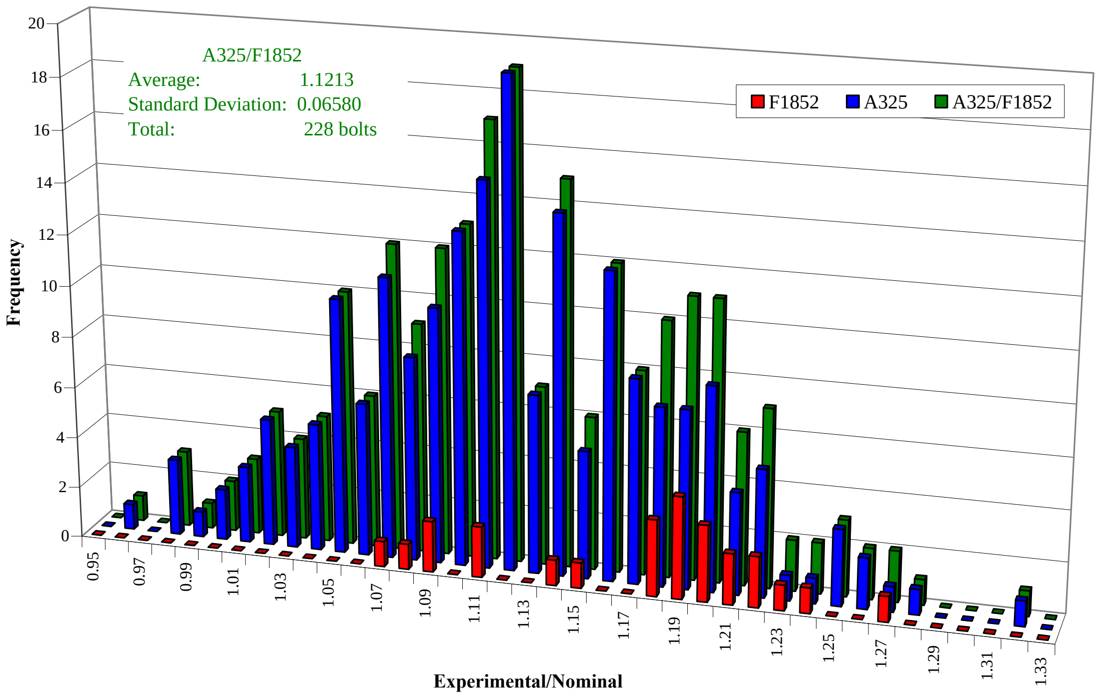

Figure 5-38: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of A325/F1852 Bolts

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[10] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

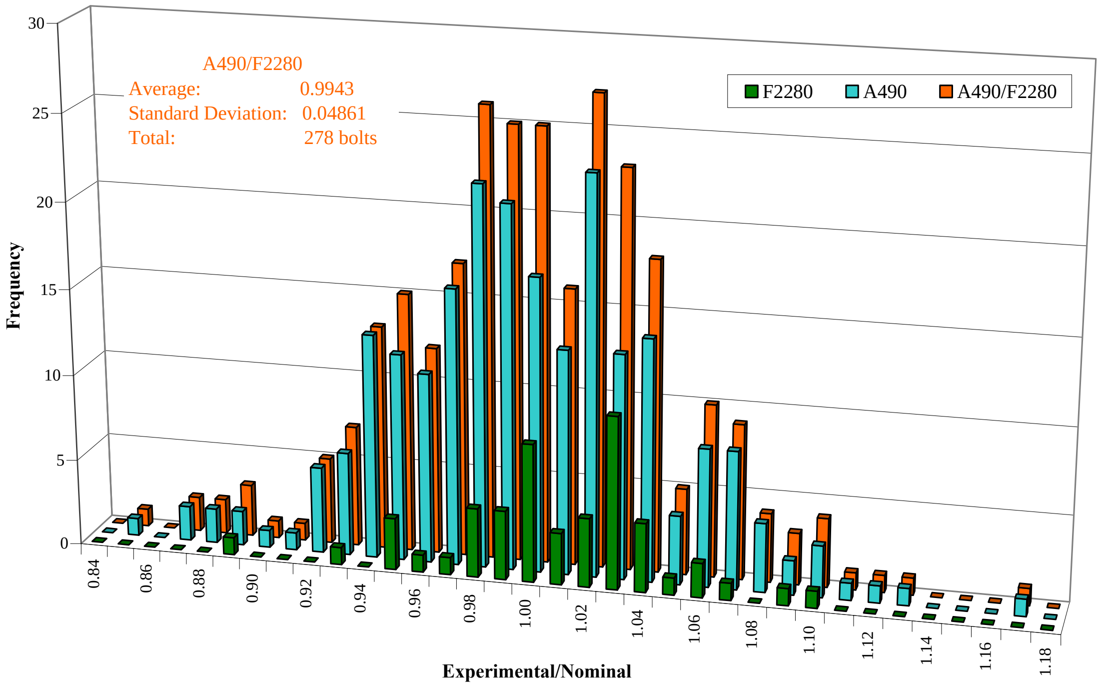

Figure 5-39: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of A490/F2280 Bolts

For the 228 A325/F1852 and the 278 A490/F2280 high-strength bolts tested, the average ratio of the experimental to nominal shear strength with the threads not excluded from the shear plane was 1.121 and 0.994, respectively, as can be seen from Figures 5-38 and 5-39. The 228 A325 and F1852 bolts tested in shear with the threads not excluded from the shear plane, on average had a strength twelve 12% higher than the AISC specified value. On the other hand, the 278 A490 and F2280 bolts had an average shear strength with the threads not excluded from the shear plane approximately equal to the AISC specification. Compared to the ratios of the same lot of bolts tested in tension and shear with the threads excluded from the shear plane, the averages are somewhat lower.

Unlike the frequency distribution graphs in Sections 5.3.2.3.1, 5.3.2.3.2 and 5.3.2.3.3 for A325 and F1852 bolts, the frequency distribution for the experimental to nominal shear strength with the threads not excluded (Figure 5-38) forms a single bell curve. For completeness the frequency distributions, based on the bolt diameter, for the bolts tested with the threads not excluded from the shear plane, are included. Figures 5-40 and 5-41 show the frequency distributions based on the bolt diameter for A325 and F1852 bolts, respectively. The frequency distributions based on the bolt diameter for A490 and F2280 bolts are shown in Figures 5-42 and 5-43, respectively.

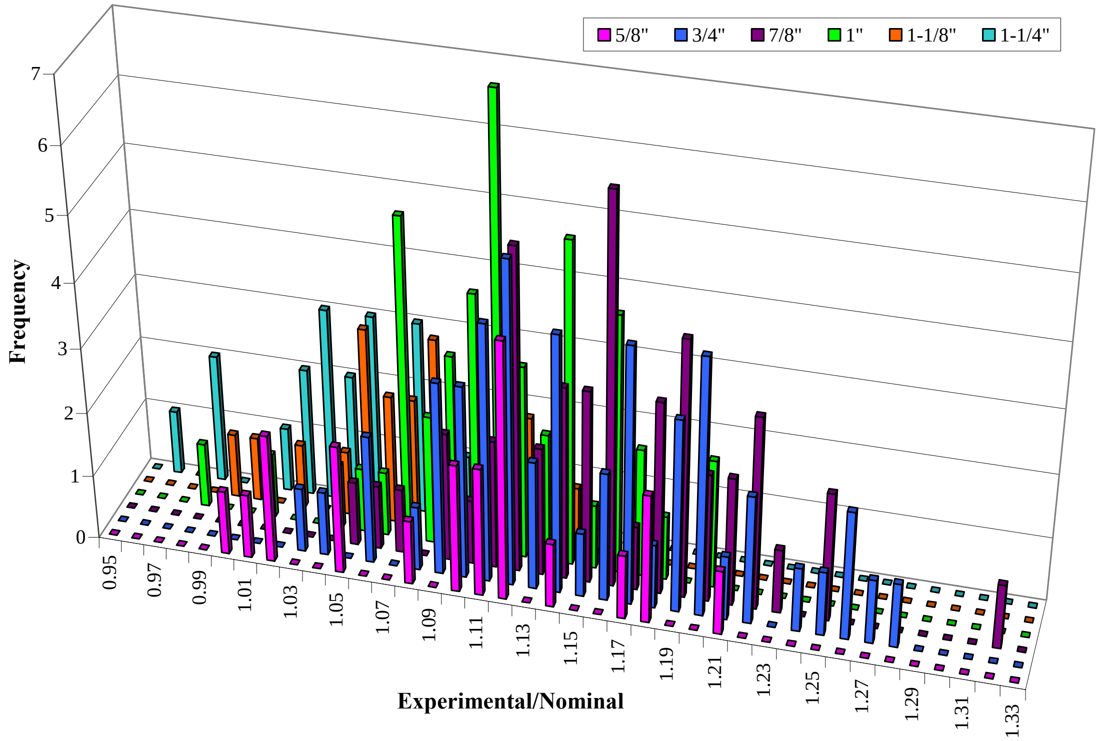

Figure 5-40: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of A325 Bolts

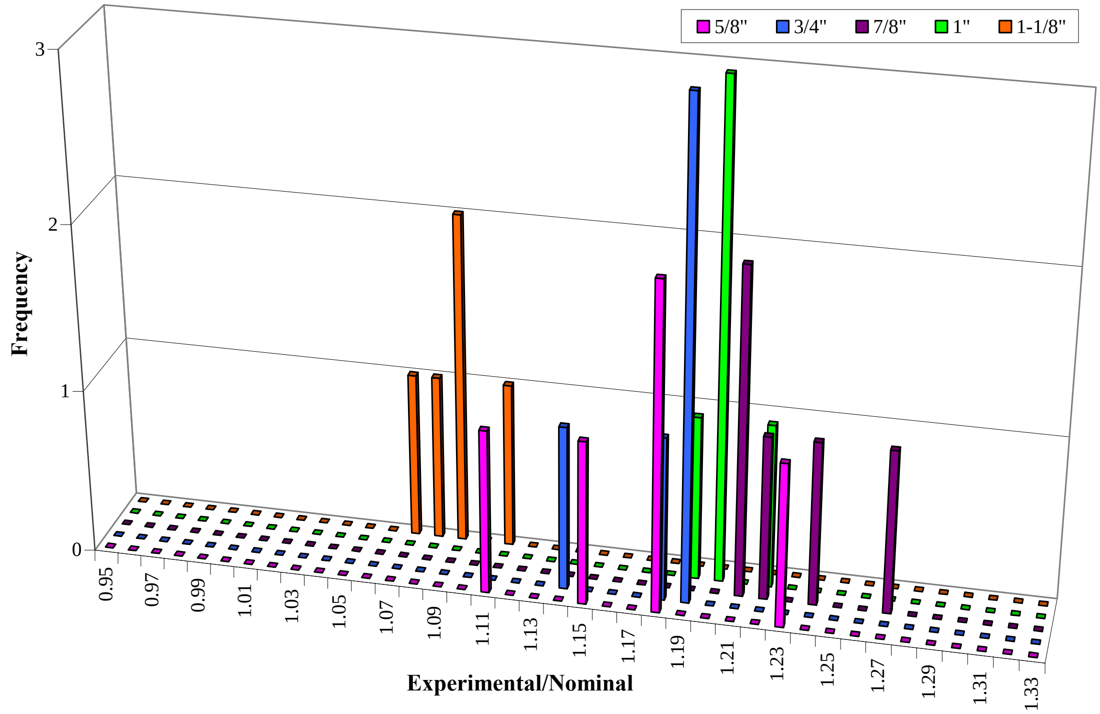

Figure 5-41: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of F1852 Bolts

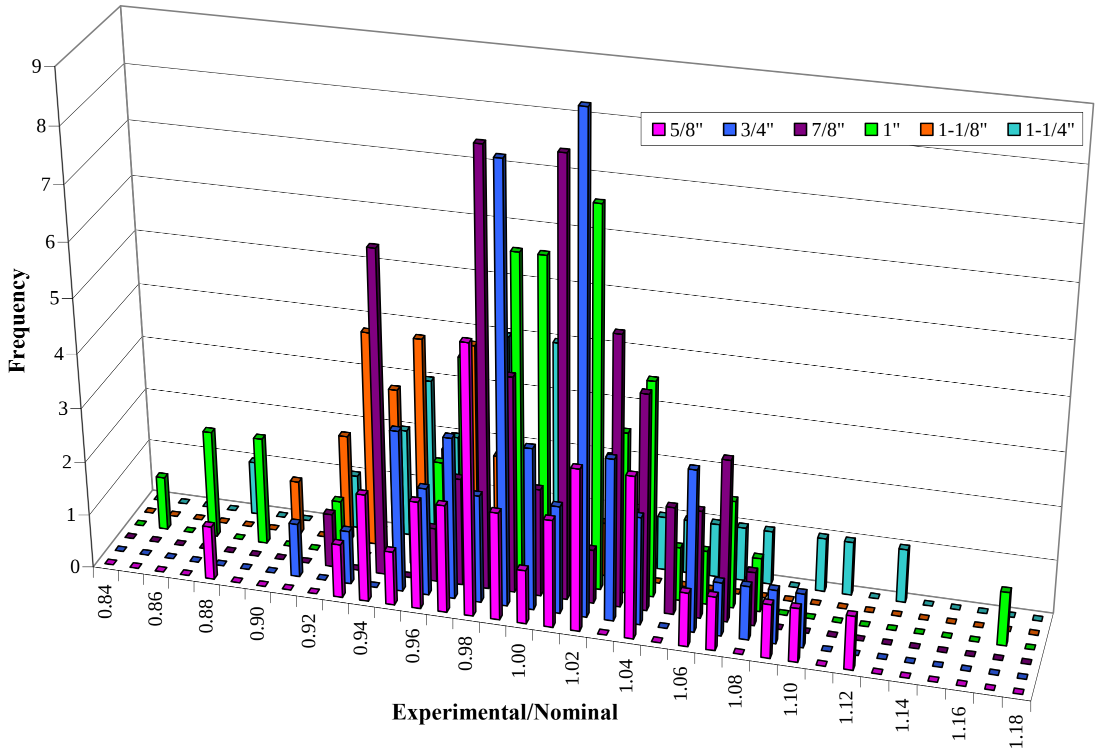

Figure 5-42: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of A490 Bolts

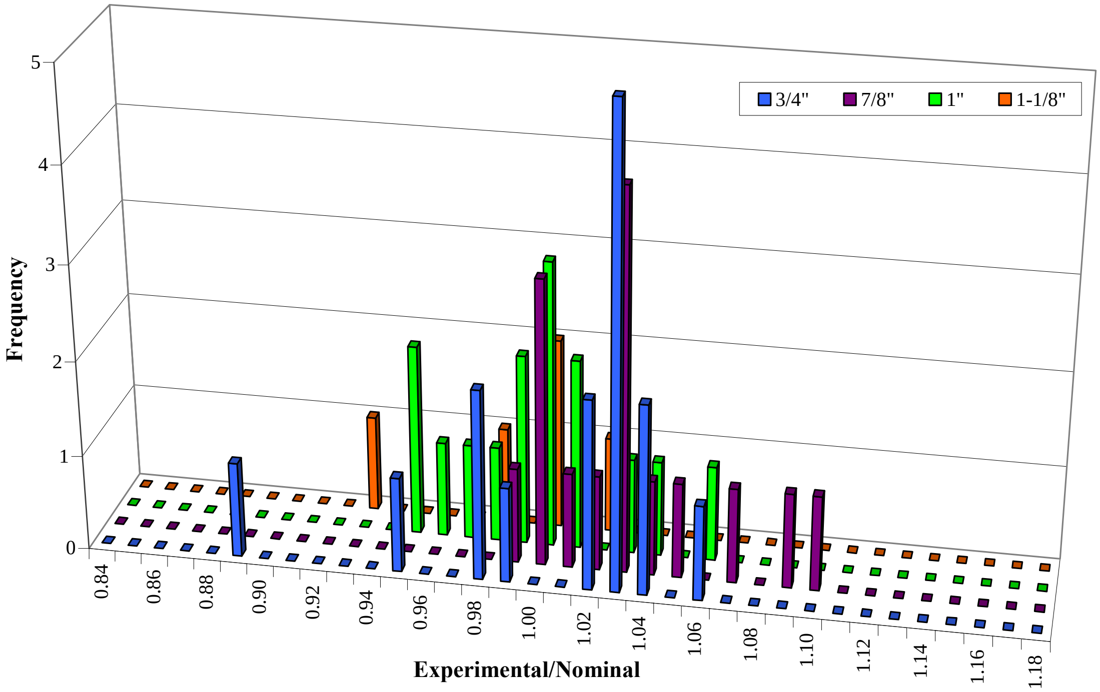

Figure 5-43: Frequency Distribution of Experimental/Nominal for Shear Not Excluded of F2280 Bolts

Summary

The experimental to nominal tensile strength from Figures 5-20, 5-21, 5-26, and 5-27 are summarized in Table 5-10, whereas the experimental to nominal shear strength (threads excluded and not excluded) from Figures 5-32, 5-33, 5-38, and 5-39 are summarized in Table 5-11. The tables summarize the experimental to nominal ratios based on the bolt grade as discussed previously in Sections 5.3.2.3.1 through 5.3.2.3.4.

Table 5-10: Ratio of Experimental/Nominal by Grade for Tension

		Experimental/Nominal - Tension (Based on Approximation)			**Experimental/Nominal - Tension (Based on Effective Area)**		
Grade	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC
A325	209	1.2176 (0.05703)	1.0666 1.3146	0 0.00%	1.1936 (0.05775)	1.0129 1.3023	0 0.00%
F1852	28	1.2552 (0.05039)	1.1557 1.3317	0 0.00%	1.2392 (0.05036)	1.1288 1.3007	0 0.00%
A325/F1852	237	1.2220 (0.05749)	1.0666 1.3317	0 0.00%	1.1990 (0.05872)	1.0129 1.3023	0 0.00%
A490	228	1.1138 (0.03659)	1.0233 1.2148	0 0.00%	1.0914 (0.02823)	1.0137 1.1538	0 0.00%
F2280	50	1.1427 (0.01988)	1.1042 1.2271	0 0.00%	1.1195 (0.02100)	1.0785 1.1986	0 0.00%
A490/F2280	278	1.1190 (0.03594)	1.0233 1.2271	0 0.00%	1.0964 (0.02912)	1.0137 1.1986	0 0.00%
All Grades	515	1.1664 (0.06970)	1.0233 1.3317	0 0.00%	1.1436 (0.06825)	1.0129 1.3023	0 0.00%

Table 5-11: Ratio of Experimental/Nominal by Grade for Shear

	Experimental/Nominal - Shear Excluded				**Experimental/Nominal - Shear Not Excluded**			
Grade	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC
A325	208	1.1764 (0.05764)	1.0099 1.2941	0 0.00%	203	1.1156 (0.06483)	0.9569 1.3158	7 3.45%
F1852	25	1.2174 (0.06996)	1.0722 1.2803	0 0.00%	25	1.1682 (0.05483)	1.0613 1.2605	0 0.00%
A325/F1852	233	1.1808 (0.06026)	1.0099 1.2941	0 0.00%	228	1.1213 (0.06580)	0.9569 1.3158	7 3.07%
A490	228	1.0528 (0.03855)	0.9231 1.1501	20 8.77%	228	0.9919 (0.05025)	0.8405 1.1664	132 57.89%
F2280	51	1.0720 (0.02384)	1.0019 1.1095	0 0.00%	50	1.0053 (0.03881)	0.8895 1.0928	23 46.00%
A490/F2280	279	1.0563 (0.03703)	0.9231 1.1501	20 7.17%	278	0.9943 (0.04861)	0.8405 1.1664	155 55.76%
All Grades	512	1.1130 (0.07903)	0.9231 1.2941	20 3.91%	506	1.0516 (0.08511)	0.8405 1.3158	162 32.02%

To further examine the experimental to nominal ratios, they were investigated based on the diameter of the bolt. Tables 5-12 and 5-13 summarize the experimental to nominal ratios for tension and shear, respectively, based on the bolt diameter. Figures 5-22 through 5-25 and Figures 5-28 through 5-31 are summarized in Table 5-12 whereas Figures 5-34 through 5-37 and Figures 5-40 through 5-43 are summarized in Table 5-13.

Table 5-12: Ratio of Experimental/Nominal by Diameter for Tension

			Experimental/Nominal - Tension (Based on Approximation)			**Experimental/Nominal - Tension (Based on Effective Area)**		
Diameter	Grade	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC
5/8	A325/F1852	25	1.1683 (0.04325)	1.1271 1.2605	0 0.00%	1.1894 (0.04403)	1.1475 1.2833	0 0.00%
	A490	30	1.0686 (0.02836)	1.0372 1.1180	0 0.00%	1.0879 (0.02887)	1.0560 1.1383	0 0.00%
	All Grades	55	1.1139 (0.06143)	1.0372 1.2605	0 0.00%	1.1341 (0.06254)	1.0560 1.2833	0 0.00%
3/4	A325/F1852	59	1.2377 (0.03110)	1.1551 1.3146	0 0.00%	1.2262 (0.03081)	1.1443 1.3023	0 0.00%
	A490/F2280	60	1.1097 (0.03649)	1.0233 1.1581	0 0.00%	1.0994 (0.03615)	1.0137 1.1473	0 0.00%
	All Grades	119	1.1732 (0.07259)	1.0233 1.3146	0 0.00%	1.1622 (0.07191)	1.0137 1.3023	0 0.00%
7/8	A325/F1852	51	1.2678 (0.02905)	1.2131 1.3317	0 0.00%	1.2383 (0.02837)	1.1849 1.3007	0 0.00%
	A490/F2280	66	1.1244 (0.03055)	1.0587 1.2271	0 0.00%	1.0983 (0.02984)	1.0341 1.1986	0 0.00%
	All Grades	117	1.1869 (0.07734)	1.0587 1.3317	0 0.00%	1.1593 (0.07554)	1.0341 1.3007	0 0.00%
1	A325/F1852	55	1.2516 (0.03113)	1.1542 1.3139	0 0.00%	1.2171 (0.03027)	1.1224 1.2777	0 0.00%
	A490/F2280	60	1.1338 (0.02404)	1.0847 1.1777	0 0.00%	1.1026 (0.02338)	1.0548 1.1452	0 0.00%
	All Grades	115	1.1902 (0.06518)	1.0847 1.3139	0 0.00%	1.1574 (0.06338)	1.0548 1.2777	0 0.00%
1 1/8	A325/F1852	26	1.1422 (0.03657)	1.0741 1.2043	0 0.00%	1.1156 (0.03572)	1.0491 1.1763	0 0.00%
	A490/F2280	30	1.1157 (0.02500)	1.0703 1.1843	0 0.00%	1.0897 (0.02442)	1.0454 1.1567	0 0.00%
	All Grades	56	1.1280 (0.03340)	1.0703 1.2043	0 0.00%	1.1017 (0.03262)	1.0454 1.1763	0 0.00%
1 1/4	A325	21	1.1526 (0.04609)	1.0666 1.2338	0 0.00%	1.0946 (0.04377)	1.0129 1.1718	0 0.00%
	A490	32	1.1474 (0.02546)	1.0986 1.2148	0 0.00%	1.0897 (0.02418)	1.0434 1.1538	0 0.00%
	All Grades	53	1.1495 (0.03479)	1.0666 1.2338	0 0.00%	1.0917 (0.03304)	1.0129 1.1718	0 0.00%
All Diameters	All Grades	515	1.1664 (0.06970)	1.0233 1.3317	0 0.00%	1.1436 (0.06825)	1.0129 1.3023	0 0.00%

Table 5-13: Ratio of Experimental/Nominal by Diameter for Shear

		Experimental/Nominal - Shear Excluded				Experimental/Nominal - Shear Not Excluded			
Diameter	Grade	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC	Total Tested	Average (St. Dev.)	Minimum & Maximum	Number & Percent Below AISC
5/8	A325/F1852	25	1.1766 (0.04051)	1.1197 1.2612	0 0.00%	25	1.1103 (0.06321)	0.9917 1.2263	1 4.00%
	A490	30	1.0504 (0.01990)	1.0097 1.0836	0 0.00%	30	0.9952 (0.05307)	0.8726 1.1111	17 56.67%
	All Grades	55	1.1078 (0.07048)	1.0097 1.2612	0 0.00%	55	1.0475 (0.08145)	0.8726 1.2263	18 32.73%
3/4	A325/F1852	58	1.2194 (0.03416)	1.1435 1.2771	0 0.00%	55	1.1499 (0.05900)	1.0289 1.2797	0 0.00%
	A490/F2280	60	1.0684 (0.03490)	0.9848 1.1501	2 3.33%	61	1.0022 (0.04167)	0.8895 1.0959	28 45.90%
	All Grades	118	1.1427 (0.08325)	0.9848 1.2771	2 1.69%	116	1.0722 (0.08961)	0.8895 1.2797	28 24.14%
7/8	A325/F1852	52	1.2216 (0.04024)	1.1584 1.2941	0 0.00%	51	1.1621 (0.05506)	1.0496 1.3158	0 0.00%
	A490/F2280	66	1.0670 (0.03468)	0.9807 1.1324	2 3.03%	65	1.0055 (0.04005)	0.9150 1.0928	28 43.08%
	All Grades	118	1.1351 (0.08551)	0.9807 1.2941	2 1.69%	116	1.0744 (0.09111)	0.9150 1.3158	28 24.14%
1	A325/F1852	50	1.1786 (0.03880)	1.1051 1.2596	0 0.00%	51	1.1161 (0.05105)	0.9785 1.2191	1 1.96%
	A490/F2280	63	1.0524 (0.03609)	0.9485 1.1061	6 9.52%	62	0.9919 (0.05401)	0.8405 1.1664	36 58.06%
	All Grades	113	1.1083 (0.07311)	0.9485 1.2596	6 5.31%	113	1.0480 (0.08130)	0.8405 1.2191	37 32.74%
1 1/8	A325/F1852	25	1.1087 (0.02860)	1.0571 1.1688	0 0.00%	26	1.0679 (0.03537)	0.9843 1.1357	2 7.69%
	A490/F2280	30	1.0352 (0.03070)	0.9564 1.0746	5 16.67%	30	0.9556 (0.03323)	0.8976 1.0245	27 90.00%
	All Grades	55	1.0686 (0.04723)	0.9564 1.1688	5 9.09%	56	1.0078 (0.06590)	0.8976 1.1357	29 51.79%
1 1/4	A325	23	1.0789 (0.02895)	1.0099 1.1144	0 0.00%	20	1.0353 (0.03950)	0.9569 1.1243	3 15.00%
	A490	30	1.0438 (0.05089)	0.9231 1.1297	5 16.67%	30	0.9969 (0.05828)	0.8778 1.1264	19 63.33%
	All Grades	53	1.0591 (0.04591)	0.9231 1.1297	5 9.43%	50	1.0122 (0.05457)	0.8778 1.1264	22 44.00%
All Diameters	All Grades	512	1.1130 (0.07903)	0.9231 1.2941	20 3.91%	506	1.0516 (0.08511)	0.8405 1.3158	162 32.02%

Some observations about the experimental to nominal tensile strength were made based on Tables 5-10 and 5-12. The ratio of experimental tensile strength to the nominal strength was never less than 1.023 when the nominal strength was based on AISC. This means that all of the 515 bolts tested in direct tension had a strength of at least 2.3 percent greater than the nominal strength specified by AISC. When the nominal strength was based on the effective area, the ratio of experimental tensile strength to nominal strength was 1.013 at a minimum. Comparing the ratio of experimental strength to nominal strength it can be seen that on average the nominal strength calculated with the effective area better predicts the failure load (i.e. the ratio of experimental to nominal strength is closer to one). It was determined from Table 5-12 that the nominal strength based on the effective area better predicts the failure load for 3/4-inch, 7/8-inch, 1-inch, 1-1/8-inch, and 1-1/4-inch bolts compared to the nominal strength based on the approximation AISC uses in its specification. This was to be expected since the ratio of the effective area to the shank area was greater than 0.75, the approximation used by AISC, for diameters 3/4-inch to 1-1/4-inch, as previously discussed in Section 2.2 and as shown in Table 2-12. It should be noted that none of the high-strength bolts tested in tension had a tensile strength lower than the nominal strength predicated by AISC or based on the effective area. This implies that the AISC equation is accurately predicting the strength of structural bolts in tension based on the 515 bolts tested.

Some observations about the experimental to nominal shear strength were also made based on Tables 5-11 and 5-13. Twenty out of the 512 shear bolts tested with the threads excluded from the shear plane had an experimental to nominal ratio less than one. These bolts were of grade A490 and from Table 5-13 the diameters were from 3/4-inch to 1-1/4-inch. This means that of the 512 bolts tested in shear with the threads excluded from the shear plane, about 3.9 % of the bolts had a shear strength less than the nominal AISC value. Therefore based on the 512 bolts tested in shear with the threads excluded from the shear plane, it can be observed that the AISC equation closely predicts the shear strength with the threads excluded since only 3.9 percent of the tested bolts were below the AISC nominal value.

As for the bolts in shear with the threads not excluded from the shear plane, there were seven out of 203 A325 bolts tested with an experimental to nominal ratio lower than one. In other words, about 3.45 % of the A325 bolts had a strength with the threads not excluded from the shear plane lower than the AISC specified value. Also there were 132 out of the 228 A490 bolts tested and twenty-three out of the fifty F2280 bolts tested which had a ratio less than one. Thus about 55.8 percent of the A490 and F2280 bolts tested had a shear strength with the threads not excluded from the shear plane below the AISC nominal value. Therefore the AISC equation for the shear strength with the threads not excluded from the shear plane for structural bolts is over predicting the strength more than 50% of the time for A490 and F2280 bolts based on the 278 bolts tested. When looking at the 506 total bolts tested in shear with the threads not excluded, 162 or about thirty-two percent were below AISC's nominal value. Thus more than 30% of the time AISC's equation is over predicting the shear strength of bolts with the threads not excluded from the shear plane based on the 506 bolts tested.

5.3.2.4 Strengths Compared

As previously discussed in Section 2.3, the shear strength is estimated as a percentage of the bolt's tensile strength. The strength of a single bolt with the threads excluded from the shear plane is taken equal to approximately 62% of the bolt's tensile strength (Kulak et al. 2001). For a bolt with the threads not excluded from the shear plane the shear strength is approximately 83% of the shear strength with the threads excluded from the shear plane (RCSC 2004). Section 5.3.2.4.1 determines the shear strength as a percentage of the tensile strength for the structural bolts tested. The shear strength with the threads not excluded from the shear plane is compared to the shear strength with the threads excluded from the shear plane in Section 5.3.2.4.2. Section 5.3.2.4.3 summarizes the findings.

Shear X versus Tensile Strength

The shear strength with the threads excluded from the shear plane was compared to the tensile strength. Figures 5-44 through 5-46 show the shear strength with the threads excluded from the shear plane versus the tensile strength for all one hundred lots of 120 ksi bolts, 150 ksi bolts, and all bolts tested, respectively.

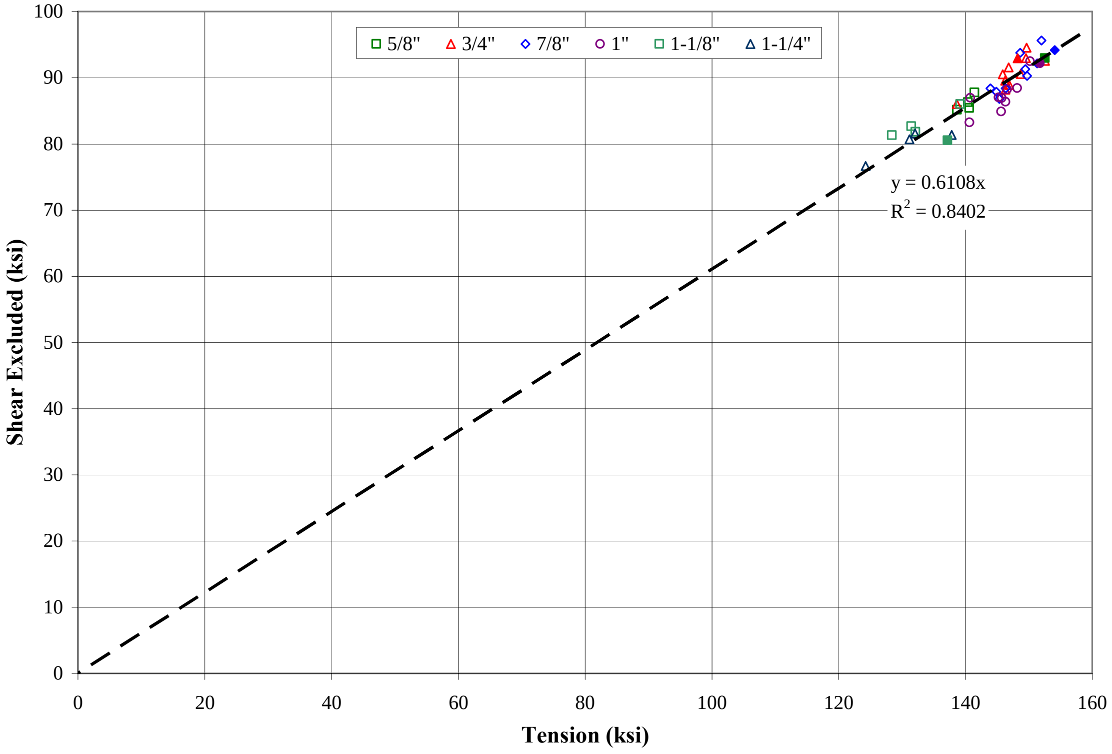

Figure 5-44: Shear Strength Excluded versus Tensile Strength for A325/F1852 Bolts

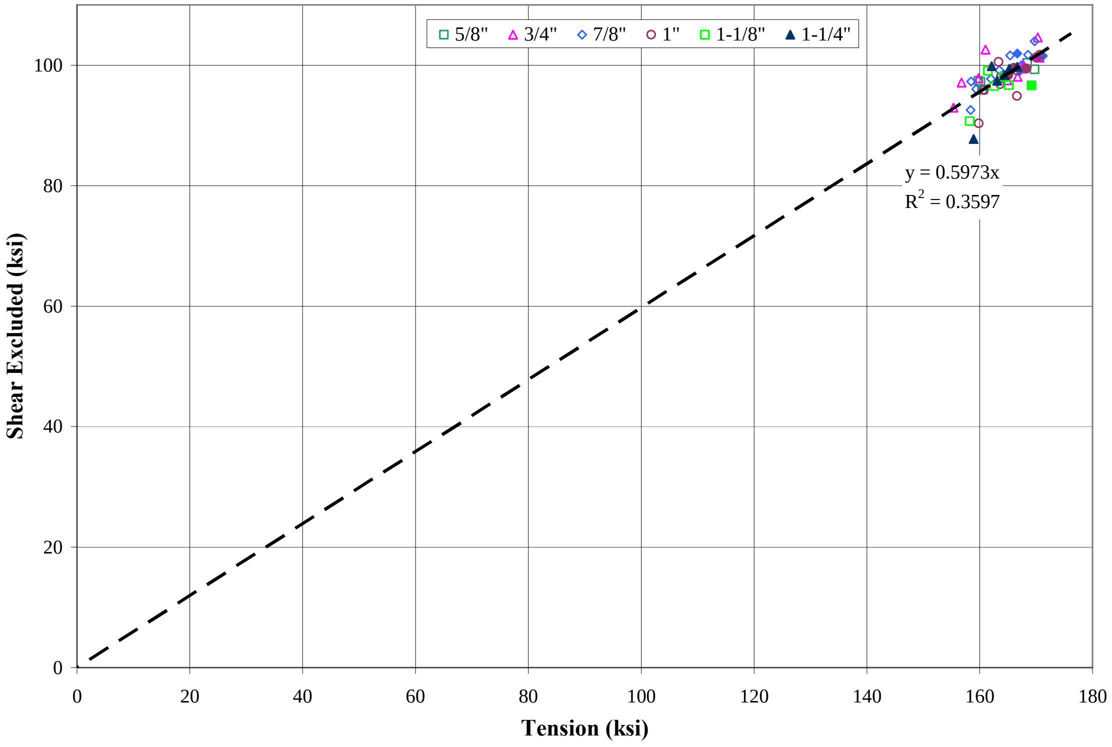

Figure 5-45: Shear Strength Excluded versus Tensile Strength for A490/F2280 Bolts

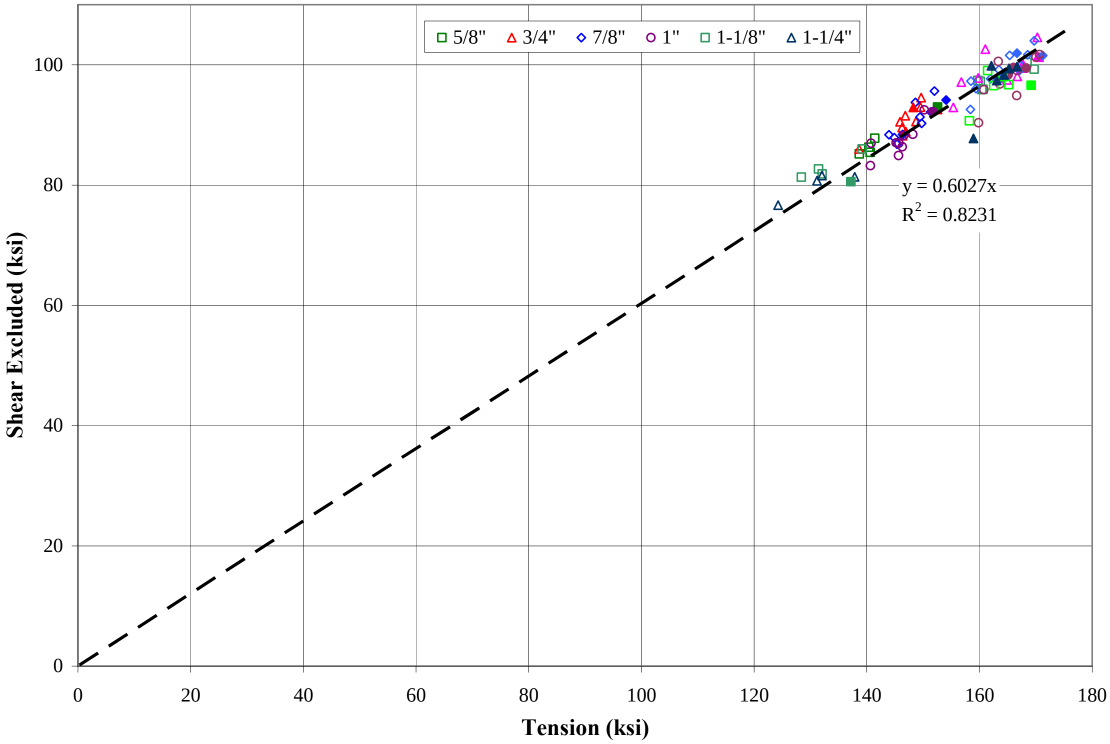

Figure 5-46: Shear Strength Excluded versus Tensile Strength for all Bolt Grades

As can be seen from Figures 5-44 and 5-45, the ratio of shear excluded to tensile strength is largely independent of the bolt grade. The average shear strength with the threads excluded from the shear plane is approximately 60% of the average tensile strength based on the one hundred lots tested, as shown in Figure 5-46. According to the “Guide to Design Criteria for Bolted and Riveted Joints” (Kulak et al. 2001), “the average shear strength is approximately 62% of the tensile strength”. It should be noted that this value from Kulak et al. in 2001 was determined based on bolts tested in double shear in a tension jig.

The frequency distribution of the ratio of the shear strength with the threads excluded from the shear plane to the tensile strength is shown in Figure 5-47. From the one hundred lots of bolts tested, the average ratio was 0.6036 with a standard deviation of 0.01494.

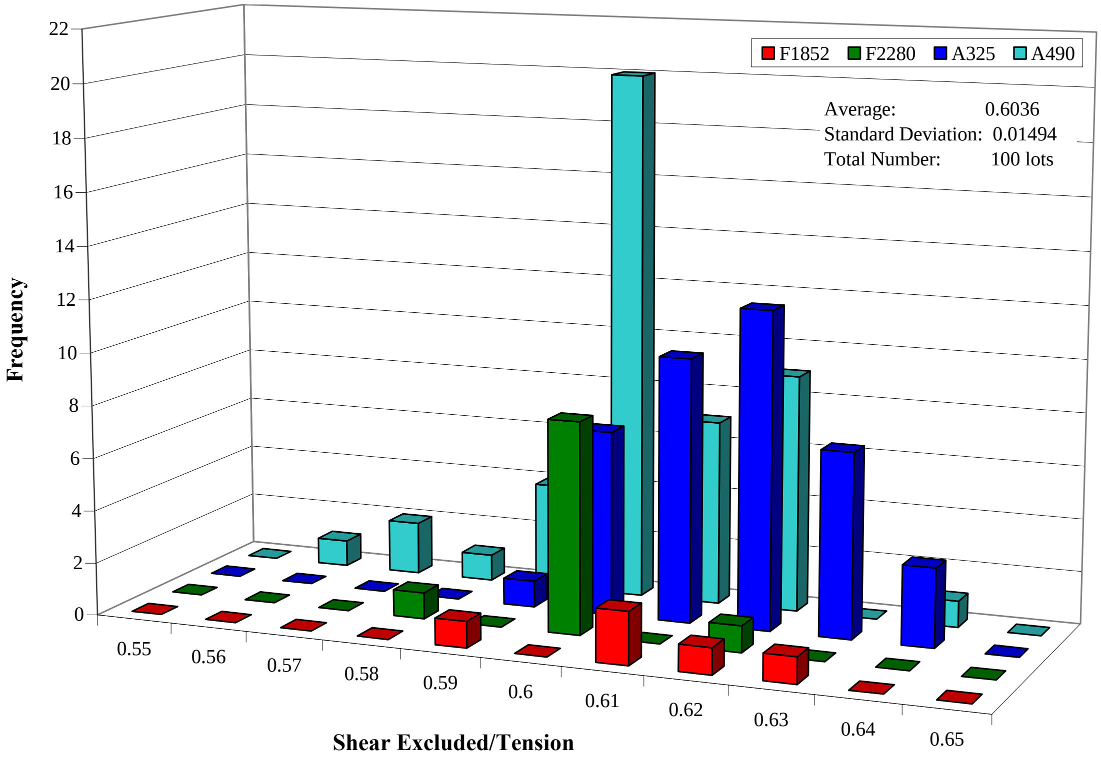

Figure 5-47: Frequency Distribution of Shear Excluded Strength to Tensile Strength

Shear N versus Shear X Strength

The shear strength with the threads not excluded from the shear plane was compared to the shear strength with the threads excluded from the shear plane. Figures 5-48 through 5-50 show the shear strength with the threads not excluded from the shear plane versus the shear strength with the threads excluded based on 120 ksi bolts, 150 ksi bolts, and all bolt grades, respectively.

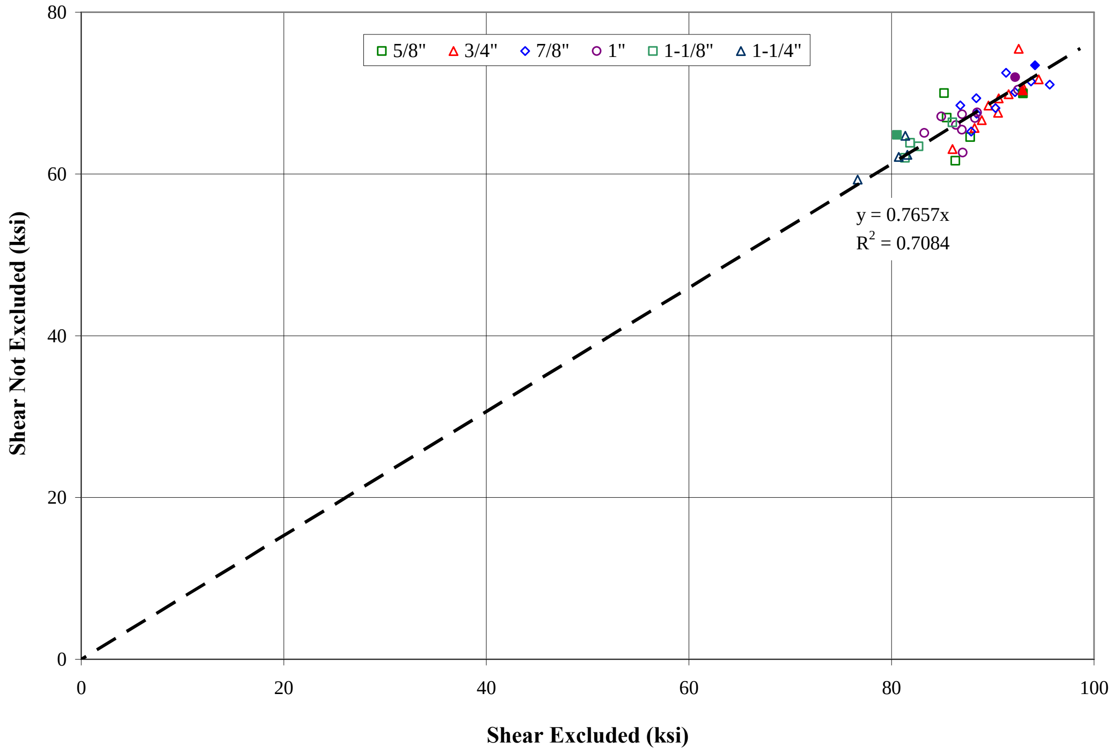

Figure 5-48: Shear Not Excluded versus Shear Excluded for A325/F1852 Bolts

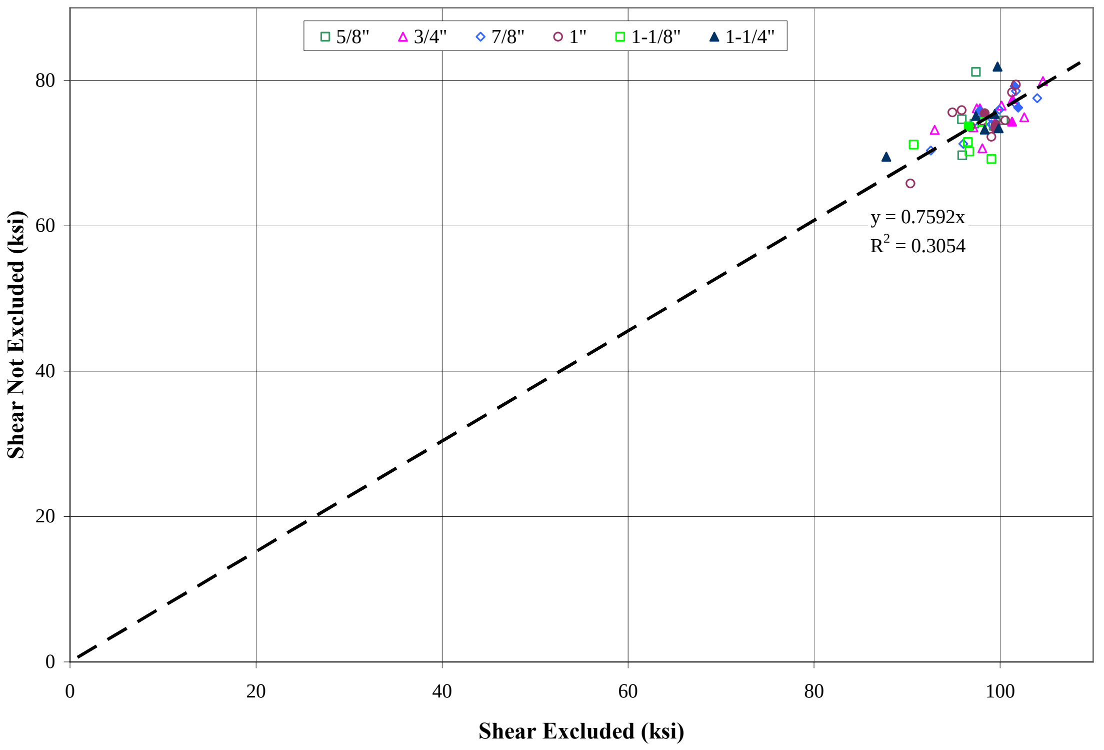

Figure 5-49: Shear Not Excluded versus Shear Excluded for A490/F2280 Bolts

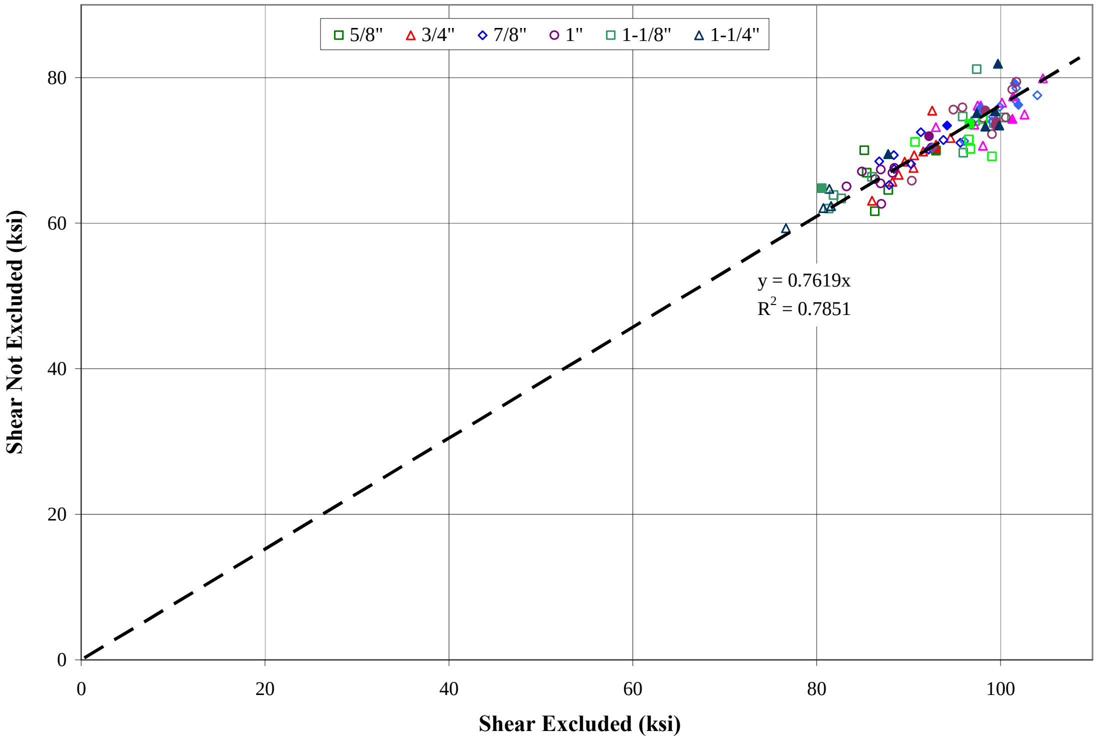

Figure 5-50: Shear Not Excluded versus Shear Excluded for all Bolt Grades

The ratio of shear not excluded to shear excluded is largely independent of the bolt grade, as can be seen from Figures 5-48 and 5-49. The average shear strength with the threads not excluded from the shear plane is approximately 76% of the average shear strength with the threads excluded from the shear plane. The frequency distribution of the ratio of the shear strength with the threads not excluded from the shear plane to the shear strength with the threads excluded is shown in Figure 5-51. From the one hundred lots of bolts tested, the average ratio is 0.7621 with a standard deviation of 0.02356. From RCSC (2004) a fastener with the threads not excluded from the shear plane had a strength approximately equal to 83% of the strength with the threads excluded with a standard deviation of 0.03. AISC takes this value as roughly 80%. It is believed that the AISC value is based on a lack of data (as discussed previously in Chapter 3) which results in the difference between the AISC value and the valued obtained from the shear testing.

It was observed that the ratio of 0.7621 is close to the ratio of the area of the threaded portion to the gross bolt area (which AISC takes as 0.75).

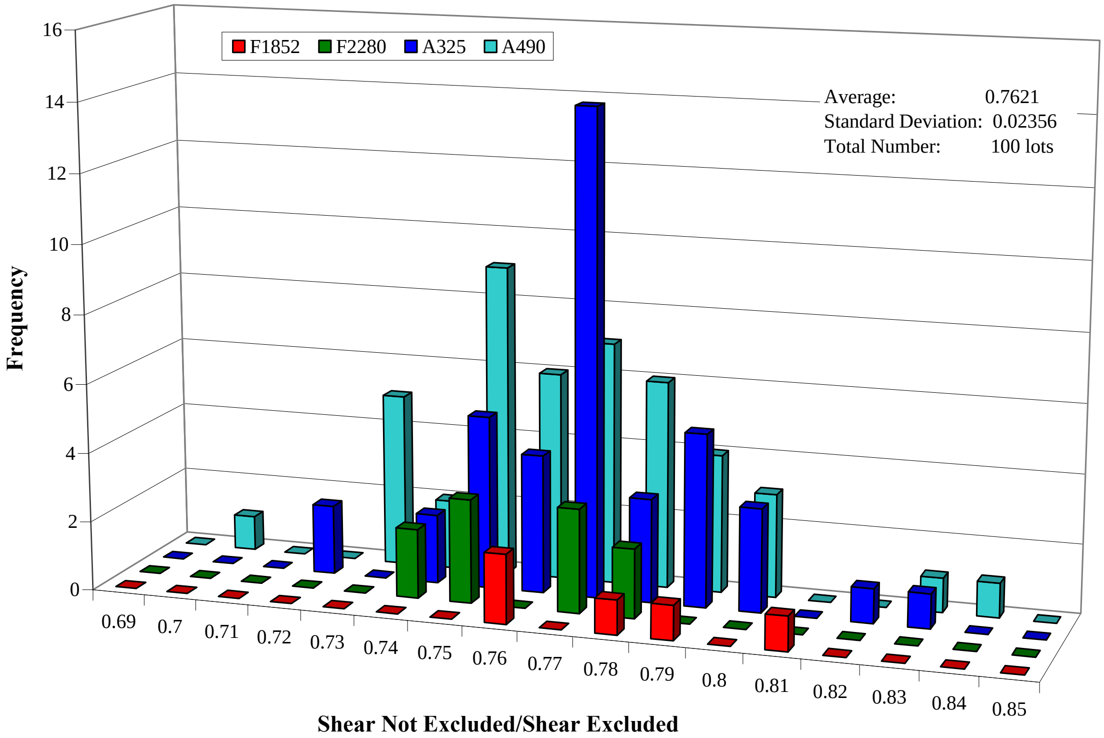

Figure 5-51: Frequency Distribution of Shear Not Excluded to Shear Excluded

Summary

Tables 5-14 and 5-15 were created to further examine the ratios of shear excluded to tensile strength and shear not excluded to shear excluded. Tables 5-14 and 5-15 summarize these ratios based on the bolt grade and diameter, respectively.

Table 5-14: Strength Ratios by Grade

Grade	Total Lots Tested	**Shear Excluded/ Tension** Average (St. Dev.)	**Shear Excluded/ Tension** Minimum & Maximum	**Shear Not Excluded/ Shear Excluded** Average (St. Dev.)	**Shear Not Excluded/ Shear Excluded** Minimum & Maximum
A325	40	0.6113 (0.01234)	0.5831 0.6335	0.7650 (0.02213)	0.7141 0.8217
F1852	5	0.6085 (0.01418)	0.5872 0.6270	0.7747 (0.02112)	0.7523 0.8047
A325/F1852	45	0.6110 (0.01241)	0.5831 0.6335	0.7661 (0.02200)	0.7141 0.8217
A490	45	0.5984 (0.01495)	0.5522 0.6372	0.7595 (0.02608)	0.6983 0.8332
F2280	10	0.5940 (0.00993)	0.5711 0.6116	0.7560 (0.01606)	0.7340 0.7800
A490/F2280	55	0.5976 (0.01419)	0.5522 0.6372	0.7589 (0.02448)	0.6983 0.8332
All Grades	100	0.6036 (0.01494)	0.5522 0.6372	0.7621 (0.02356)	0.6983 0.8332

Table 5-15: Strength Ratios by Diameter

			Shear Excluded/ Tension		Shear Not Excluded/ Shear Excluded	
Diameter	Grade	Total Lots Tested	Average (St. Dev.)	Minimum & Maximum	Average (St. Dev.)	Minimum & Maximum
5/8	A325/F1852	5	0.6134 (0.005069)	0.6077 0.6206	0.7614 (0.04220)	0.7141 0.8217
	A490	6	0.5988 (0.00884)	0.5851 0.6098	0.7642 (0.03827)	0.7265 0.8332
	All Grades	11	0.6054 (0.01038)	0.5851 0.6206	0.7629 (0.03804)	0.7141 0.8332
3/4	A325/F1852	11	0.6165 (0.00967)	0.6028 0.6317	0.7599 (0.02089)	0.7335 0.8154
	A490/F2280	12	0.6027 (0.01481)	0.5883 0.6372	0.7559 (0.02146)	0.7203 0.7876
	All Grades	23	0.6093 (0.01419)	0.5883 0.6372	0.7578 (0.02080)	0.7203 0.8154
7/8	A325/F1852	10	0.6116 (0.01084)	0.5971 0.6308	0.7673 (0.01858)	0.7424 0.7939
	A490/F2280	13	0.6025 (0.00935)	0.5844 0.6144	0.7598 (0.01256)	0.7422 0.7800
	All Grades	23	0.6065 (0.01081)	0.5844 0.6308	0.7631 (0.01554)	0.7422 0.7939
1	A325/F1852	10	0.6002 (0.01105)	0.5831 0.6179	0.7648 (0.01968)	0.7198 0.7902
	A490/F2280	12	0.5925 (0.01332)	0.5653 0.6157	0.7592 (0.02358)	0.7286 0.7967
	All Grades	22	0.5960 (0.01267)	0.5653 0.6179	0.7617 (0.02157)	0.7198 0.7967
1 1/8	A325/F1852	5	0.6175 (0.01808)	0.5872 0.6335	0.7771 (0.01683)	0.7621 0.8047
	A490/F2280	6	0.5891 (0.01597)	0.5711 0.6136	0.7450 (0.03032)	0.6983 0.7847
	All Grades	11	0.6020 (0.02186)	0.5711 0.6335	0.7596 (0.02921)	0.6983 0.8047
1 1/4	A325	4	0.6101 (0.01322)	0.5904 0.6177	0.7757 (0.01361)	0.7645 0.7953
	A490	6	0.5939 (0.02159)	0.5522 0.6158	0.7706 (0.03192)	0.7354 0.8215
	All Grades	10	0.6004 (0.01968)	0.5522 0.6177	0.7726 (0.02520)	0.7354 0.8215
All Diameters	All Grades	100	0.6036 (0.01494)	0.5522 0.6372	0.7621 (0.02356)	0.6983 0.8332

On average, the shear strength with the threads excluded from the shear plane is 60.4 % of the tensile strength with a standard deviation of 0.01494. The minimum and maximum ratios of the shear strength with the threads excluded to the tensile strength are 0.552 and 0.637, respectively. The ratio of the shear strength with the threads not excluded to the shear strength with the threads excluded on average is 76.2 % with a standard deviation of 0.02356. The ratios of shear not excluded to shear excluded varies from 0.698 to 0.833. As previously discussed in Section 2.3, these ratios are taken as 62% and 80% in the AISC code for the shear excluded to tensile strength and the shear not excluded to shear excluded strength, respectively.

5.4 Elongation at Failure

The elongation at failure of high-strength bolts was considered by studying the elongation of the 515 bolts tested in direct tension. After the tension bolts were tested, the thread length was measured and compared to the measured thread length as calculated in Section 5.2. This resulted in the percent elongation of the tension bolt. Due to the reduced area in the threads, the elongation occurs mostly in this region and not in the bolt shank. Figure 5-52 shows examples of elongation in the tension bolts tested.

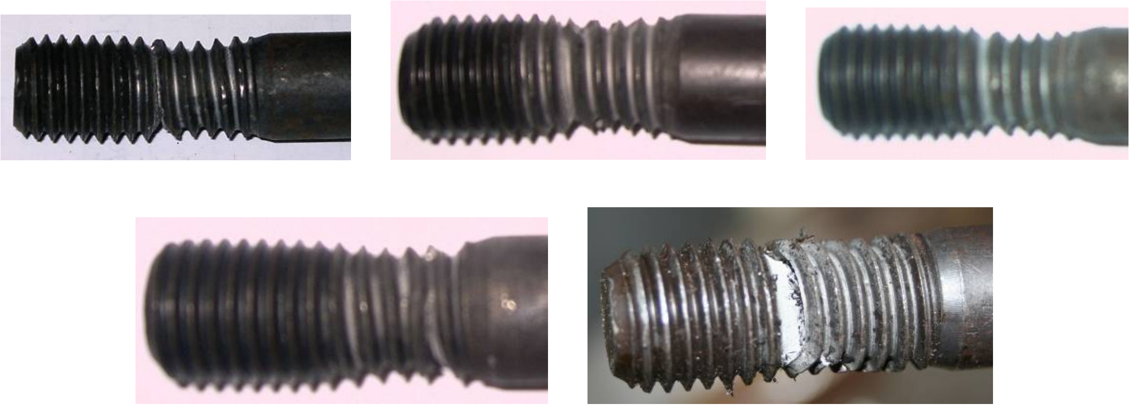

Figure 5-52: Elongation of Threads in Tension Bolts

Figures 5-53 and 5-54 show the frequency distributions of the percent elongation for A325/F1852 and A490/F2280 bolts, respectively. The frequency distribution of all of the high-strength bolts tested is shown in Figure 5-55. Tables 5-16 and 5-17 summarize the results based on diameter and grade, respectively.

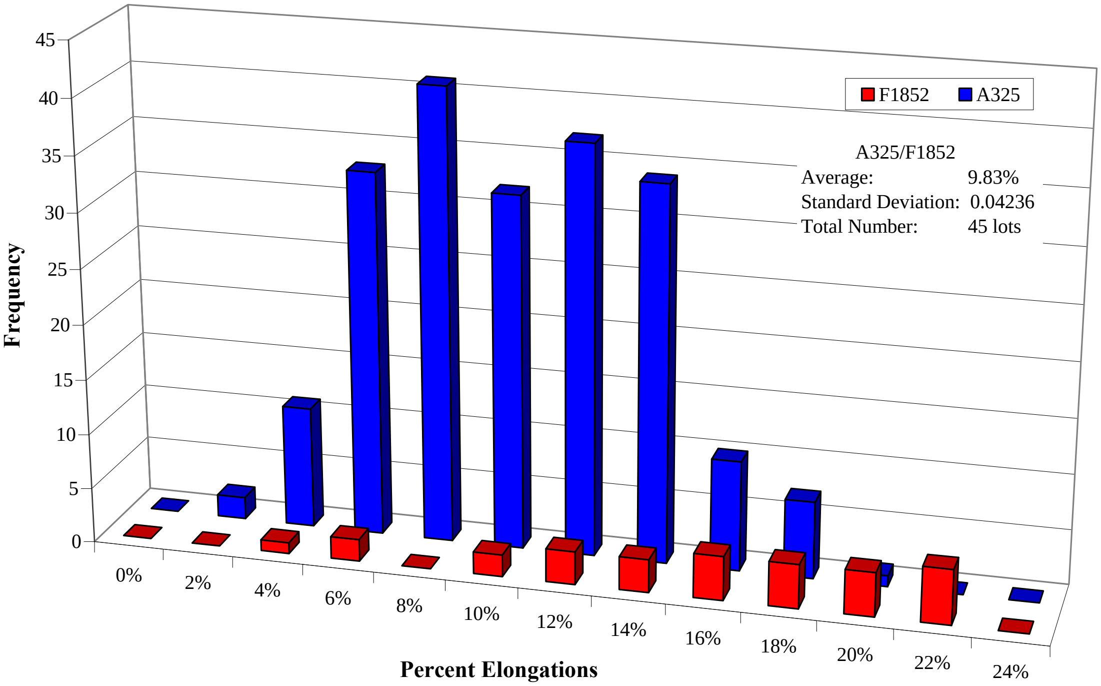

Figure 5-53: Frequency Distribution of Percent Elongation for A325/F1852 Bolts

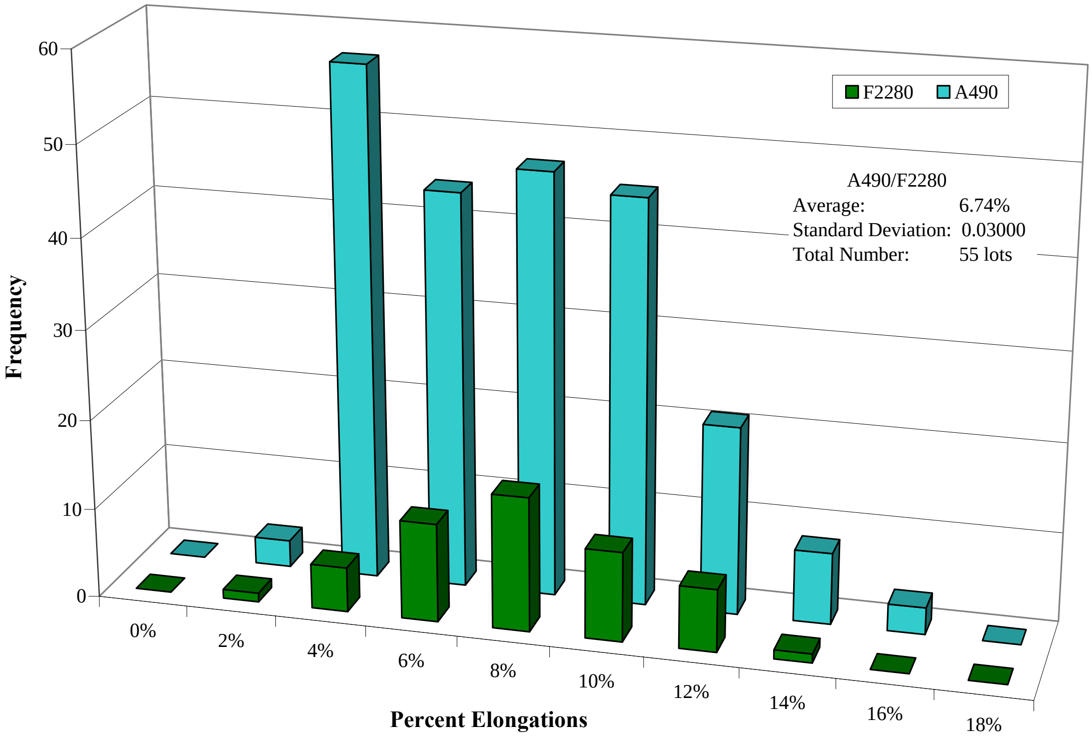

Figure 5-54: Frequency Distribution of Percent Elongation for A490/F2280 Bolts

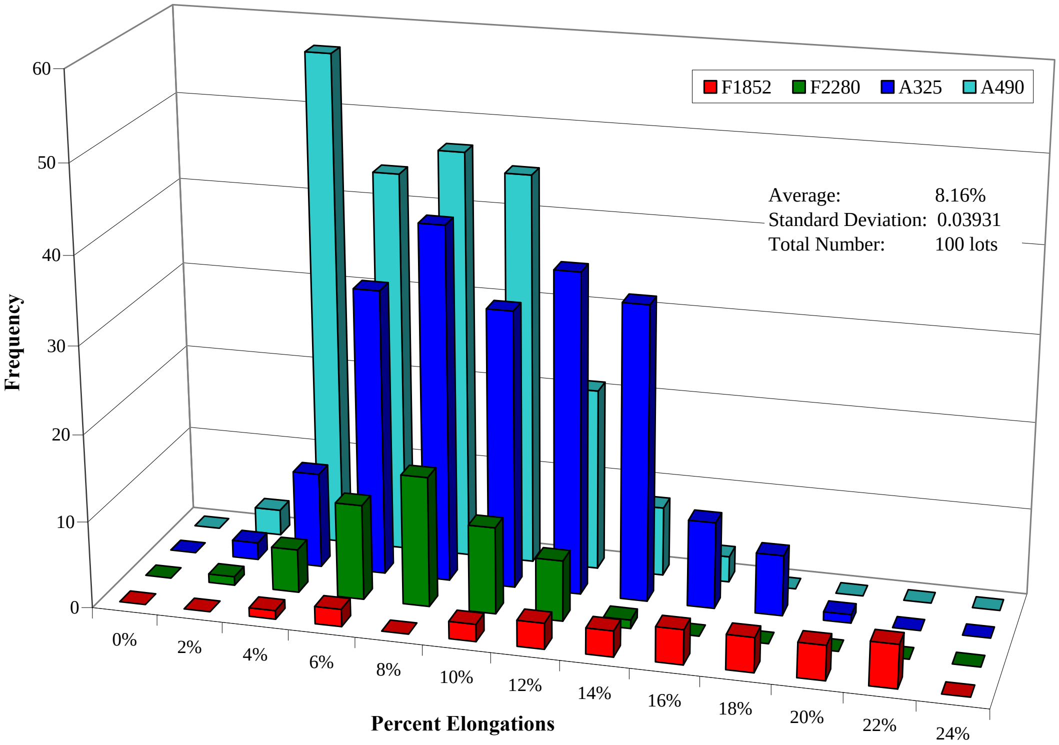

Figure 5-55: Frequency Distribution of Percent Elongation for all Bolt Grades

Table 5-16: Percent Elongation Summarized Based on Bolt Diameter

Diameter	Grade	Total Lots Tested	Average (St. Dev.)	Minimum & Maximum
5/8	A325/F1852	5	10.75% (0.02640)	5.48% 16.06%
	A490	6	8.51% (0.02566)	4.71% 13.75%
	All Grades	11	9.53% (0.02811)	4.71% 16.06%
3/4	A325/F1852	11	11.04% (0.05415)	0.58% 21.94%
	A490/F2280	12	8.84% (0.03092)	1.54% 15.76%
	All Grades	23	9.93% (0.04519)	0.58% 21.94%
7/8	A325/F1852	10	11.78% (0.03422)	6.42% 21.98%
	A490/F2280	13	8.09% (0.01794)	4.43% 12.52%
	All Grades	23	9.70% (0.03199)	4.43% 21.98%
1	A325/F1852	10	8.96% (0.03705)	2.35% 16.96%
	A490/F2280	12	5.45% (0.02104)	1.33% 12.65%
	All Grades	22	7.11% (0.03444)	1.33% 16.96%
1 1/8	A325/F1852	5	7.26% (0.02431)	2.26% 12.95%
	A490/F2280	6	3.25% (0.00879)	2.03% 5.31%
	All Grades	11	5.11% (0.02676)	2.03% 12.95%
1 1/4	A325	4	6.01% (0.01822)	2.56% 10.13%
	A490	6	4.06% (0.01516)	0.35% 7.67%
	All Grades	10	4.84% (0.01890)	0.35% 10.13%
All Diameters	All Grades	100	8.16% (0.03931)	0.35% 21.98%

Table 5-17: Percent Elongation Summarized Based on Bolt Grade

Grade	Total Lots Tested	Average (St. Dev.)	Minimum & Maximum
A325	40	9.19% (0.03635)	0.58% 18.14%
F1852	5	14.59% (0.05309)	2.26% 21.98%
A325/F1852	45	9.83% (0.04236)	0.58% 21.98%
A490	45	6.65% (0.03090)	0.35% 15.76%
F2280	10	7.17% (0.02530)	1.35% 13.20%
A490/F2280	55	6.74% (0.03000)	0.35% 15.76%
All Grades	100	8.16% (0.03931)	0.35% 21.98%

The average percent elongation for A325/F1852 bolts and A490/F2280 bolts is 9.83% and 6.74%, with a standard deviation of 0.04236 and 0.03000, respectively, as can be seen from Table 5-17. Comparing the minimum percent elongation for A325/F1852 (0.58%) and A490/F2280 (0.35%), the values are not much different. The results in Tables 5-16 and 5-17 show the A490/F2280 bolts have a lower elongation at failure than A325/F1852 high-strength bolts.

5.5 Resistance Factors

Resistance factors were calculated from the 1533 bolts tested. From Figure 2-31 in Section 2.4.1, the resistance factors were calculated for five different levels of detail. There are two methods of calculating resistance factors, which were previously discussed in Section 2.4.1. Appendix B contains Level 5 example calculations for the 7/8-inch A490 bolts.

Resistance factors were calculated with an adjustment factor based on a live-to-dead load ratio of 1.0 or 3.0 and a reliability index equal to 4.5 or 4.0. The resistance factors based on a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 1.0 and 3.0, respectively, are tabulated in Sections 5.5.1 and 5.5.2. Sections 5.5.3 and 5.5.4 contain the resistance factors with a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 1.0 and 3.0, respectively.

5.5.1 Resistance Factors with a Reliability Index Equal to 4.5 & an Adjustment Factor Based on a L/D = 1.0

Resistance factors based on a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 1.0 are shown in Tables 5-18 through 5-26. The resistance factors calculated from the tension bolts are shown in Tables 5-18 through 5-21, whereas Tables 5-22 through 5-25 show the resistance factors for the shear bolts. Tables 5-18 and 5-22 show the resistance factors calculated based on the bolt diameter and grade in tension and shear, respectively (Level V). The resistance factors based on the grade of the bolts for the tension and shear bolts are summarized in Tables 5-19 and 5-23, respectively (Level IV). Tables 5-20 and 5-24 show the resistance factors based on the bolt strength (Level III) for tension and shear, respectively. The resistance factors calculated for tension and shear regardless of the bolt diameter or grade (Level II) are shown in Tables 5-21 and 5-25, respectively. Lastly, Table 5-26 shows the resistance factors calculated from the 1533 bolts tested in tension and shear (Level I).

Table 5-18: Resistance Factors – Tension – Level V – β = 4.5 – L/D = 1.0

Diameter	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
5/8	A325 (4 lots)	0.982	1.000	0.987	1.007
	F1852 (1 lot)	1.090	1.110	1.090	1.111
	A490 (6 lots)	0.870	0.886	0.876	0.894
3/4	A325 (10 lots)	1.016	1.007	0.994	0.987
	F1852 (1 lot)	1.089	1.079	1.089	1.086
	A490 (9 lots)	0.886	0.877	0.885	0.879
	F2280 (3 lots)	0.974	0.965	0.971	0.967
7/8	A325 (9 lots)	1.050	1.025	1.052	1.029
	F1852 (1 lot)	1.148	1.121	1.148	1.122
	A490 (10 lots)	0.916	0.895	0.912	0.892
	F2280 (3 lots)	0.944	0.922	0.936	0.915
1	A325 (9 lots)	1.032	1.004	1.029	1.003
	F1852 (1 lot)	1.136	1.104	1.136	1.105
	A490 (9 lots)	0.934	0.908	0.933	0.908
	F2280 (3 lots)	0.972	0.946	0.970	0.946
1 1/8	A325 (4 lots)	0.908	0.887	0.906	0.887
	F1852 (1 lot)	1.022	0.998	1.022	1.002
	A490 (5 lots)	0.928	0.907	0.928	0.907
	F2280 (1 lot)	1.008	0.985	1.008	0.988
1 1/4	A325 (4 lots)	0.906	0.860	0.904	0.860
	A490 (6 lots)	0.961	0.913	0.960	0.913
	Minimum	0.870	0.860	0.876	0.860
	Maximum	1.148	1.121	1.148	1.122

Table 5-19: Resistance Factors – Tension – Level IV – β = 4.5 – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
A325 (40 lots)	0.947	0.925	0.930	0.920
F1852 (5 lots)	0.981	0.966	0.975	0.974
A490 (45 lots)	0.899	0.897	0.897	0.896
F2280 (10 lots)	0.967	0.942	0.925	0.913
Minimum	0.899	0.897	0.897	0.896
Maximum	0.981	0.966	0.975	0.974

Table 5-20: Resistance Factors – Tension – Level III – β = 4.5 – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
120 ksi (A325/F1852) (45 lots)	0.949	0.927	0.932	0.923
150 ksi (A490/F2280) (55 lots)	0.905	0.900	0.897	0.892
Minimum	0.905	0.900	0.897	0.892
Maximum	0.949	0.927	0.932	0.923

Table 5-21: Resistance Factors – Tension – Level II – β = 4.5 – L/D = 1.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
0.878	0.862	0.868	0.859

Table 5-22: Resistance Factors – Shear – Level V – $\beta = 4.5$ – L/D = 1.0

Diameter	Grade	Shear Excluded		Shear NOT Excluded	
		Method 1A	Method 2A	Method 1A	Method 2A
5/8	A325 (4 lots)	0.978	0.981	0.837	0.827
	F1852 (1 lot)	1.091	1.091	1.018	1.018
	A490 (6 lots)	0.876	0.855	0.769	0.740
3/4	A325 (10 lots)	0.992	0.974	0.885	0.898
	F1852 (1 lot)	1.091	1.091	1.023	1.023
	A490 (9 lots)	0.854	0.847	0.800	0.777
	F2280 (3 lots)	0.921	0.907	0.827	0.819
7/8	A325 (9 lots)	0.979	0.995	0.931	0.930
	F1852 (1 lot)	1.105	1.105	1.068	1.068
	A490 (10 lots)	0.856	0.854	0.800	0.795
	F2280 (3 lots)	0.891	0.876	0.846	0.839
1	A325 (9 lots)	0.951	0.951	0.894	0.881
	F1852 (1 lot)	1.082	1.082	1.047	1.047
	A490 (9 lots)	0.836	0.839	0.761	0.767
	F2280 (3 lots)	0.915	0.903	0.834	0.817
1 1/8	A325 (4 lots)	0.914	0.888	0.866	0.851
	F1852 (1 lot)	0.945	0.945	0.943	0.943
	A490 (5 lots)	0.831	0.839	0.776	0.762
	F2280 (1 lots)	0.907	0.907	0.858	0.858
1 1/4	A325 (4 lots)	0.875	0.834	0.828	0.812
	A490 (6 lots)	0.809	0.824	0.760	0.779
	Minimum	0.809	0.824	0.760	0.740
	Maximum	1.105	1.105	1.068	1.068

Table 5-23: Resistance Factors – Shear – Level IV – $\beta = 4.5$ – L/D = 1.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
A325 (40 lots)	0.912	0.898	0.857	0.840
F1852 (5 lots)	0.911	0.950	0.909	0.912
A490 (45 lots)	0.845	0.844	0.777	0.772
F2280 (10 lots)	0.896	0.861	0.826	0.796
Minimum	0.845	0.844	0.777	0.772
Maximum	0.912	0.950	0.909	0.912

Table 5-24: Resistance Factors – Shear – Level III – $\beta = 4.5$ – L/D = 1.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
120 ksi (A325/F1852) (45 lots)	0.910	0.900	0.859	0.845
150 ksi (A490/F2280) (55 lots)	0.851	0.842	0.785	0.772
Minimum	0.851	0.842	0.785	0.772
Maximum	0.910	0.900	0.859	0.845

Table 5-25: Resistance Factors – Shear – Level II – $\beta = 4.5$ – L/D = 1.0

Shear Excluded		Shear NOT Excluded	
Method 1A	Method 2A	Method 1A	Method 2A
0.817	0.825	0.759	0.768

Table 5-26: Resistance Factors – Level I – β = 4.5 – L/D = 1.0

Tension 1A Shear 1A	Tension 1B Shear 1A	Tension 2A Shear 2A	Tension 2B Shear 2A
0.795	0.796	0.797	0.800

5.5.2 Resistance Factors with a Reliability Index Equal to 4.5 & an Adjustment Factor Based on a L/D = 3.0

The resistance factors based on a reliability index equal to 4.5 and an adjustment factor based on a live-to-dead load ratio of 3.0 are shown in Tables 5-27 through 5-35. The resistance factors calculated from the tension bolts are shown in Tables 5-27 through 5-30, whereas Tables 5-31 through 5-34 show the resistance factors for the shear bolts. Tables 5-27 and 5-31 show the resistance factors calculated based on the bolt diameter and grade (Level V) in tension and shear, respectively. The resistance factors based on the grade of the bolts (Level IV) for the tension and shear bolts are summarized in Tables 5-28 and 5-32, respectively. Tables 5-29 and 5-33 show the resistance factors based on the bolt strength (Level III) for tension and shear, respectively. The resistance factors calculated for tension and shear regardless of the bolt diameter or grade (Level II) are shown in Tables 5-30 and 5-34, respectively. Lastly, Table 5-35 shows the resistance factors calculated from the 1533 bolts tested in tension and shear (Level I).

Table 5-27: Resistance Factors – Tension – Level V – β = 4.5 – L/D = 3.0

Diameter	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A ($0.75A_g$)	Method 2B (A_{eff})
5/8	A325 (4 lots)	0.963	0.980	0.968	0.987
	F1852 (1 lot)	1.068	1.088	1.068	1.089
	A490 (6 lots)	0.853	0.868	0.859	0.876
3/4	A325 (10 lots)	0.996	0.987	0.974	0.967
	F1852 (1 lot)	1.067	1.057	1.067	1.065
	A490 (9 lots)	0.868	0.860	0.867	0.862
	F2280 (3 lots)	0.955	0.946	0.952	0.948
7/8	A325 (9 lots)	1.029	1.005	1.031	1.009
	F1852 (1 lot)	1.125	1.099	1.125	1.100
	A490 (10 lots)	0.898	0.877	0.894	0.875
	F2280 (3 lots)	0.925	0.904	0.918	0.897
1	A325 (9 lots)	1.012	0.984	1.009	0.983
	F1852 (1 lot)	1.113	1.082	1.113	1.083
	A490 (9 lots)	0.915	0.890	0.914	0.890
	F2280 (3 lots)	0.953	0.927	0.951	0.927
1 1/8	A325 (4 lots)	0.890	0.870	0.888	0.869
	F1852 (1 lot)	1.001	0.978	1.001	0.982
	A490 (5 lots)	0.910	0.889	0.909	0.889
	F2280 (1 lot)	0.988	0.965	0.988	0.968
1 1/4	A325 (4 lots)	0.888	0.843	0.886	0.843
	A490 (6 lots)	0.942	0.895	0.941	0.895
	Minimum	0.853	0.843	0.859	0.843
	Maximum	1.125	1.099	1.125	1.100

Table 5-28: Resistance Factors – Tension – Level IV – β = 4.5 – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
A325 (40 lots)	0.928	0.906	0.912	0.902
F1852 (5 lots)	0.961	0.947	0.956	0.955
A490 (45 lots)	0.881	0.879	0.879	0.878
F2280 (10 lots)	0.948	0.924	0.907	0.894
Minimum	0.881	0.879	0.879	0.878
Maximum	0.961	0.947	0.956	0.955

Table 5-29: Resistance Factors – Tension – Level III – β = 4.5 – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
120 ksi (A325/F1852) (45 lots)	0.930	0.909	0.913	0.904
150 ksi (A490/F2280) (55 lots)	0.887	0.882	0.879	0.874
Minimum	0.887	0.882	0.879	0.874
Maximum	0.930	0.909	0.913	0.904

Table 5-30: Resistance Factors – Tension – Level II – β = 4.5 – L/D = 3.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
0.861	0.845	0.851	0.842

Table 5-31: Resistance Factors – Shear – Level V – $\beta = 4.5$ – L/D = 3.0

Diameter	Grade	Shear Excluded		Shear NOT Excluded	
		Method 1A	Method 2A	Method 1A	Method 2A
5/8	A325 (4 lots)	0.959	0.962	0.821	0.811
	F1852 (1 lot)	1.069	1.069	0.998	0.998
	A490 (6 lots)	0.859	0.838	0.753	0.725
3/4	A325 (10 lots)	0.972	0.955	0.868	0.880
	F1852 (1 lot)	1.069	1.069	1.003	1.003
	A490 (9 lots)	0.837	0.830	0.785	0.762
	F2280 (3 lots)	0.903	0.889	0.811	0.802
7/8	A325 (9 lots)	0.960	0.975	0.912	0.912
	F1852 (1 lot)	1.083	1.083	1.047	1.047
	A490 (10 lots)	0.839	0.837	0.784	0.779
	F2280 (3 lots)	0.874	0.859	0.829	0.822
1	A325 (9 lots)	0.933	0.932	0.877	0.863
	F1852 (1 lot)	1.061	1.061	1.026	1.026
	A490 (9 lots)	0.819	0.822	0.745	0.752
	F2280 (3 lots)	0.897	0.885	0.818	0.801
1 1/8	A325 (4 lots)	0.896	0.870	0.849	0.834
	F1852 (1 lot)	0.926	0.926	0.924	0.924
	A490 (5 lots)	0.814	0.822	0.761	0.747
	F2280 (1 lots)	0.889	0.889	0.841	0.841
1 1/4	A325 (4 lots)	0.858	0.818	0.811	0.796
	A490 (6 lots)	0.793	0.807	0.745	0.764
	Minimum	0.793	0.807	0.745	0.725
	Maximum	1.083	1.083	1.047	1.047

Table 5-32: Resistance Factors – Shear – Level IV – $\beta = 4.5$ – L/D = 3.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
A325 (40 lots)	0.893	0.880	0.840	0.823
F1852 (5 lots)	0.893	0.931	0.891	0.894
A490 (45 lots)	0.828	0.828	0.762	0.756
F2280 (10 lots)	0.878	0.844	0.810	0.780
Minimum	0.828	0.828	0.762	0.756
Maximum	0.893	0.931	0.891	0.894

Table 5-33: Resistance Factors – Shear – Level III – $\beta = 4.5$ – L/D = 3.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
120 ksi (A325/F1852) (45 lots)	0.892	0.882	0.842	0.828
150 ksi (A490/F2280) (55 lots)	0.834	0.825	0.769	0.757
Minimum	0.834	0.825	0.769	0.757
Maximum	0.892	0.882	0.842	0.828

Table 5-34: Resistance Factors – Shear – Level II – $\beta = 4.5$ – L/D = 3.0

Shear Excluded		Shear NOT Excluded	
Method 1A	Method 2A	Method 1A	Method 2A
0.800	0.809	0.744	0.753

Table 5-35: Resistance Factors – Level I – β = 4.5 – L/D = 3.0

Tension 1A Shear 1A	Tension 1B Shear 1A	Tension 2A Shear 2A	Tension 2B Shear 2A
0.779	0.780	0.781	0.784

5.5.3 Resistance Factors with a Reliability Index Equal to 4.0 & an Adjustment Factor Based on a L/D = 1.0

The resistance factors based on a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 1.0 are shown in Tables 5-36 through 5-44. Tables 5-36 through 5-39 show the resistance factors calculated from the tension bolts whereas Tables 5-40 through 5-43 show the resistance factors calculated from the shear bolts. Tables 5-36 and 5-40 show the resistance factors calculated based on the diameter and grade of the bolts in tension and shear (Level V), respectively. The tension and shear resistance factors based on the bolt grade (Level IV) are summarized in Tables 5-37 and 5-41, respectively. The resistance factors based on the strength of the bolts (Level III) are shown in Tables 5-38 and 5-42 for tension and shear, respectively. Tables 5-39 and 5-43 show the resistance factors calculated from all of the data regardless of the bolt diameter or grade (Level II) for tension and shear, respectively. Finally, the Level I resistance factors calculated from the 1533 high-strength bolts tested in tension and shear are shown in Table 5-44.

Table 5-36: Resistance Factors – Tension – Level V – $\beta = 4.0$ – L/D = 1.0

Diameter	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A ($0.75A_g$)	Method 2B (A_{eff})
5/8	A325 (4 lots)	1.028	1.047	1.033	1.054
	F1852 (1 lot)	1.139	1.159	1.139	1.161
	A490 (6 lots)	0.916	0.933	0.922	0.941
3/4	A325 (10 lots)	1.069	1.059	1.048	1.041
	F1852 (1 lot)	1.137	1.127	1.137	1.135
	A490 (9 lots)	0.933	0.925	0.932	0.927
	F2280 (3 lots)	1.020	1.011	1.017	1.013
7/8	A325 (9 lots)	1.102	1.077	1.105	1.081
	F1852 (1 lot)	1.199	1.171	1.199	1.172
	A490 (10 lots)	0.964	0.941	0.960	0.939
	F2280 (3 lots)	0.992	0.969	0.985	0.962
1	A325 (9 lots)	1.085	1.055	1.082	1.054
	F1852 (1 lot)	1.186	1.153	1.186	1.154
	A490 (9 lots)	0.981	0.954	0.981	0.954
	F2280 (3 lots)	1.019	0.990	1.016	0.991
1 1/8	A325 (4 lots)	0.958	0.936	0.956	0.935
	F1852 (1 lot)	1.067	1.042	1.067	1.046
	A490 (5 lots)	0.974	0.951	0.973	0.952
	F2280 (1 lot)	1.053	1.029	1.053	1.032
1 1/4	A325 (4 lots)	0.957	0.909	0.956	0.909
	A490 (6 lots)	1.009	0.958	1.008	0.958
	Minimum	0.916	0.909	0.922	0.909
	Maximum	1.199	1.171	1.199	1.172

Table 5-37: Resistance Factors – Tension – Level IV – β = 4.0 – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A ($0.75A_g$)	Method 2B (A_{eff})
A325 (40 lots)	1.002	0.979	0.986	0.975
F1852 (5 lots)	1.037	1.022	1.032	1.030
A490 (45 lots)	0.947	0.943	0.946	0.943
F2280 (10 lots)	1.013	0.988	0.975	0.961
Minimum	0.947	0.943	0.946	0.943
Maximum	1.037	1.022	1.032	1.030

Table 5-38: Resistance Factors – Tension – Level III – β = 4.0 – L/D = 1.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A ($0.75A_g$)	Method 2B (A_{eff})
120 ksi (A325/F1852) (45 lots)	1.004	0.982	0.988	0.978
150 ksi (A490/F2280) (55 lots)	0.954	0.947	0.946	0.939
Minimum	0.954	0.947	0.946	0.939
Maximum	1.004	0.982	0.988	0.978

Table 5-39: Resistance Factors – Tension – Level II – β = 4.0 – L/D = 1.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A ($0.75A_g$)	Method 2B (A_{eff})
0.933	0.915	0.923	0.912

Table 5-40: Resistance Factors – Shear – Level V – $\beta = 4.0$ – L/D = 1.0

Diameter	Grade	Shear Excluded		Shear NOT Excluded	
		Method 1A	Method 2A	Method 1A	Method 2A
5/8	A325 (4 lots)	1.025	1.028	0.888	0.878
	F1852 (1 lot)	1.140	1.140	1.063	1.063
	A490 (6 lots)	0.920	0.900	0.814	0.787
3/4	A325 (10 lots)	1.044	1.027	0.938	0.949
	F1852 (1 lot)	1.139	1.139	1.069	1.069
	A490 (9 lots)	0.900	0.894	0.844	0.823
	F2280 (3 lots)	0.965	0.952	0.870	0.862
7/8	A325 (9 lots)	1.032	1.047	0.981	0.980
	F1852 (1 lot)	1.154	1.154	1.116	1.116
	A490 (10 lots)	0.902	0.901	0.844	0.839
	F2280 (3 lots)	0.937	0.923	0.890	0.883
1	A325 (9 lots)	1.002	1.001	0.943	0.930
	F1852 (1 lot)	1.130	1.130	1.094	1.094
	A490 (9 lots)	0.882	0.885	0.806	0.812
	F2280 (3 lots)	0.958	0.946	0.875	0.859
1 1/8	A325 (4 lots)	0.962	0.937	0.912	0.898
	F1852 (1 lot)	0.987	0.987	0.985	0.985
	A490 (5 lots)	0.876	0.883	0.817	0.804
	F2280 (1 lots)	0.947	0.947	0.896	0.896
1 1/4	A325 (4 lots)	0.921	0.883	0.873	0.858
	A490 (6 lots)	0.857	0.870	0.806	0.824
	Minimum	0.857	0.870	0.806	0.787
	Maximum	1.154	1.154	1.116	1.116

Table 5-41: Resistance Factors – Shear – Level IV – $\beta = 4.0$ – L/D = 1.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
A325 (40 lots)	0.965	0.952	0.908	0.892
F1852 (5 lots)	0.968	1.005	0.962	0.964
A490 (45 lots)	0.891	0.890	0.822	0.816
F2280 (10 lots)	0.940	0.908	0.869	0.840
Minimum	0.891	0.890	0.822	0.816
Maximum	0.968	1.005	0.962	0.964

Table 5-42: Resistance Factors – Shear – Level III – $\beta = 4.0$ – L/D = 1.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
120 ksi (A325/F1852) (45 lots)	0.964	0.955	0.911	0.897
150 ksi (A490/F2280) (55 lots)	0.897	0.889	0.829	0.817
Minimum	0.897	0.889	0.829	0.817
Maximum	0.964	0.955	0.911	0.897

Table 5-43: Resistance Factors – Shear – Level II – $\beta = 4.0$ – L/D = 1.0

Shear Excluded		Shear NOT Excluded	
Method 1A	Method 2A	Method 1A	Method 2A
0.870	0.878	0.810	0.818

Table 5-44: Resistance Factors – Level I – β = 4.0 – L/D = 1.0

Tension 1A Shear 1A	Tension 1B Shear 1A	Tension 2A Shear 2A	Tension 2B Shear 2A
0.848	0.849	0.851	0.853

5.5.4 Resistance Factors with a Reliability Index Equal to 4.0 & an Adjustment Factor Based on a L/D = 3.0

The resistance factors based on a reliability index equal to 4.0 and an adjustment factor based on a live-to-dead load ratio of 3.0 are shown in Tables 5-45 through 5-53. Tables 5-45 through 5-48 show the resistance factors calculated from the tension bolts whereas Tables 5-49 through 5-52 show the resistance factors calculated from the shear bolts. Tables 5-45 and 5-49 show the resistance factors calculated based on the diameter and grade of the bolts in tension and shear (Level V), respectively. The tension and shear resistance factors based on the bolt grade (Level IV) are summarized in Tables 5-46 and 5-50, respectively. The resistance factors based on the strength of the bolts (Level III) are shown in Tables 5-47 and 5-51 for tension and shear, respectively. Tables 5-48 and 5-52 show the resistance factors calculated from all of the data regardless of the bolt diameter or grade (Level II) for tension and shear, respectively. Finally, the Level I resistance factors calculated from the 1533 high-strength bolts tested in tension and shear are shown in Table 5-53.

Table 5-45: Resistance Factors – Tension – Level V – β = 4.0 – L/D = 3.0

Diameter	Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
5/8	A325 (4 lots)	1.014	1.032	1.018	1.039
	F1852 (1 lot)	1.123	1.143	1.123	1.144
	A490 (6 lots)	0.903	0.920	0.909	0.927
3/4	A325 (10 lots)	1.054	1.044	1.033	1.026
	F1852 (1 lot)	1.121	1.111	1.121	1.119
	A490 (9 lots)	0.920	0.912	0.919	0.914
	F2280 (3 lots)	1.006	0.996	1.003	0.999
7/8	A325 (9 lots)	1.087	1.061	1.089	1.065
	F1852 (1 lot)	1.182	1.155	1.182	1.156
	A490 (10 lots)	0.950	0.928	0.947	0.926
	F2280 (3 lots)	0.978	0.955	0.971	0.949
1	A325 (9 lots)	1.069	1.040	1.067	1.039
	F1852 (1 lot)	1.169	1.137	1.169	1.138
	A490 (9 lots)	0.967	0.941	0.967	0.941
	F2280 (3 lots)	1.004	0.976	1.002	0.977
1 1/8	A325 (4 lots)	0.944	0.922	0.942	0.922
	F1852 (1 lot)	1.052	1.028	1.052	1.032
	A490 (5 lots)	0.960	0.938	0.960	0.939
	F2280 (1 lot)	1.038	1.014	1.038	1.018
1 1/4	A325 (4 lots)	0.944	0.896	0.942	0.896
	A490 (6 lots)	0.994	0.944	0.994	0.945
	Minimum	0.903	0.896	0.909	0.896
	Maximum	1.182	1.155	1.182	1.156

Table 5-46: Resistance Factors – Tension – Level IV – $\beta = 4.0$ – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
A325 (40 lots)	0.988	0.965	0.972	0.961
F1852 (5 lots)	1.023	1.008	1.017	1.015
A490 (45 lots)	0.934	0.930	0.932	0.929
F2280 (10 lots)	0.999	0.975	0.961	0.947
Minimum	0.934	0.930	0.932	0.929
Maximum	1.023	1.008	1.017	1.015

Table 5-47: Resistance Factors – Tension – Level III – $\beta = 4.0$ – L/D = 3.0

Grade	Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
120 ksi (A325/F1852) (45 lots)	0.990	0.968	0.974	0.964
150 ksi (A490/F2280) (55 lots)	0.940	0.933	0.932	0.926
Minimum	0.940	0.933	0.932	0.926
Maximum	0.990	0.968	0.974	0.964

Table 5-48: Resistance Factors – Tension – Level II – $\beta = 4.0$ – L/D = 3.0

Method 1A (0.75Ag)	Method 1B (A_{eff})	Method 2A (0.75A_g)	Method 2B (A_{eff})
0.919	0.902	0.910	0.899

Table 5-49: Resistance Factors – Shear – Level V – β = 4.0 – L/D = 3.0

Diameter	Grade	Shear Excluded		Shear NOT Excluded	
		Method 1A	Method 2A	Method 1A	Method 2A
5/8	A325 (4 lots)	1.011	1.014	0.875	0.866
	F1852 (1 lot)	1.124	1.124	1.048	1.048
	A490 (6 lots)	0.907	0.887	0.803	0.776
3/4	A325 (10 lots)	1.029	1.013	0.924	0.936
	F1852 (1 lot)	1.123	1.123	1.054	1.054
	A490 (9 lots)	0.887	0.881	0.832	0.811
	F2280 (3 lots)	0.951	0.939	0.858	0.850
7/8	A325 (9 lots)	1.018	1.032	0.967	0.966
	F1852 (1 lot)	1.138	1.138	1.100	1.100
	A490 (10 lots)	0.890	0.888	0.832	0.827
	F2280 (3 lots)	0.924	0.910	0.877	0.870
1	A325 (9 lots)	0.988	0.987	0.929	0.916
	F1852 (1 lot)	1.114	1.114	1.078	1.078
	A490 (9 lots)	0.870	0.872	0.795	0.801
	F2280 (3 lots)	0.944	0.933	0.863	0.847
1 1/8	A325 (4 lots)	0.948	0.924	0.899	0.885
	F1852 (1 lot)	0.973	0.973	0.971	0.971
	A490 (5 lots)	0.864	0.871	0.805	0.792
	F2280 (1 lots)	0.934	0.934	0.883	0.883
1 1/4	A325 (4 lots)	0.908	0.870	0.861	0.846
	A490 (6 lots)	0.844	0.858	0.795	0.812
	Minimum	0.844	0.858	0.795	0.776
	Maximum	1.138	1.138	1.100	1.100

Table 5-50: Resistance Factors – Shear – Level IV – $\beta = 4.0$ – L/D = 3.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
A325 (40 lots)	0.951	0.939	0.895	0.879
F1852 (5 lots)	0.954	0.990	0.948	0.951
A490 (45 lots)	0.878	0.878	0.810	0.805
F2280 (10 lots)	0.927	0.895	0.856	0.828
Minimum	0.878	0.878	0.810	0.805
Maximum	0.954	0.990	0.948	0.951

Table 5-51: Resistance Factors – Shear – Level III – $\beta = 4.0$ – L/D = 3.0

Grade	Shear Excluded		Shear NOT Excluded	
	Method 1A	Method 2A	Method 1A	Method 2A
120 ksi (A325/F1852) (45 lots)	0.950	0.941	0.898	0.884
150 ksi (A490/F2280) (55 lots)	0.884	0.876	0.817	0.805
Minimum	0.884	0.876	0.817	0.805
Maximum	0.950	0.941	0.898	0.884

Table 5-52: Resistance Factors – Shear – Level II – $\beta = 4.0$ – L/D = 3.0

Shear Excluded		Shear NOT Excluded	
Method 1A	Method 2A	Method 1A	Method 2A
0.857	0.866	0.798	0.807

Table 5-53: Resistance Factors – Level I – $\beta = 4.0$ – L/D = 3.0

Tension 1A Shear 1A	Tension 1B Shear 1A	Tension 2A Shear 2A	Tension 2B Shear 2A
0.836	0.837	0.839	0.841

5.6 Recommendations/Conclusions

After the 1533 bolts were tested in tension and shear with the threads excluded and not excluded from the shear plane, some recommendations and conclusions were made. Section 5.2 studied the thread length. From Section 5.3.2 the comparisons showed that the bolts have consistent strength. The elongation of high-strength bolts was studied in Section 5.4. Finally, resistance factors were calculated and presented in Section 5.5 so a recommendation for a modified resistance factor could be made.

It was concluded in Section 5.2 that the average percent error in the thread length was less for the smaller bolts than for bolts larger than or equal to 1-inch in diameter. The thread length varied as much as being 1.34 percent shorter than AISC's manual and as much as 10.38 percent too long. The average error in the thread length was 4.82 percent with a 0.02513 standard deviation. The longer thread length could result in a shear bolt failing in the threads instead of the shank if the shear plane was designed too close to the nominal lengths

The 79 material data sheets obtained from the manufacturers were compared to the experimental tensile strength and were reported in Section 5.3.2.1. It was found that on average the experimental tensile strength was 99.8 percent of the strength reported by the manufacturer's material data sheets. The minimum and maximum values of the ratio of experimental tensile strength to the material data sheets were 0.961 and 1.051, respectively.

Section 5.3.2.2 compared the tensile strength of the four bolt grades to the minimum and maximum values specified in ASTM and RCSC. From the 515 high-strength bolts tested in direct tension, none of the bolts had a strength less then the specified ASTM minimum strength of 120 ksi[11] for A325 and F1852 bolts or 150 ksi for A490 and F2280 bolts. On average the tensile strength was 143.2 ksi and 148.7 ksi for A325 and F1852 bolts, respectively. For the A490 and F2280, bolts the average tensile strength was 163.7 ksi and 167.9 ksi, respectively. ASTM specifies a maximum tensile strength, for A490 and F2280 bolts, of 173 ksi whereas RCSC specifies this maximum as 170 ksi. About 10.8 percent of the A490 and F2280 bolts had a tensile strength greater than RCSC's specified maximum of 170 ksi whereas only about 1.1 percent of the A490 and F2280 bolts did not meet ASTM's maximum specified 173 ksi. When considering the average tensile strength of the lots tested, about 10.9 percent of the A490 and F2280 lots were above RCSC's maximum strength but no lots were above ASTM's 173 ksi maximum tensile strength.

The experimental bolt strength and the nominal strength according to AISC were compared in Section 5.3.2.3. A325 and F1852 bolts, on average, had a 22% greater tensile strength than AISC, a 20% greater tensile strength based on the effective area, an 18% greater shear strength with the threads excluded, and a 12% larger shear strength with the threads not excluded than the nominal strength specified by AISC with a standard deviation of 0.0575, 0.0587, 0.0603, and 0.0658, respectively. Similarly, A490 and F2280 bolts had a tensile strength 12% higher than AISC, a 10% higher tensile strength based on the effective area, a 6% greater shear strength with the threads excluded, and no increase in the shear strength with the threads not excluded when compared to the nominal AISC strength with a standard deviation of 0.0359, 0.0291, 0.0370, and 0.0486, respectively. Since none of the 515 bolts tested in direct tension had a tensile strength lower than the nominal strength calculated based on AISC's equation, it was concluded that AISC's equation accurately predicts the tensile strength of high-strength bolts. On average, however, the nominal strength based on the effective area better predicted the tensile failure load compared to AISC's approximation. It was also concluded that the AISC equation for the shear strength of bolts in shear with the threads excluded from the shear plane closely predicts the strength since only 3.9% of the 512 bolts tested in shear with the threads excluded had a strength below the AISC nominal strength. However, a number of the bolts tested in shear with the

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[11] According to ASTM A325 and F1852 the minimum stress is 105 ksi for bolts larger than 1-inch in diameter. AISC and RCSC do not account for this and use 120 ksi regardless of the bolt diameter.

threads not excluded from the shear plane had a strength below AISC's nominal value. Since about 32% of the 506 bolts tested in shear with the threads not excluded had strength lower than what prescribed in AISC's equation, it was concluded that AISC's equation for the shear strength with the threads not excluded is over predicting the strength.

The higher experimental tensile strength compared to the AISC nominal strength resulted in a higher resistance factor for bolts in tension, as was seen in Section 5.5. Likewise, due to the minimal increase in shear strength with the threads not excluded from the shear plane the resistance factor is not too much higher. However due to the low standard deviations it can be concluded that the bolts have consistent strength in tension and shear with the threads excluded and not excluded from the shear plane.

The tensile and shear strengths were compared in Section 5.3.2.4. From the one hundred lots, the average shear strength with the threads excluded from the shear plane was approximately 60% (with a standard deviation of 0.0149) of the average tensile strength which closely compares to the 62% that was reported in the "Guide to Design Criteria for Bolted and Riveted Joints" (Kulak et al. 2001). It was also determined that the average shear strength with the threads not excluded from the shear plane is roughly 76% (with a standard deviation of 0.0236) of the average shear strength with the threads excluded from the shear plane which is less than the 80% used by RCSC and AISC (reported as 83% by RCSC in 2004). The ratio of average shear strength with the threads not excluded to the average shear strength with the threads excluded is very close to the ratio of the effective area (area of the threads) to the shank area that AISC and RCSC approximate as 75%.

Section 5.4 evaluated the elongation of the 515 structural bolts tested in direct tension. The A490/F2280 high-strength bolts had a lower elongation compared to the A325/F1852 bolts. The average percent elongation for A490/F2280 bolts was 6.74% (with a 0.030 standard deviation) compared to 9.83% (0.042 standard deviation) for A325/F1852 high-strength bolts.

After evaluating the resistance factors, which were summarized in Section 5.5, it was found that the current resistance factor can be increased for bolts in tension, shear with the threads excluded, and shear with the threads not excluded from the shear plane without sacrificing safety, which will result in improved efficiency of bolted connections. A summary of the resistance factors from Section 5.5 are shown in Tables 5-54 through 5-56 based on Level III, Level II, and Level I calculations respectively for tension, shear with the threads excluded, and shear with the threads not excluded from the shear plane.

Table 5-54: Resistance Factors – Level III – Summary

		120 ksi (A325/F1852)				150 ksi (A490/F2280)			
		β = 4.0		β = 4.5		β = 4.0		β = 4.5	
		L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension	**Method 1A (0.75Ag)**	1.004	0.990	0.949	0.930	0.954	0.940	0.905	0.887
	Method 1B (A_{eff})	0.982	0.968	0.927	0.909	0.947	0.933	0.900	0.882
	Method 2A (0.75A_g)	0.988	0.974	0.932	0.913	0.946	0.932	0.897	0.879
	Method 2B (A_{eff})	0.978	0.964	0.923	0.904	0.939	0.926	0.892	0.874
Shear Excluded	**Method 1A**	0.964	0.950	0.910	0.892	0.897	0.884	0.851	0.834
	Method 2A	0.955	0.941	0.900	0.882	0.889	0.876	0.842	0.825
Shear NOT Excluded	**Method 1A**	0.911	0.898	0.859	0.842	0.829	0.817	0.785	0.769
	Method 2A	0.897	0.884	0.845	0.828	0.817	0.805	0.772	0.757

Table 5-55: Resistance Factors – Level II – Summary

		β = 4.0		β = 4.5	
		L/D = 1.0	**L/D = 3.0**	**L/D = 1.0**	**L/D = 3.0**
Tension	**Method 1A (0.75Ag)**	0.933	0.919	0.878	0.861
	Method 1B (A_{eff})	0.915	0.902	0.862	0.845
	Method 2A (0.75A_g)	0.923	0.910	0.868	0.851
	Method 2B (A_{eff})	0.912	0.899	0.859	0.842
Shear Excluded	**Method 1A**	0.870	0.857	0.817	0.800
	Method 2A	0.878	0.866	0.825	0.809
Shear NOT Excluded	**Method 1A**	0.810	0.798	0.759	0.744
	Method 2A	0.818	0.807	0.768	0.753

Table 5-56: Resistance Factors – Level I – Summary

	β = 4.0		β = 4.5	
	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension 1A **Shear 1A**	0.848	0.836	0.795	0.779
Tension 1B **Shear 1A**	0.849	0.837	0.796	0.780
Tension 2A **Shear 2A**	0.851	0.839	0.797	0.781
Tension 2B **Shear 2A**	0.853	0.841	0.800	0.784

As can be seen from Tables 5-54 and 5-55, the resistance factors for tension, shear with the threads excluded, and shear with the threads not excluded vary substantially. Therefore it is recommended that a different resistance factor be used for the three types of bolt failures instead of Level I calculations from Table 5-56. The resistance factors calculated for A325/F1852 high-strength bolts are higher compared to the resistance factors calculated for A490/F2280 bolts, as can be seen from Table 5-54. The resistance factors based on all grades of high-strength bolts (Table 5-55) will be considered due to the added complexity with different resistance factors based on grade as well as failure modes.

From Table 5-55 with a live-to-dead load ratio of one, the minimum resistance factors for tension with a reliability index, β, equal to 4.0 and 4.5 are 0.912 and 0.859, respectively. For bolts in tension, minimum resistance factors of 0.899 and 0.842 were calculated for a reliability index, β, equal to 4.0 and 4.5 with a live-to-dead load ratio of 3.0, respectively, from Table 5-55. These minimum values are based on Method 2B, which is from equation (2-9) assuming the threaded area equals an effective area calculated from the average mean root and pitch diameters. Since AISC does not use this effective area but uses an approximation of 75% of the shank cross-sectional area, the resistance factor based on Method 2A shall be considered. From Table 5-55, for tension, based on Method 2A, the resistance factors based on a reliability index of 4.0 and 4.5

are 0.923 and 0.868 for a live-to-dead load ratio of 1.0 and 0.910 and 0.851 for a live-to-dead load ratio of 3.0, respectively.

Minimum resistance factors of 0.870 and 0.817 were calculated for bolts in shear with the threads excluded from the shear plane with a live-to-dead load ratio of 1.0 and a reliability index, β, equal to 4.0 and 4.5, respectively, from Table 5-55. Based on a live-to-dead load ratio of 3.0, the minimum resistance factors for bolts in shear with the threads excluded from the shear plane are 0.857 and 0.800 for a reliability index, β, equal to 4.0 and 4.5. These values were calculated from equation (2-8), which uses Method 1. Equation (2-9), Method 2, is the more recent equation for calculating resistance factors thus the values from Method 2A shall be considered. The resistance factors for shear with the threads excluded from the shear plane, based on Method 2A, are 0.878 and 0.825 with a live-to-dead load ratio of 1.0 and 0.866 and 0.809 for a live-to-dead load ratio of 3.0 with a reliability index of 4.0 and 4.5, respectively.

Similarly, for bolts in shear with the threads not excluded from the shear plane with a reliability index, β, equal to 4.0 and 4.5, the minimum resistance factors from Table 5-55 are 0.810 and 0.759, respectively, with a live-to-dead load ratio of 1.0. For a live-to-dead load ratio of 3.0, the minimum resistance factors for shear with the threads not excluded from the shear plane are 0.798 and 0.744 for a reliability index, β, equal to 4.0 and 4.5, respectively. Like the resistance factors for shear with the threads excluded from the shear plane these minimum values are based on Method 1A from equation (2-8). Method 2A shall be considered since equation (2-9) for Method 2 is a more recent resistance factor equation. Based on Method 2A for shear with the threads not excluded from the shear plane with a reliability index, β, equal to 4.0 and 4.5 the resistance factors are 0.818 and 0.768 with a live-to-dead load ratio of 1.0 and 0.807 and 0.753 with a live-to-dead load ratio of 3.0, respectively.

The current AISC Specification's Commentary (2005) incorporates a reliability index of 4.0 and a live-to-dead load ratio of 3.0; therefore the recommendations will be based on this. Keeping the reliability index as a factor of five thousandths, the following recommendations are made. A resistance factor of 0.90, 0.85, and 0.80 are recommended for bolts in tension, shear with the threads excluded from the shear plane and shear with the threads not excluded from the shear plane, respectively.

It was observed that the AISC equation for the shear strength with the threads not excluded from the shear plane does not accurately predict the strength based on the bolts tested for this research, which is why the recommended resistance factor is lower compared to tension. Using the ratios found in Section 5.3.2.4, equations (2-5) and (2-6), the nominal resistance for one bolt with the threads not excluded and excluded from the shear plane based on AISC, respectively, are revised. It was found from the bolts tested that the shear strength of a single high-strength bolt with the threads excluded from the shear plane was approximately 60% of the tensile strength regardless of the bolt grade. Therefore based on this ratio, determined experimentally from the one hundred lots tested, the nominal shear strength for a single bolt with the threads excluded from the shear plane, equation (2-6), should become

$$R_n = 0.60 F_u A_b \tag{5-5}$$

Regardless of the bolt grade, the shear strength with the threads not excluded from the shear plane was found to be approximately 76% of the average shear strength with the threads excluded from the shear plane for a single structural bolt, based on the bolts tested. Thus modifying equation (2-5) to reflect the two new ratios found from the one hundred lots tested, the nominal shear strength for a single high-strength bolt with the threads not excluded from the shear plane would be given by

$$R_n = 0.76\left(0.6 F_u A_b\right) = 0.456 F_u A_b \approx 0.46 F_u A_b \tag{5-6}$$

Resistance factors were also evaluated using the modified equations for the shear strength, equations (5-5) and (5-6). Tables 5-57 through 5-59 summarize these resistance factors based on Level III, Level II, and Level I calculations, respectively. The tension resistance factors did not change but are still shown in Tables 5-57 and 5-58 for completeness.

Table 5-57: Resistance Factors Based on Experimental Ratios – Level III – Summary

		120 ksi (A325/F1852)				150 ksi (A490/F2280)			
		β = 4.0		β = 4.5		β = 4.0		β = 4.5	
		L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension	**Method 1A (0.75Ag)**	1.004	0.990	0.949	0.930	0.954	0.940	0.905	0.887
	Method 1B (A_{eff})	0.982	0.968	0.927	0.909	0.947	0.933	0.900	0.882
	Method 2A (0.75A_g)	0.988	0.974	0.932	0.913	0.946	0.932	0.897	0.879
	Method 2B (A_{eff})	0.978	0.964	0.923	0.904	0.939	0.926	0.892	0.874
Shear Excluded	**Method 1A**	0.996	0.982	0.940	0.922	0.927	0.914	0.880	0.862
	Method 2A	0.987	0.973	0.930	0.912	0.918	0.905	0.870	0.853
Shear NOT Excluded	**Method 1A**	0.990	0.976	0.934	0.915	0.901	0.888	0.853	0.836
	Method 2A	0.975	0.961	0.918	0.900	0.888	0.875	0.839	0.822

Table 5-58: Resistance Factors Based on Experimental Ratios – Level II – Summary

		β = 4.0		β = 4.5	
		L/D = 1.0	L/D = 3.0	L/D = 1.0	L/D = 3.0
Tension	**Method 1A (0.75Ag)**	0.933	0.919	0.878	0.861
	Method 1B (A_{eff})	0.915	0.902	0.862	0.845
	Method 2A (0.75A_g)	0.923	0.910	0.868	0.851
	Method 2B (A_{eff})	0.912	0.899	0.859	0.842
Shear Excluded	**Method 1A**	0.899	0.886	0.844	0.827
	Method 2A	0.907	0.894	0.853	0.836
Shear NOT Excluded	**Method 1A**	0.880	0.868	0.825	0.809
	Method 2A	0.890	0.877	0.835	0.818

Table 5-59: Resistance Factors Based on Experimental Ratios – Level I – Summary

	β = 4.0		β = 4.5	
	L/D = 1.0	**L/D = 3.0**	**L/D = 1.0**	**L/D = 3.0**
Tension 1A **Shear 1A**	0.903	0.890	0.848	0.831
Tension 1B **Shear 1A**	0.897	0.885	0.843	0.826
Tension 2A **Shear 2A**	0.906	0.893	0.851	0.835
Tension 2B **Shear 2A**	0.903	0.890	0.849	0.832

Using Level II resistance factors, Table 5-58, based on Method 2A, the resistance factors for shear with the threads excluded from the shear plane are 0.907 and 0.853 with a live-to-dead load ratio of 1.0 and 0.894 and 0.836 for a live-to-dead load ratio of 3.0, with a reliability index of 4.0 and 4.5, respectively. Similarly, the resistance factors are 0.890 and 0.835 with a live-to-dead load ratio of 1.0 and 0.877 and 0.818 with a live-to-dead load ratio of 3.0, with a reliability index, β, equal to 4.0 and 4.5, respectively, for shear with the threads not excluded from the shear plane based on Method 2A.

To better show the impact the modified shear resistance equations have on the resistance factors, Table 5-60 and 5-61 tabulate the resistance factors from Tables 5-55 and 5-56, based on the AISC equations, and Tables 5-58 and 5-59, based on the modified shear equations.

Table 5-60: Comparing Resistance Factors – Level II

		β = 4.0				β = 4.5			
		L/D = 1.0		L/D = 3.0		L/D = 1.0		L/D = 3.0	
		AISC	Modified	AISC	Modified	AISC	Modified	AISC	Modified
Tension	**Method 1A (0.75Ag)**	0.933		0.919		0.878		0.861	
	Method 1B (A_{eff})	0.915		0.902		0.862		0.845	
	Method 2A (0.75A_g)	0.923		0.910		0.868		0.851	
	Method 2B (A_{eff})	0.912		0.899		0.859		0.842	
Shear Excluded	**Method 1A**	0.870	0.899	0.857	0.886	0.817	0.844	0.800	0.827
	Method 2A	0.878	0.907	0.866	0.894	0.825	0.853	0.809	0.836
Shear NOT Excluded	**Method 1A**	0.810	0.880	0.798	0.868	0.759	0.825	0.744	0.809
	Method 2A	0.818	0.890	0.807	0.877	0.768	0.835	0.753	0.818

Table 5-61: Comparing Resistance Factors– Level I

	β = 4.0				β = 4.5			
	L/D = 1.0		L/D = 3.0		L/D = 1.0		L/D = 3.0	
	AISC	Modified	AISC	Modified	AISC	Modified	AISC	Modified
Tension 1A Shear 1A	0.848	0.903	0.836	0.890	0.795	0.848	0.779	0.831
Tension 1B Shear 1A	0.849	0.897	0.837	0.885	0.796	0.843	0.780	0.826
Tension 2A Shear 2A	0.851	0.906	0.839	0.893	0.797	0.851	0.781	0.835
Tension 2B Shear 2A	0.853	0.903	0.841	0.890	0.800	0.849	0.784	0.832

As can be seen from Tables 5-60 and 5-61, the resistance factors for shear with the threads excluded and not excluded from the shear plane increased with the modified nominal shear equations. If the nominal shear equations are modified in AISC to reflect the ratios obtained from the one hundred lots tested in this research, resistance factors of 0.90 and 0.85 are recommended for bolts in tension and shear with both the threads excluded and not excluded from the shear plane, respectively, based on a reliability index equal to 4.0 and a live-to-dead load ratio of 3.0.

CHAPTER 6

CONCLUSIONS

The main objective of this research was to evaluate the current resistance factor for high-strength bolts in direct tension, shear with the threads excluded and not excluded from the shear plane. The current resistance factor of 0.75, in AISC (2005), for the tensile and shear strength of structural bolts is believed to be somewhat conservative. Therefore an evaluation was performed.

A complete literature review was carried out. From journal articles, reports, MS theses, and PhD dissertations, more than 668 high-strength bolts were tested in direct tension, forty-four were tested in shear with the threads excluded from the shear plane, and eight were reported as being tested in shear with the threads not excluded from the shear plane. Resistance factors were calculated based on the test results reported. Most of the bolts tested in direct tension were specified to ASTM's minimum strength. Due to the lack of high-strength bolts tested in shear and the minimum ASTM strength being specified, 1533 high-strength bolts were tested as part of this research.

Five hundred and fifteen bolts were tested in direct tension, 512 bolts were tested in shear with the threads excluded and 506 bolts were tested in shear with the threads not excluded from the shear plane, for a total of 1533 high-strength bolts. Results of the bolts tested were evaluated and some conclusions were made. Resistance factors were calculated for the tensile and shear strength based on the data obtained from testing. Along with the resistance factors, the stiffness and elongation at failure of the fasteners was studied.

Section 6.1 draws conclusions on the results of the 1533 bolts tested. Section 6.2 summarizes the resistance factors based on the bolts reported in literature and the 1533 bolts tested as part of this research. Design recommendations based on the research can be found in Section 6.3. Lastly, Section 6.4 discusses a few items to consider for future research.

6.1 Results of 1533 High-Strength Bolts Tested

Several conclusions were drawn from the high-strength bolts tested in direct tension and shear, along with some other investigations, such as bolt thread length and elongation at failure.

- The thread length of one bolt per lot was measured and compared to the AISC Manual (2005) values, due to the tolerances allowed on the thread length when manufacturing high-strength bolts. For the 5/8-inch, 3/4-inch, and 7/8-inch bolts (all grades) the average percent error in the thread length compared to AISC were less than five percent, though the percent error increased as the bolt diameter increased. The maximum percent error on the thread length was 10.38% and the average was 4.82%. This error in the thread length could result in some problems if the engineer designed the shear plane too close to the nominal thread length.
- The tensile strength compared to the 79 material data sheets were on average approximately equal. On average the ratio of experimental tensile strength to the material data sheets was 99.8%.
- The minimum tensile strength according to ASTM for A325 and F1852 high-strength bolts larger than 1-inch in diameter is 105 ksi. AISC and RCSC use 120 ksi regardless of the bolt diameter. It was concluded after testing 237 A325 and F1852 bolts in tension that the tensile strength for the bolts larger than 1-inch in diameter was always greater than 120 ksi.

Sections 6.1.1 and 6.1.2 summarize the results of the 120 ksi (A325 and F1852) and 150 ksi (A490 and F2280) strength bolts tested in tension, respectively. The high-strength bolts tested in shear with the threads excluded and not excluded from the shear plane are discussed in Sections 6.1.3 and 6.1.4, respectively. The strengths are compared in Section 6.1.5. Lastly, Section 6.1.6 discusses the elongation at failure.

6.1.1 A325 and F1852 Bolts in Tension

- The tensile strength of the A325 and F1852 bolts was never below the ASTM minimum strength of 120 ksi, regardless of the bolt diameter.

- On average, the 237 A325 and F1852 bolts had a tensile strength of 143.9 ksi with a standard deviation of 7.05 ksi. The tensile strength of the A325 and F1852 bolts ranged between 121.6 ksi and 156.3 ksi.
- The 237 A325 and F1852 bolts had a 22% greater tensile failure load than the nominal AISC tensile load with a standard deviation of 0.0575. The ratio of the experimental failure load to the AISC failure load ranged from 1.067 to 1.332 for A325 and F1852 bolts. This means that the experimental tensile loads varied from 6.7% to 33.2% greater than the AISC predicted failure load.
- The experimental tensile load was also compared to the nominal tensile load based on the effective area. It was found that on average the 237 A325 and F1852 bolts had a 20% greater tensile strength with a standard deviation of 0.0587. The ratio of the experimental failure load to the nominal failure load based on the effective area for the A325 and F1852 bolts ranged from 1.013 to 1.302. This means that the failure loads for the A325 and F1852 bolts varied from 1.3% to 30.2% greater than the nominal strength based on the effective area.
- On average, the nominal failure load calculated using the effective area predicted the failure load better than AISC's equation based on an approximation of the thread area.
- Even though there is no maximum bolt tensile strength for A325 and F1852 bolts, about 15.6% (37 out of 237) of the A325 and F1852 bolts had a tensile strength greater than 150 ksi.
- The average tensile strength of the 45 A325 and F1852 lots was 143.9 ksi with a standard deviation of 7.05 ksi. For the lots of A325 and F1852 bolts, the average tensile strength ranged from 124.2 ksi to 154.1 ksi.
- Seven out of the 45 lots of A325 and F1852 (about 15.6%) had an average tensile strength greater than 150 ksi, even though there is no maximum bolt tensile strength specified in ASTM.

6.1.2 A490 and F2280 Bolts in Tension

- The 278 A490 and F2280 bolts never showed a tensile strength below the specified ASTM minimum of 150 ksi.

- The tensile strength on average for the 278 A490 and F2280 bolts tested was 164.5 ksi with a standard deviation of 4.37 ksi. The tensile strength of the 278 A490 and F2280 bolts tested ranged from 152.1 ksi to 179.8 ksi.
- Thirty out of 278 (10.8%) A490 and F2280 bolts tested had a tensile strength greater than the maximum specified by RCSC of 170 ksi.
- Three of the 278 (1.08%) A490 and F2280 bolts' tensile strength exceeded ASTM's maximum tensile strength of 173 ksi.
- The 278 A490 and F2280 bolts tested in direct tension had a failure load on average 12% greater than the predicted failure load given by AISC with a standard deviation of 0.0359. When comparing the experimental failure loads to the nominal AISC failure load the ratio was between 1.023 and 1.227. This means that the experimental load was never less than 2.3 percent greater than AISC. For the A490 and F2280 bolts, the maximum experimental load was 22.7% larger than AISC.
- The 278 A490 and F2280 bolts on average had a 10% greater tensile failure load than the nominal tensile load based on the effective area with a standard deviation of 0.0291. The ratio of the experimental failure load to the failure load based on the effective area ranged from 1.014 to 1.199 for the 278 A490 and F2280 bolts. This means that the experimental tensile loads varied from 1.4% to 19.9% greater than the predicted failure load based on the effective area.
- The failure load calculated based on the effective area better predicted the failing tensile load for the A490 and F2280 bolts.
- From the 55 A490 and F2280 lots tested the average tensile strength was 164.5 ksi with a standard deviation of 4.09 ksi. The average tensile strength ranged from 155.3 ksi to 171.2 ksi for the A490 and F2280 lots of bolts.
- The average tensile strength of 6 out of 55 (10.9%) lots of A490 and F2280 bolts was greater than RCSC's maximum strength of 170 ksi.
- No A490 or F2280 lots had an average tensile strength greater than ASTM's maximum strength of 173 ksi.

6.1.3 Bolts in Shear with the Threads Excluded

- The 233 A325 and F1852 bolts tested in shear with the threads excluded from the shear plane, on average, had a failure load 18% greater than the AISC shear load. The ratio of experimental failure load to nominal AISC ranged between 1.01 and 1.294. This means that the minimum experimental failure load was 1% greater and the maximum was 29% greater than AISC's nominal failure load.
- On average, a 6% greater failure load was encountered in the 279 A490 and F2280 bolts tested in shear with the threads excluded from the shear plane compared to AISC. From the A490 and F2280 bolts tested, the minimum failure load in shear with the threads excluded from the shear plane was 7.7% lower than AISC and the maximum was 15% greater than AISC.
- Of the 512 bolts tested in shear with the threads excluded from the shear plane, 20 bolts had an experimental failure load smaller than the value predicted by AISC. These 20 bolts were comprised of 3/4-inch, 7/8-inch, 1-inch, 1-1/8-inches and 1-1/4-inches A490 bolts. Meaning of the 512 bolts tested in shear with the threads excluded from the shear plane, approximately 3.9% of the bolts had a failure load smaller than the nominal AISC value. Or from the 228 A490 bolts tested about 8.77% were below the nominal AISC failure load.
- It was concluded, based on the 512 bolts tested in shear with the threads excluded, that the AISC equation closely predicts the shear strength with the threads excluded from the shear plane.

6.1.4 Bolts in Shear with the Threads Not Excluded

- The 228 A325 and F1852 bolts tested in shear with the threads not excluded from the shear plane had an average 12% greater failure load than AISC. The minimum failure load in shear with the threads not excluded from the shear plane was 4.3% lower than AISC and the maximum was 31.6% higher.
- On average, the shear strength with the threads not excluded from the shear plane for the 278 A490 and F2280 bolts was approximately equal to the AISC predicted failure load. The ratio

of the experimental failure load to the nominal AISC load ranged from 0.841 to 1.166. This indicates that the experimental failure load of the bolts tested was approximately 16% lower than AISC's nominal load at a minimum and was approximately 17% higher as a maximum.

- From the 506 bolts tested in shear with the threads not excluded from the shear plane, 162 bolts, approximately 32%, were below the AISC nominal failure load. Of the 203 A325 bolts tested, 7 bolts, or 3.45%, had an experimental failure load below AISC. In terms of 120 ksi strength bolts 3.1% of the 228 A325 and F1852 bolts were below AISC's nominal failure load. Approximately 58% of the A490 bolts (132 out of 228) had a failure load below AISC's nominal failure load in shear with threads not excluded from the shear plane. Of the 50 F2280 bolts tested, 23 bolts, or 46%, had a lower failure load than AISC. Therefore, of the 278 A490 and F2280 bolts tested in shear with the threads not excluded from the shear plane, 55.8% had a failure load less than what predicted by AISC.
- It was concluded that AISC's equation is over predicting the shear strength of bolts with the threads not excluded from the shear plane since more than 30% of the 506 bolts tested had a lower strength.

6.1.5 Strengths Comparison

- Based on the 100 lots tested, the shear strength with the threads excluded from the shear plane was on average 60.4% of the tensile strength, regardless of the bolt grade, with a standard deviation of 0.0149.
- The average shear strength with the threads not excluded from the shear plane was about 76.2% of the average shear strength with the threads excluded from the shear plane regardless of the bolt grade with a standard deviation of 0.0236, based on the 100 lots tested.
- It was observed that the ratio of the shear strength with the threads not excluded to excluded was close to the ratio of the effective area (area of the threads) to the shank area, that AISC and RCSC approximates as 75%.

6.1.6 Elongation at Failure

- On average, the A325 and F1852 bolts elongated 9.83% with a standard deviation of 0.0424. The minimum and maximum percent elongation for the A325 and F1852 high-strength bolts were 0.58% and 21.98%, respectively.
- The A490 and F2280 bolts on average elongated 6.74% with a standard deviation of 0.030. The percent elongation for the A490 and F2280 bolts ranged from 0.35% to 15.76%, respectively.

6.2 Resistance Factors

Resistance factors were calculated based on literature data and on the 100 lots tested. Section 6.2.1 summarizes the calculated resistance factors, based on the bolt data reported in literature, which were previously summarized in Chapter 3. The resistance factors calculated from the 100 lots tested are summarized in Section 6.2.2. Lastly, Section 6.2.3 summarizes the resistance factors calculated with the modified shear resistance equations using the experimental ratios based on the 100 lots tested.

6.2.1 Based on Literature

It should be noted that the resistance factors calculated from literature and summarized here are based on Method 1, since assumptions needed to be made for Method 2 calculations for tension resistance factors and could not be performed for shear resistance factors.

- From the 668 bolts tested in direct tension, which were published in literature, the resistance factors based on Level II calculations (regardless of the bolt diameter or grade) using the AISC nominal tensile strength (Method 1A) are equal to 0.790 and 0.843 with a live-to-dead load ratio of 1.0 and equal to 0.774 and 0.831 with a live-to-dead load ratio of 3.0, for a reliability index, β, equal to 4.5 and 4.0, respectively. A majority of the bolts tested in direct tension, which were published in literature, occurred during the 1960s and were specified to have ASTM's minimum tensile strength.
- The resistance factors for the shear strength with the threads excluded from the shear plane for the 44 bolts published in literature based on Level II calculations (for all bolt diameters

and grades) and Method 1A equals 0.822 and 0.874 with a live-to-dead load ratio of 1.0 and equals 0.806 and 0.861 with a live-to-dead load ratio of 3.0, for a reliability index, β, equal to 4.5 and 4.0, respectively. Due to the small number of bolts tested, the resistance factors calculated may not be statistically valid.

- Based on Method 1A and Level II calculations (regardless of the bolt diameter and grade), the resistance factors from the 8 bolts published in literature for shear with the threads not excluded from the shear plane are 0.775 and 0.826 with a live-to-dead load ratio of 1.0 and are 0.760 and 0.814 with a live-to-dead load ratio of 3.0, for a reliability index, β, equal to 4.5 and 4.0, respectively. These resistance factors may not be statistically valid since they are just based on 8 bolts tested in shear with the threads not excluded from the shear plane.
- Based on Level I (regardless of the bolt diameter, grade, and failure mode) and Method 1A for both tension and shear, the resistance factors are 0.794 and 0.847 for a live-to-dead load ratio of 1.0 and are 0.778 and 0.835 for a live-to-dead load ratio of 3.0, with a reliability index, β, equal to 4.5 and 4.0, respectively.
- It was recommended by Fisher et al. (1978) that a resistance factor of 0.80 should be used for high-strength bolts in tension and shear.

6.2.2 Based on One Hundred Lots Tested

Resistance factors were calculated from the 100 lots tested. The resistance factors presented here are based on Method 2A. Method 2 was used since it takes into account the geometry, material, and professional factors. The AISC equation used to predict the tensile load was used in Model A.

- Different resistance factors for each of the three bolt failure modes are recommended due to the varying values of resistance factors between tension, shear with the threads excluded, and shear with the threads not excluded.
- Based on Level II calculations the resistance factors for tension are 0.923 and 0.868 with a live-to-dead load ratio equal to 1.0 and are 0.910 and 0.851 with a live-to-dead load ratio of 3.0, for a reliability index, β, of 4.0 and 4.5, respectively.

- The resistance factors for shear with the threads excluded from the shear plane equal 0.878 and 0.825 with a live-to-dead load ratio equal to 1.0 and equal 0.866 and 0.809 with a live-to-dead load ratio equal to 3.0, for a reliability index, β, of 4.0 and 4.5, respectively, based on Level II (regardless of the bolt diameter and grade) calculations.
- With a reliability index, β, equal to 4.0 and 4.5, the resistance factors for shear with the threads not excluded from the shear plane based on Level II calculations are 0.818 and 0.768 with a live-to-dead load ratio equal to 1.0 and are 0.807 and 0.753 with a live-to-dead load ratio equal to 3.0, respectively.
- Even though it is not herein recommended, the resistance factors based on all bolt diameters, grades, and failure types (Level I) can be calculated as 0.851 and 0.797 with a live-to-dead load ratio of 1.0 and as 0.839 and 0.781 with a live-to-dead load ratio of 3.0, for a reliability index, β, equal to 4.0 and 4.5, respectively based on Method 2A for both tension and shear.

6.2.3 Based on Experimental Ratios and One Hundred Lots Tested

Resistance factors were also calculated using the modified shear strength equations which were based on the experimental ratios found from the one lots tested. The resistance factors for tension are the same as was previously summarized in Section 6.2.2. The shear resistance factors summarized here are based on Method 2A calculations, which take into account the geometry, material, and professional factors.

- With a reliability index, β, of 4.0 and 4.5, the resistance factors for shear with the threads excluded from the shear plane using the modified ratios equal 0.907 and 0.853 with a live-to-dead load ratio one of 1.0 and equal 0.894 and 0.836 with a live-to-dead load ratio thereof 3.0, respectively, based on Level II (regardless of the bolt diameter and grade) calculations.
- The resistance factors for shear with the threads not excluded from the shear plane, using the modified ratios, based on Level II calculations are 0.890 and 0.835 with a live-to-dead load ratio equal to 1.0 and are 0.877 and 0.818 with a live-to-dead load ratio equal to 3.0, with a reliability index, β, equal to 4.0 and 4.5 respectively.
- Even though it is not herein recommended, the resistance factors, for a reliability index, β, equal to 4.0 and 4.5, based on all bolt diameters, grades, and failure types (Level I) can be

calculated as 0.906 and 0.851 with a live-to-dead load ratio of 1.0 and as 0.893 and 0.835 with a live-to-dead load ratio of t3.0, respectively, based on Method 2A for tension and the modified shear strengths.

6.3 Design Recommendations

Based on the resistance factors calculated from the bolts tested and published in literature and from the 100 lots tested as part of this research it was found that the current resistance factor can be increased without sacrificing safety, which would result in an improved efficiency of bolted connections making them more favorable than welded connections in some cases. With a reliability index of 4.0 and a live-to-dead load ratio of 3.0, as incorporated in AISC Specification's Commentary (2005), resistance factors of 0.90, 0.85, and 0.80 are recommended for bolts in tension, shear with the threads excluded, and shear with the threads not excluded from the shear plane, respectively. The larger resistance factor for tension is due to the experimental loads being higher than the nominal failure loads predicted by AISC. On the other hand, the lower resistance factor for shear with the threads not excluded from the shear plane is a result of the nominal failure load due to AISC over predicting the failure load compared to the experimental tests. AISC takes the shear strength with the threads not excluded from the shear plane as 80% of the shear strength with the threads excluded from the shear plane. However, based on the 100 lots tested, the shear strength with the threads not excluded from the shear plane was approximately 76% of the shear strength with the threads excluded from the shear plane. An increase in the current resistance factor can still be recommended, since the reliability index, β, is now taken as 4.0 in the new Specification compared to 4.5 and the low standard deviations imply that the bolts have consistent strength resulting in a higher resistance factor.

If the ratios of the shear strength with the threads excluded to the tensile strength and the shear strength with the threads not excluded to excluded, obtained during this research from the 100 lots tested, are incorporated into the AISC equations for the nominal shear strength, higher resistance factors are recommended. Based on a reliability index of 4.0 and a live-to-dead load ratio of 3.0, it is recommended to have a resistance factor equal to 0.90 for tension and to 0.85 for shear (both with the threads excluded and not excluded from the shear plane).

6.4 Future Research

After testing 100 lots of high-strength bolts in direct tension and shear with the threads excluded and not excluded from the shear plane, a few items arose that deserve additional research.

- A value of stiffness and ductility can be determined based on the tension data. An equation to predict both stiffness and ductility of high-strength bolts would be very useful.
- The tension tests were conducted with four threads exposed. Ductility of high-strength bolts depends on the number of threads included in the grip length. More direct tension tests should be performed varying the number of threads in the grip length to evaluate its effect on ductility.
- An equation predicting the displacement of bolts in shear would also be valuable.
- Since about half of the shear bolts with the threads excluded from the shear plane had a failure load below AISC’s nominal load, a revised equation to better predict the failure load is necessary which would also increase the resistance factor to levels closer to those of shear with the threads excluded.
- Due to the recommended increase for the resistance factor in AISC, an evaluation of the resistance factors in AASHTO is also recommended.
- A periodic statistical analysis (e.g., with a 10-year period) of the properties of the fasteners currently being produced is recommended, because new production methods and other factors may impact the quality of materials favorably or adversely, and therefore directly impact the resistance factors.

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APPENDIX A

EXPERIMENTAL DATA OF ONE HUNDRED LOTS TESTED

Appendix A contains the failure loads in tension, shear with the threads excluded, and shear with the threads not excluded. It also specifies the elongation for each tension bolt tested. Lastly, Appendix A contains a Load versus Elongation plot for the bolts tested in tension and a Load versus Displacement plot for the bolts tested in shear with the threads excluded and not excluded from the shear

C1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 4.5"
Grade:	A325
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2960 inches

Table A-1: Lot C1 – 5/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6194	31,437	11.23%	0.6187	26,722	0.6191	20,450
2	0.6195	31,632	8.49%	0.6188	25,558	0.6192	21,374
3	0.6189	31,221	10.61%	0.6189	26,141	0.6193	21,716
4	0.6194	31,120	12.15%	0.6188	26,292	0.6191	21,699
5	0.6194	31,304	11.92%	0.6189	25,963	0.6190	22,142

Note: The lever arm of the third LVDT was resting on the angle.

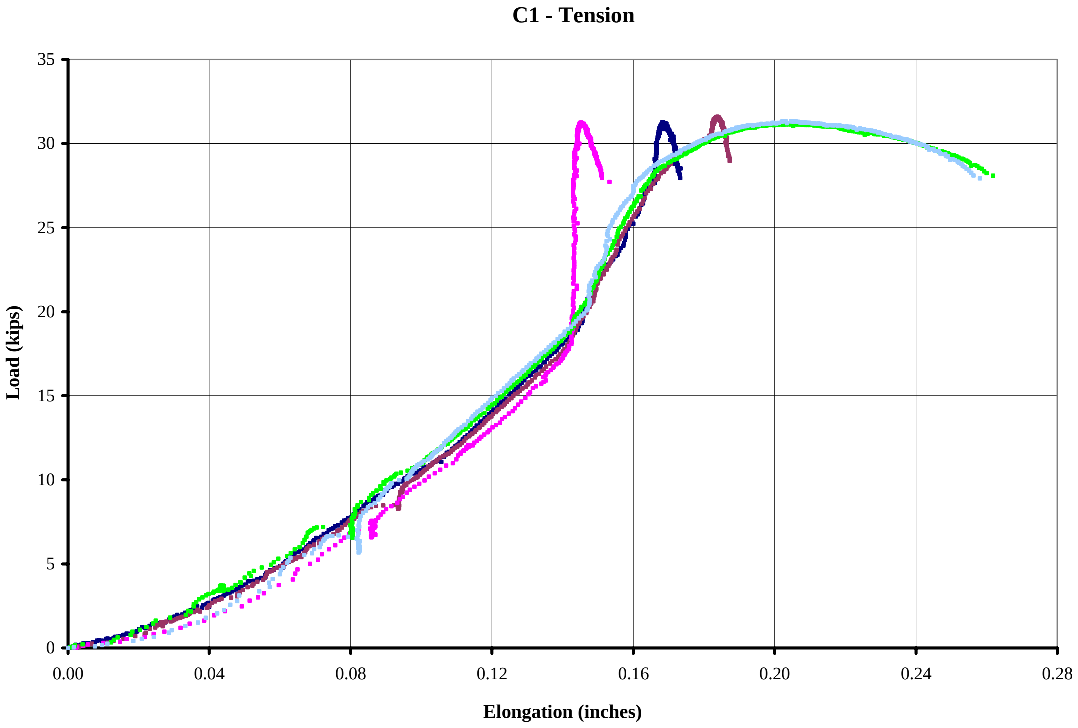

Figure A-1: Lot C1 – 5/8-inch A325 – Tension

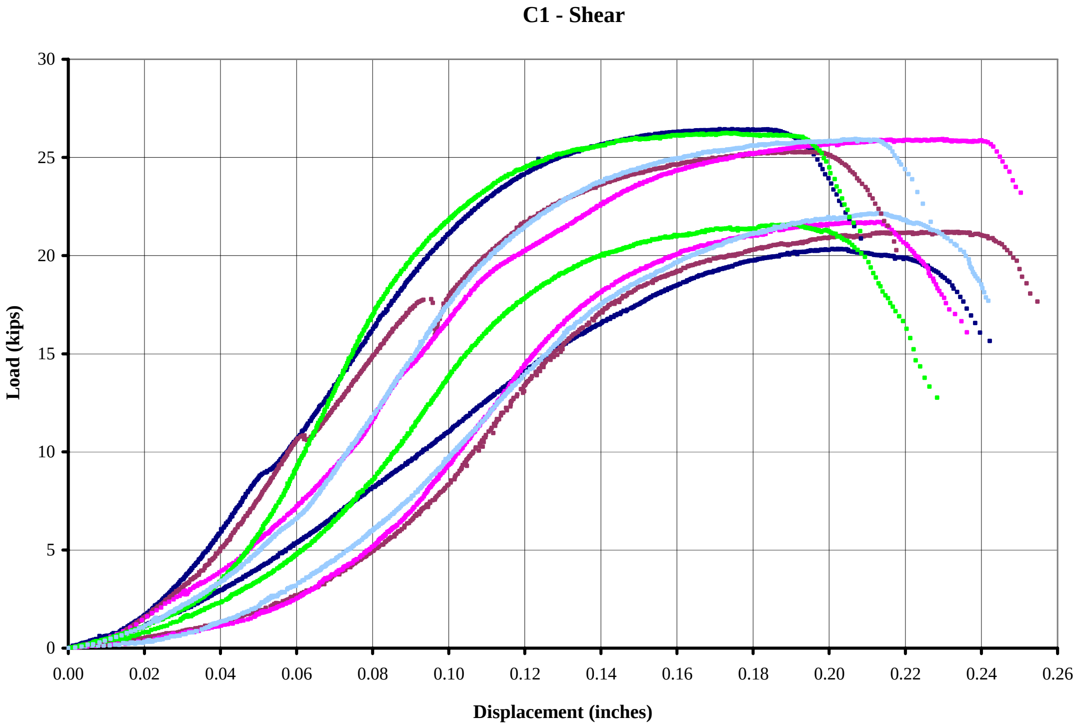

Figure A-2: Lot C1 – 5/8-inch A325 – Shear

L1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 2.75"
Grade:	A325
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.3010 inches

Table A-2: Lot L1 – 5/8-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.4125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6215	31,477	11.45%	0.6212	26,570	0.6206	18,255
2	0.6215	31,808	12.53%	0.6212	26,441	0.6211	18,754
3	0.6216	31,952	13.84%	0.6204	26,372	0.6215	19,773
4	0.6215	31,754	8.84%	0.6212	26,555	0.6207	19,225
5	0.6205	31,639	13.30%	0.6210	26,470	0.6206	18,543

Note: The lever arm of the third LVDT was resting on the bolt head.

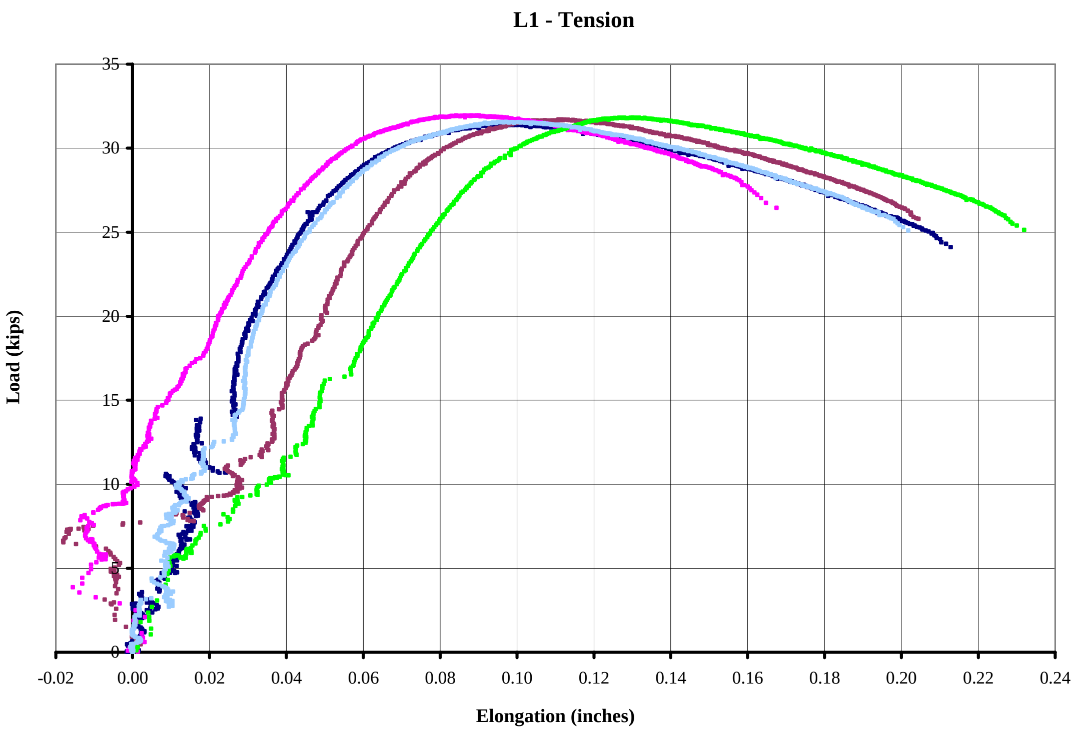

Figure A-3: Lot L1 – 5/8-inch A325 – Tension

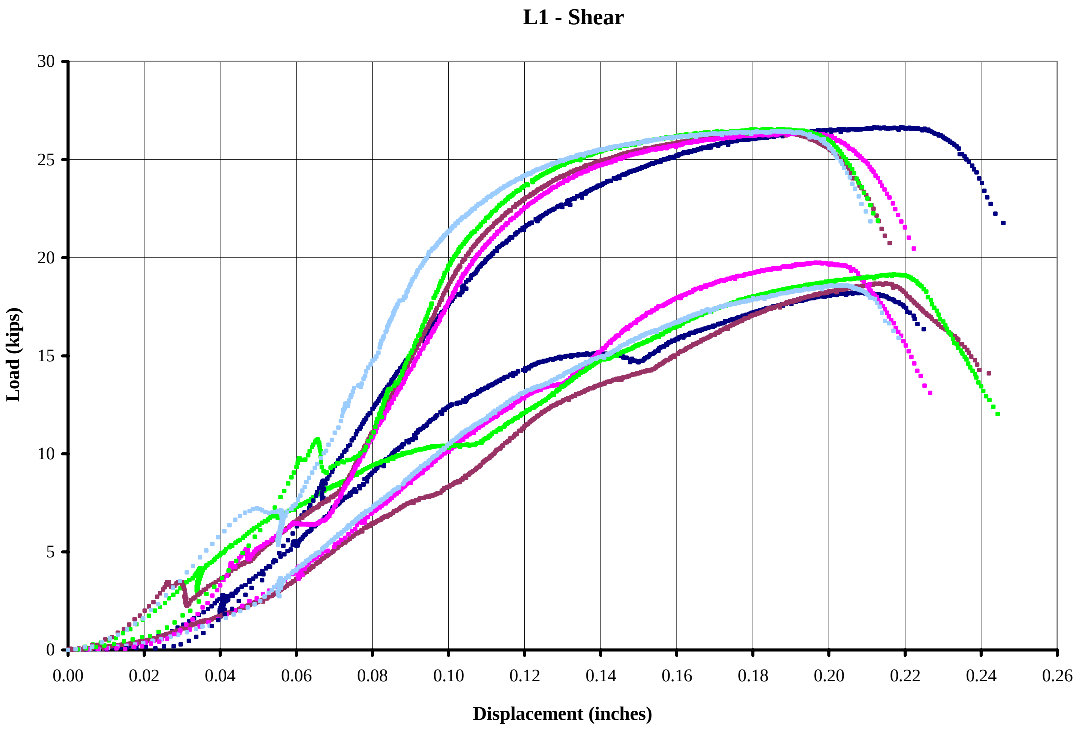

Figure A-4: Lot L1 – 5/8-inch A325 – Shear

N1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3.5"
Grade:	A325
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2625 inches

Table A-3: Lot N1 – 5/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.525 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6204	32,306	11.25%	0.6212	25,982	0.6204	20,861
2	0.6196	31,686	8.48%	0.6207	26,219	0.6205	20,395
3	0.6198	31,538	6.97%	0.6205	26,610	0.6211	20,608
4	0.6208	31,556	10.46%	0.6205	26,251	0.6205	20,593
5	0.6206	31,805	11.17%	0.6208	26,012	0.6209	20,238

Note: The lever arm of the third LVDT was resting on the bolt head.

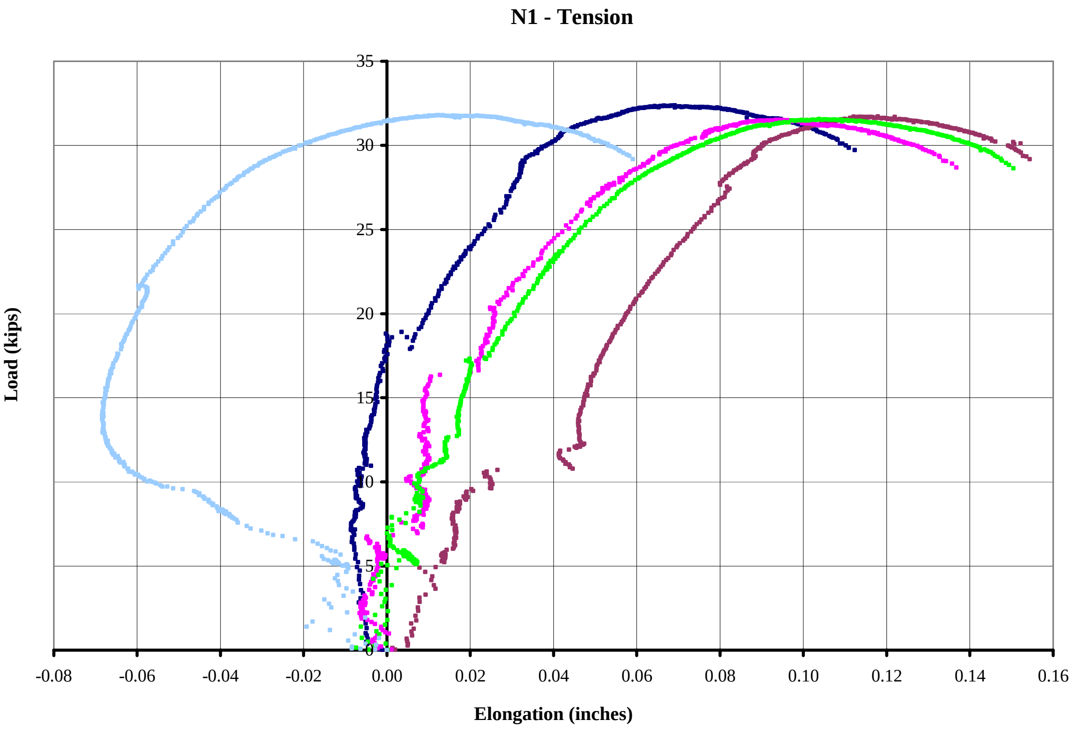

Figure A-5: Lot N1 – 5/8-inch A325 – Tension

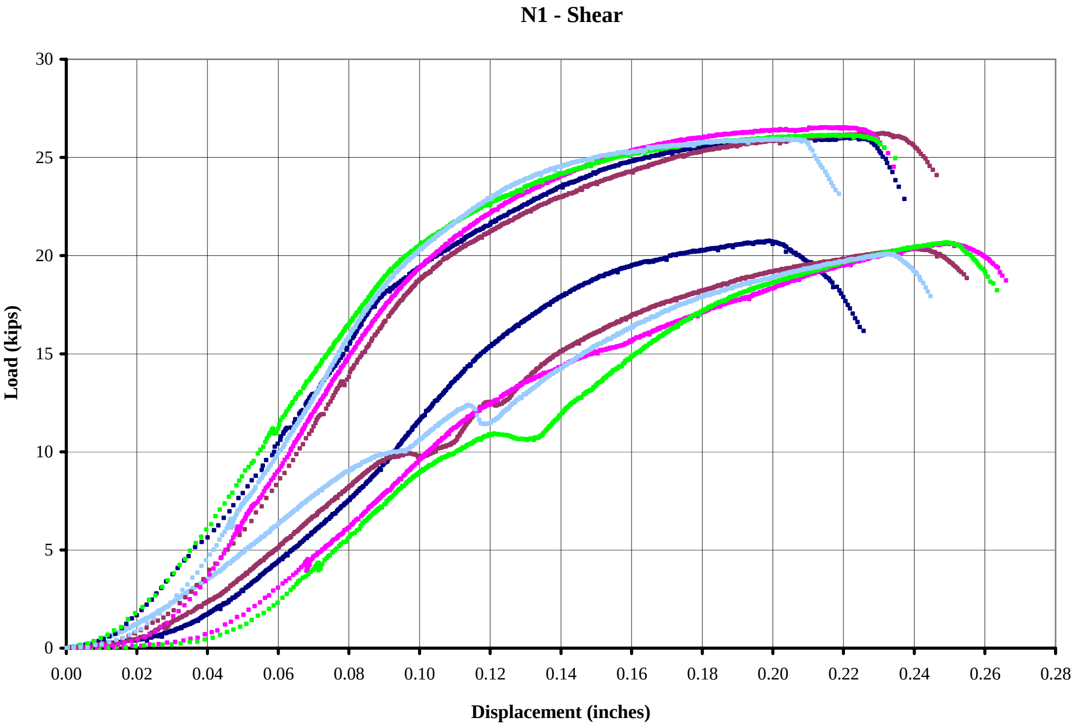

Figure A-6: Lot N1 – 5/8-inch A325 – Shear

T1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3.5"
Grade:	A325
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.3320 inches

Table A-4: Lot T1 – 5/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.525 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6220	31,873	6.23%	0.6214	27,148	0.6216	20,143
2	0.6216	32,324	8.63%	0.6214	26,821	0.6217	18,765
3	0.6227	32,417	7.85%	0.6215	26,931	0.6216	20,531
4	0.6220	31,242	5.48%	0.6217	26,910	0.6216	20,347
5	0.6226	31,960	11.07%	0.6212	26,834	0.6216	19,235

Note: The lever arm of the third LVDT was resting on the bolt head.

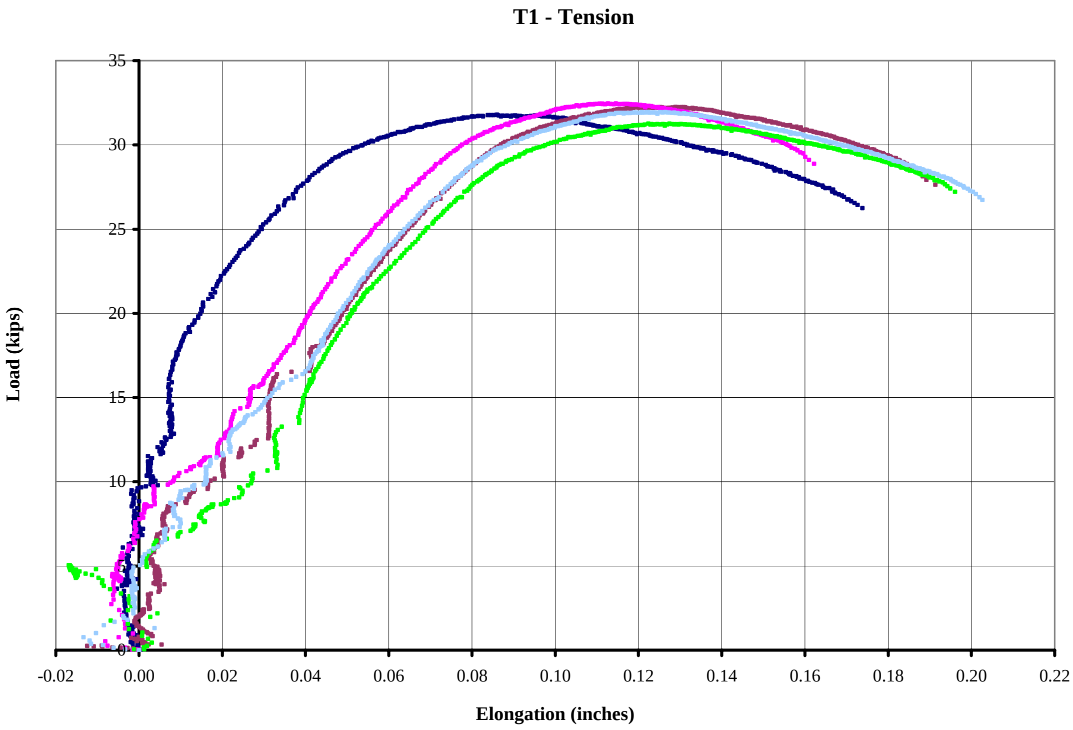

Figure A-7: Lot T1 – 5/8-inch A325 – Tension

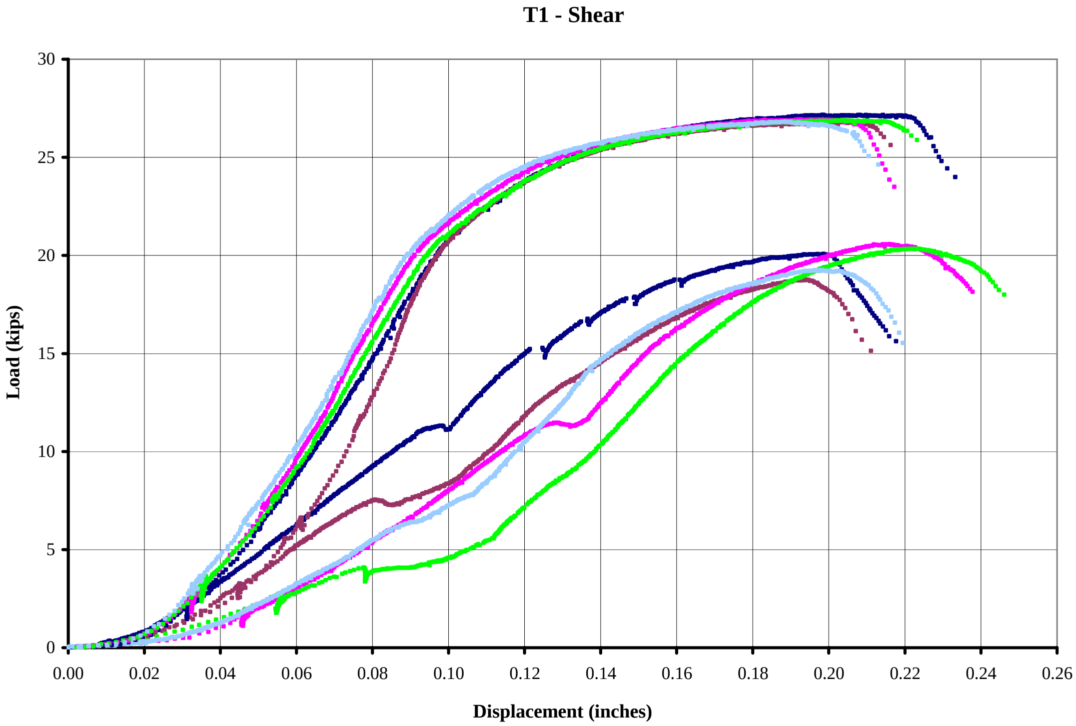

Figure A-8: Lot T1 – 5/8-inch A325 – Shear

B1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4070 inches

Table A-5: Lot B1 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.45 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7482	46,702	10.85%	0.7483	37,586	0.7475	28,088
2	0.7460	46,025	16.58%	0.7479	38,105	0.7477	28,687
3	0.7486	46,738	10.27%	0.7471	38,073	0.7482	27,274
4	0.7470	46,753	17.34%	0.7474	37,983	0.7479	27,418
5	0.7474	46,046	17.20%	0.7478	37,958	0.7483	27,883
6	0.7480	45,927	13.43%	0.7484	38,282		

Notes: The lever arm of the third LVDT was resting on the bolt head.
Data for X5 was not recorded for the Load versus Displacement graph due to technical problems.

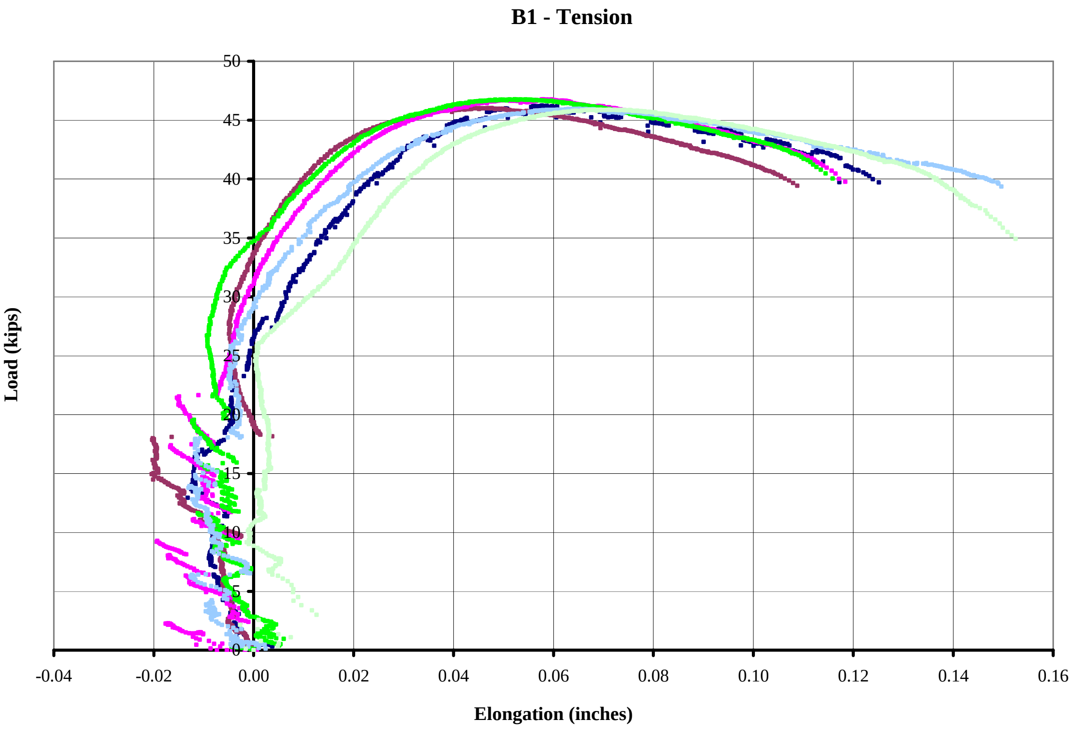

Figure A-9: Lot B1 – 3/4-inch A325 – Tension

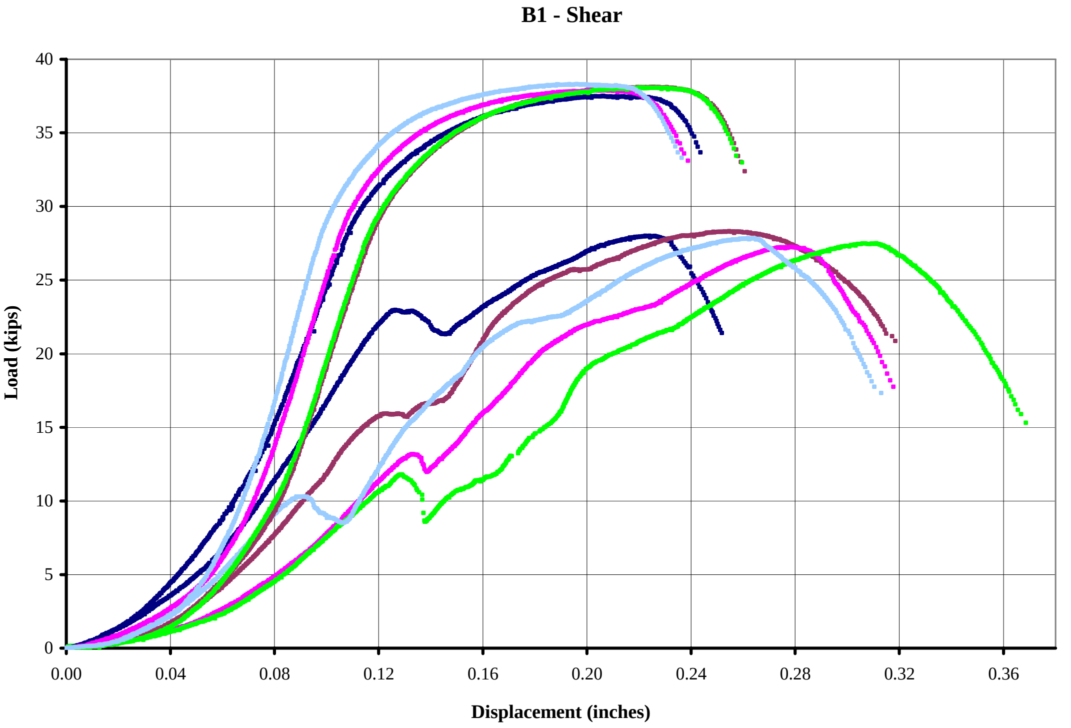

Figure A-10: Lot B1 – 3/4-inch A325 – Shear

B2

Bolt Properties:

Manufacturer:
Lot Number:
Size: 3/4"-10 x 4"
Grade: A325
Nominal Thread Length: 1 3/8 inches
Measured Thread Length: 1.4455 inches

Table A-6: Lot B2 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.60 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7452	49,438	12.69%	0.7442	39,677	0.7441	29,022
2	0.7458	48,768	5.25%	0.7441	38,567	0.7439	29,051
3	0.7460	48,544	14.98%	0.7445	39,100	0.7438	28,878
4	0.7444	48,631	15.08%	0.7442	38,826	0.7440	28,935
5	0.7448	49,326	12.18%	0.7437	38,678	0.7443	29,217

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for T5 was not recorded for the Load versus Elongation graph
due to technical problems.

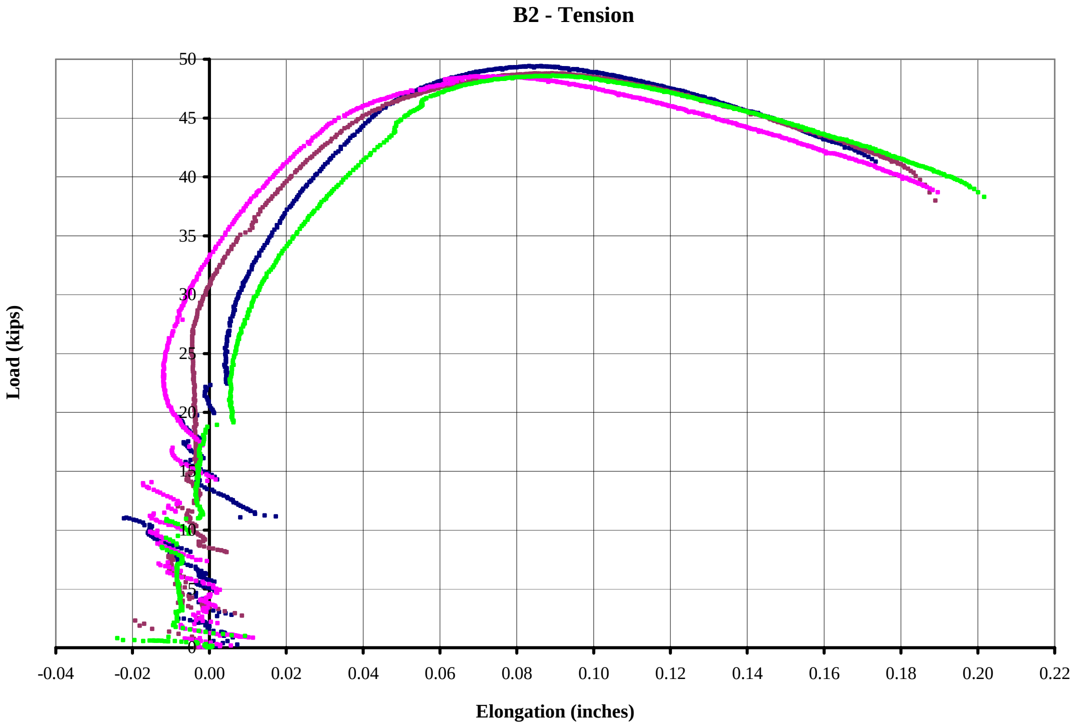

Figure A-11: Lot B2 – 3/4-inch A325 – Tension

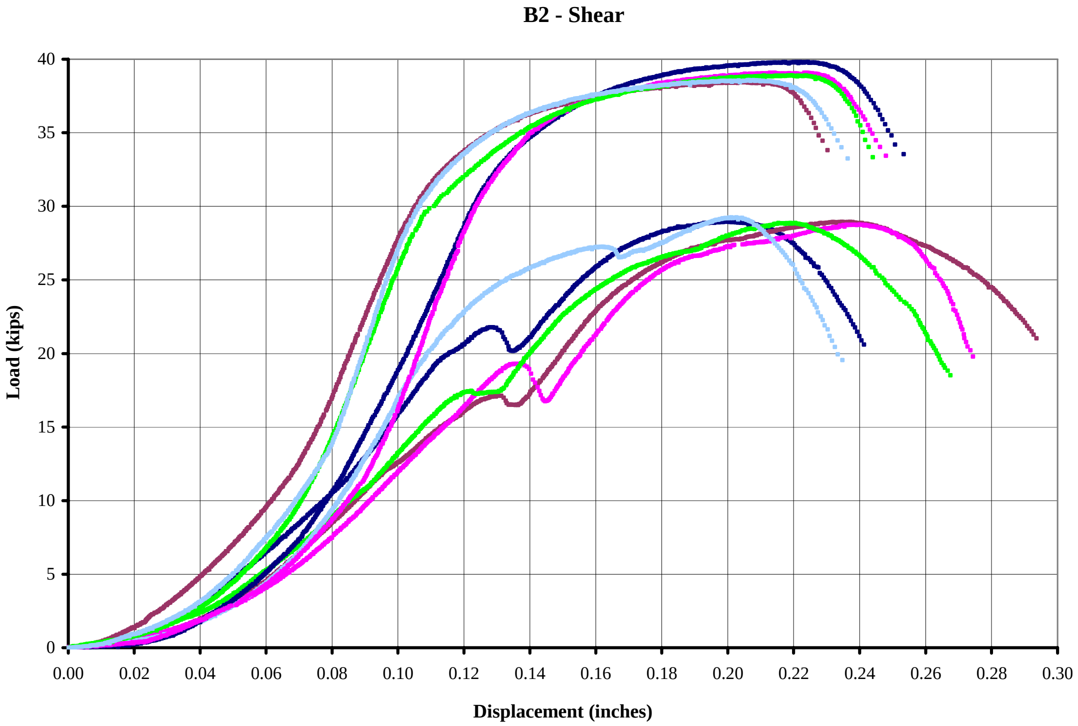

Figure A-12: Lot B2 – 3/4-inch A325 – Shear

B3

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 4.5"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.3900 inches

Table A-7: Lot B3 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7434	48,977	13.53%	0.7436	38,542	0.7434	29,581
2	0.7450	49,200	16.94%	0.7433	39,533	0.7429	29,627
3	0.7438	49,377	11.87%	0.7433	39,363	0.7438	28,575
4	0.7436	49,243	14.71%	0.7434	39,284	0.7435	29,919
5	0.7426	48,872	11.83%	0.7437	39,673	0.7431	29,555

Note: The lever arm of the third LVDT was resting on the bolt head.

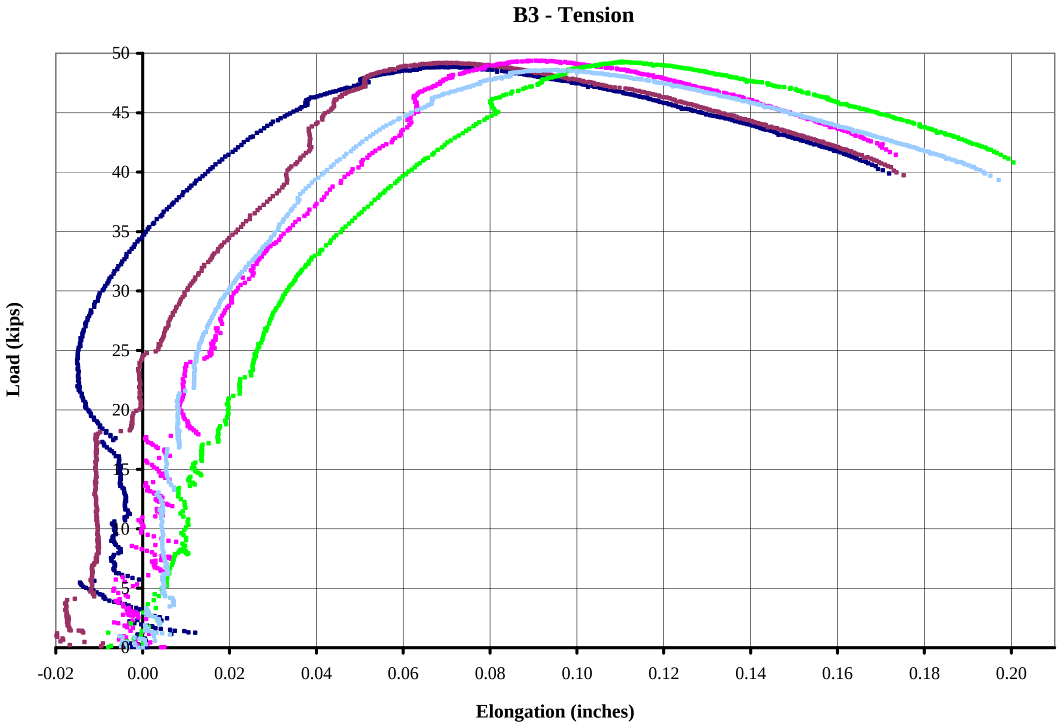

Figure A-13: Lot B3 – 3/4-inch A325 – Tension

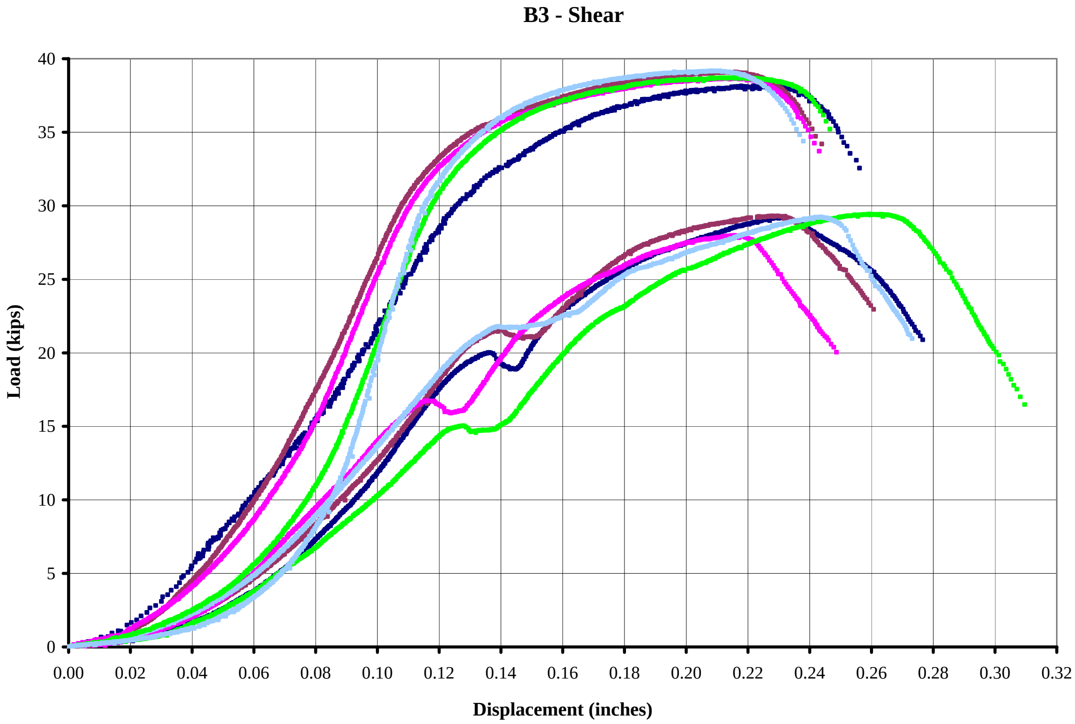

Figure A-14: Lot B3 – 3/4-inch A325 – Shear

B4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 5"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4495 inches

Table A-8: Lot B4 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7466	48,995	14.28%	0.7451	40,012	0.7451	30,060
2	0.7482	48,454	11.35%	0.7449	39,965	0.7450	30,150
3	0.7468	48,962	10.93%	0.7449	40,192	0.7449	29,649
4	0.7478	48,778	10.14%	0.7451	39,554	0.7448	30,633
5	0.7460	48,771	12.83%	0.7450	40,250	0.7451	28,788

Note: The lever arm of the third LVDT was resting on the bolt head.

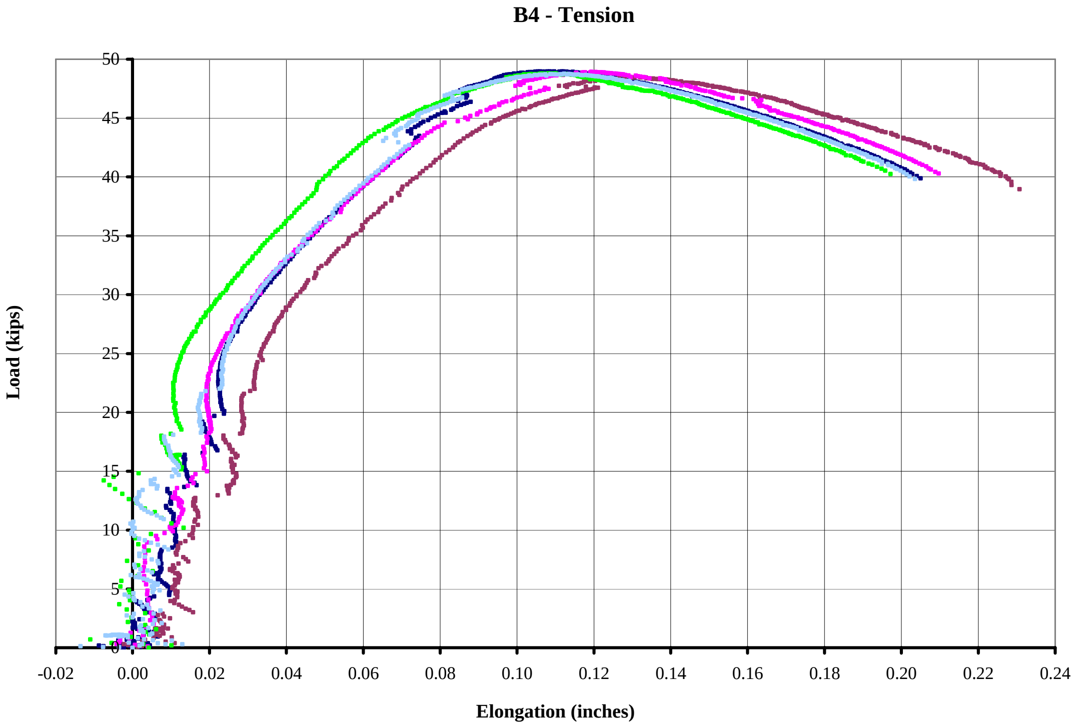

Figure A-15: Lot B4 – 3/4-inch A325 – Tension

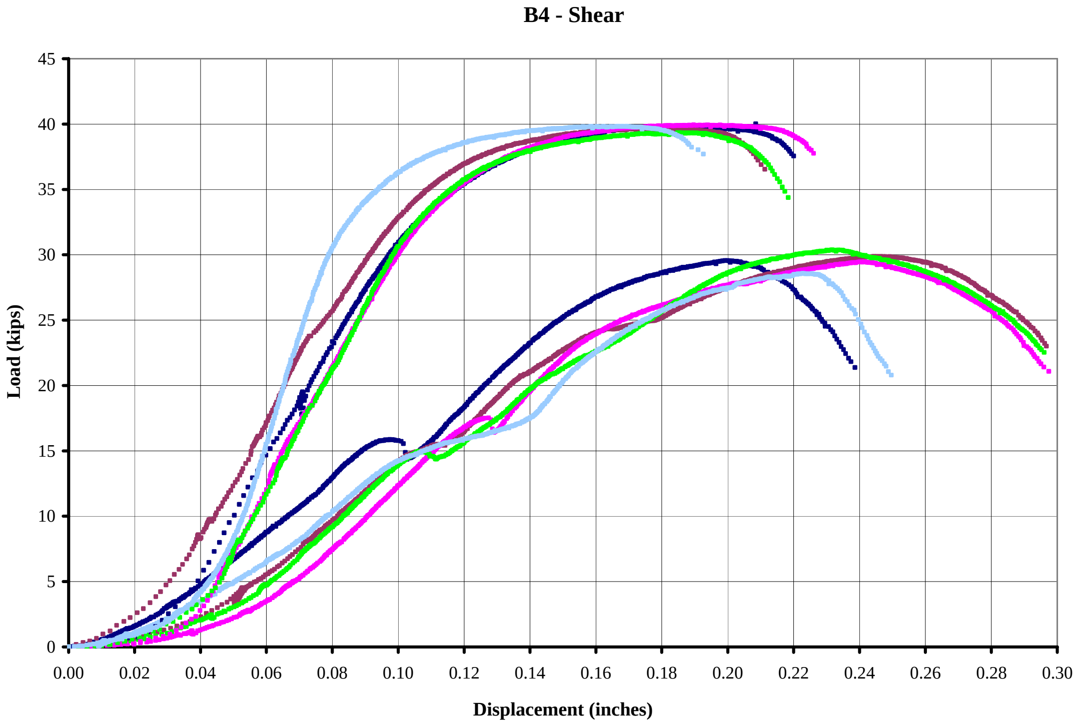

Figure A-16: Lot B4 – 3/4-inch A325 – Shear

L2

Bolt Properties:

Manufacturer:
Lot Number:
Size: 3/4"-10 x 2.75"
Grade: A325
Nominal Thread Length: 1 3/8 inches
Measured Thread Length: 1.4605 inches

Table A-9: Lot L2 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.4125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7457	51,121	5.10%	0.7439	40,715	0.7436	30,839
2	0.7446	49,366	6.23%	0.7437	40,549	0.7440	30,103
3	0.7460	49,020	3.59%	0.7436	39,846	0.7440	29,238
4	0.7442	49,344	3.22%	0.7435	39,850	0.7435	31,751
5	0.7450	49,853	4.93%	0.7438	39,136	0.7438	31,246

Note: The lever arm of the third LVDT was resting on the bolt head.

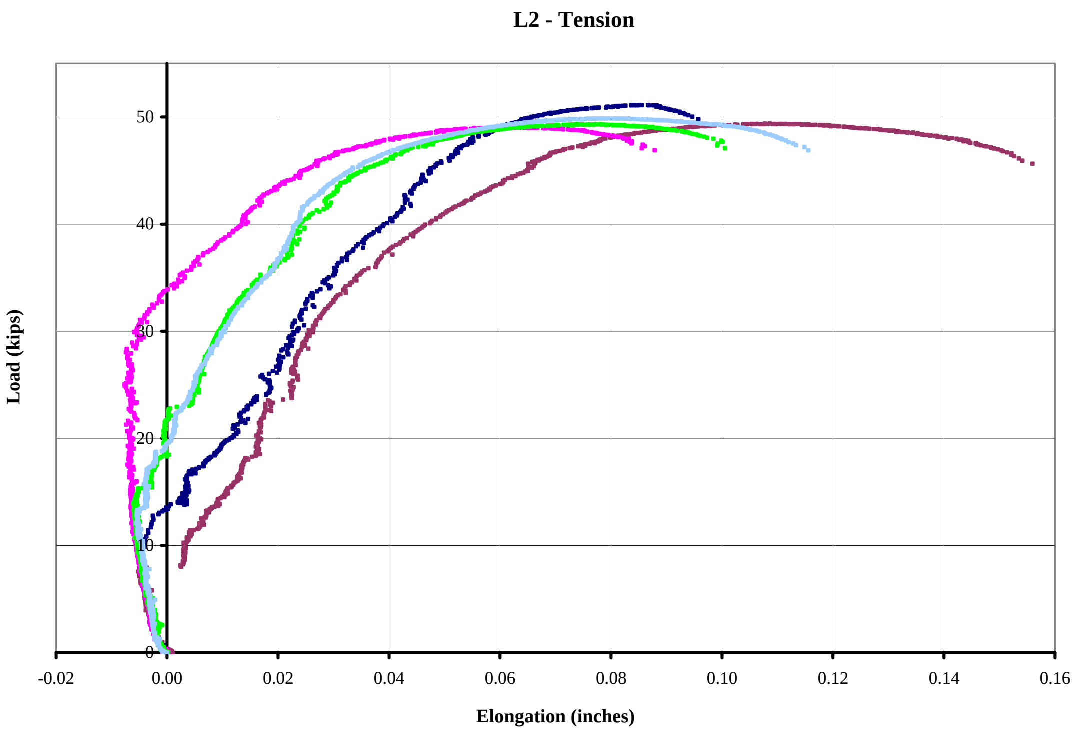

Figure A-17: Lot L2 – 3/4-inch A325 – Tension

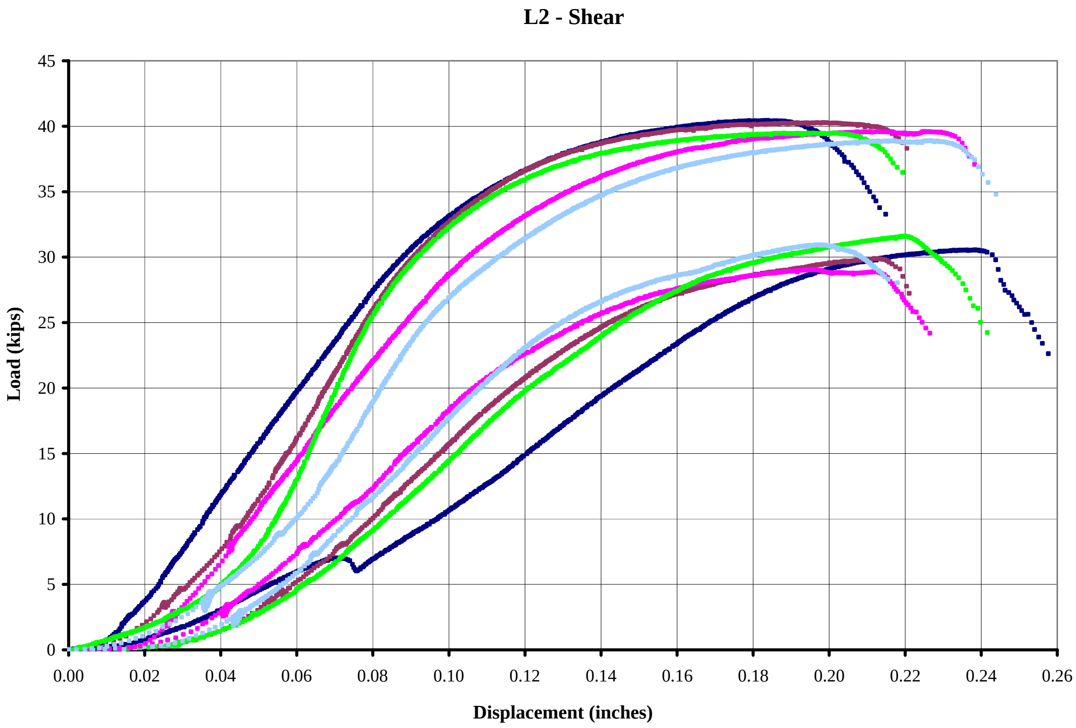

Figure A-18: Lot L2 – 3/4-inch A325 – Shear

N0

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.25"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4450 inches

Table A-10: Lot N0 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.4875 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7437	49,424	6.54%	0.7433	39,785	0.7437	31,350
2	0.7434	49,229	8.65%	0.7436	39,010	0.7432	29,162
3	0.7441	48,912	9.62%	0.7433	39,915	0.7433	29,260
4	0.7456	48,566	9.83%	0.7433	39,324	0.7437	29,689
5	0.7455	48,468	10.00%	0.7434	39,800	0.7434	31,765

Note: The lever arm of the third LVDT was resting on the bolt head.

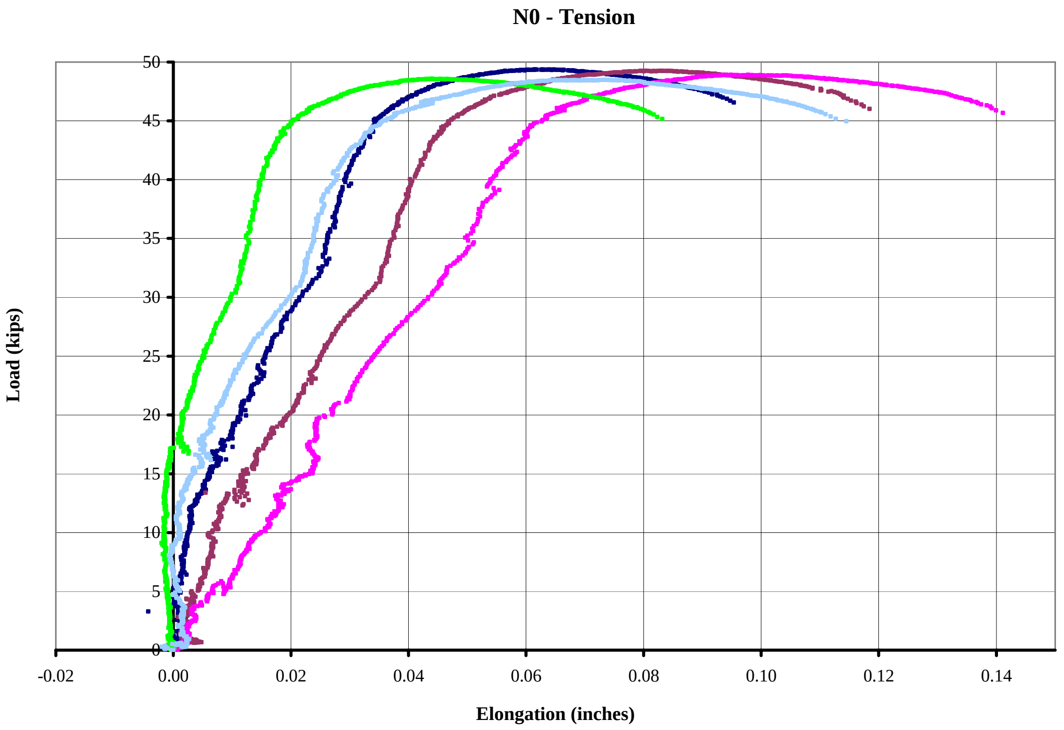

Figure A-19: Lot N0 – 3/4-inch A325 – Tension

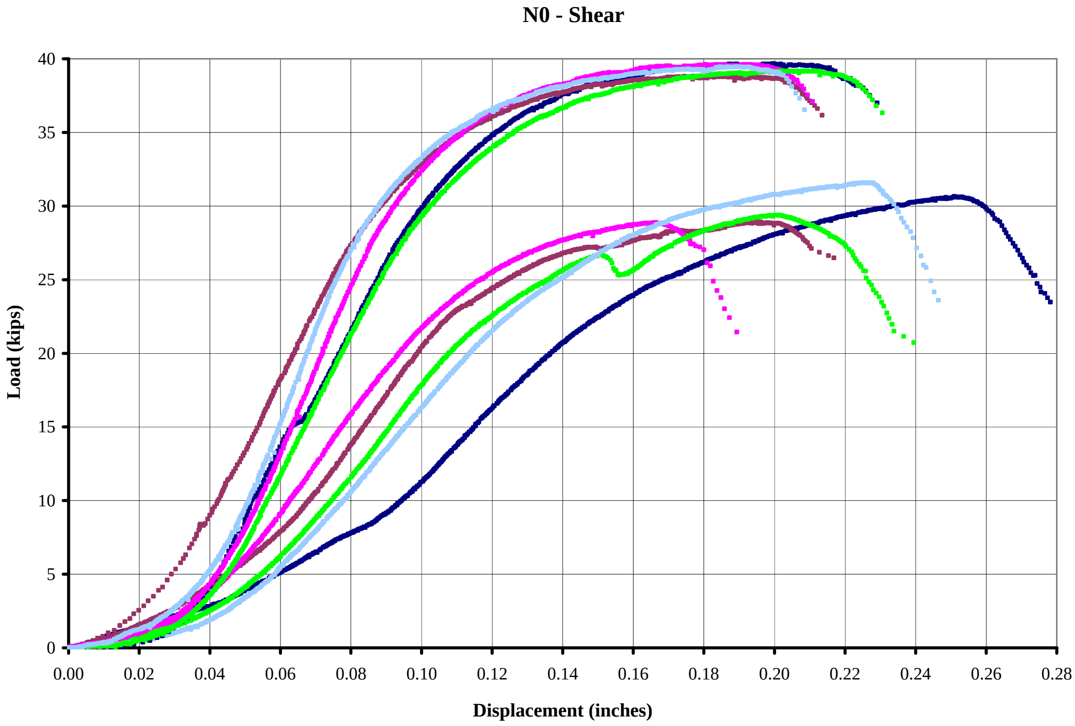

Figure A-20: Lot N0 – 3/4-inch A325 – Shear

N2

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 2.75"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4710 inches

Table A-11: Lot N2 – 3/4-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.4125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7458	48,613	4.15%	0.7445	40,546	0.7443	30,702
2	0.7458	49,024	3.67%	0.7443	40,708	0.7444	31,707
3	0.7486	49,153	0.58%	0.7445	40,254	0.7443	30,424
4	0.7459	49,229	2.01%	0.7445	40,708	0.7443	29,591
5	0.7456	49,525	0.99%	0.7442	40,589	0.7444	31,866
6				0.7423	39,908		

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for X5 was not recorded for the Load versus Displacement graph due to technical problems.

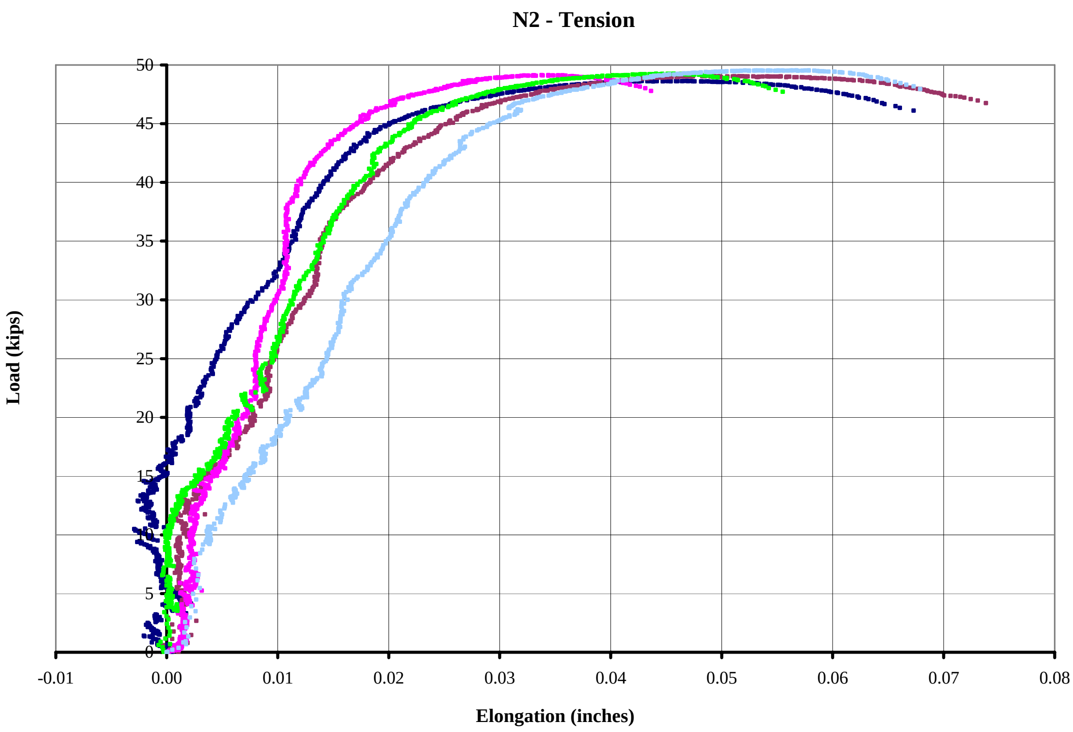

Figure A-21: Lot N2 – 3/4-inch A325 – Tension

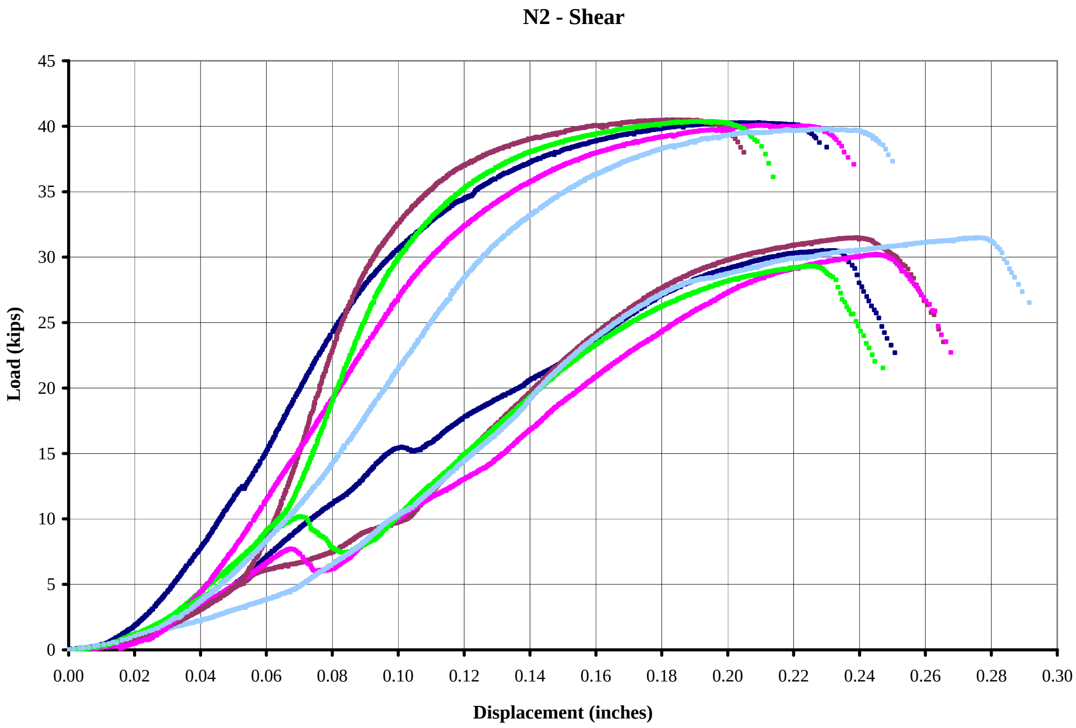

Figure A-22: Lot N2 – 3/4-inch A325 – Shear

N3

Bolt Properties:

Manufacturer:
Lot Number:
Size: 3/4"-10 x 3.25"
Grade: A325
Nominal Thread Length: 1 3/8 inches
Measured Thread Length: 1.4595 inches

Table A-12: Lot N3 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.4875 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7458	52,268	4.76%	0.7422	40,892	0.7424	32,655
2	0.7448	51,756	5.62%	0.7424	41,166	0.7427	33,365
3	0.7446	49,474	7.19%	0.7422	41,220	0.7420	33,920
4	0.7460	50,419	5.35%	0.7420	40,755	0.7423	33,423
5	0.7450	51,230	7.61%	0.7422	41,057	0.7426	33,347
6				0.7426	40,264		

Note: The lever arm of the third LVDT was resting on the bolt head. Data for X1 was not recorded for the Load versus Displacement graph due to technical problems.

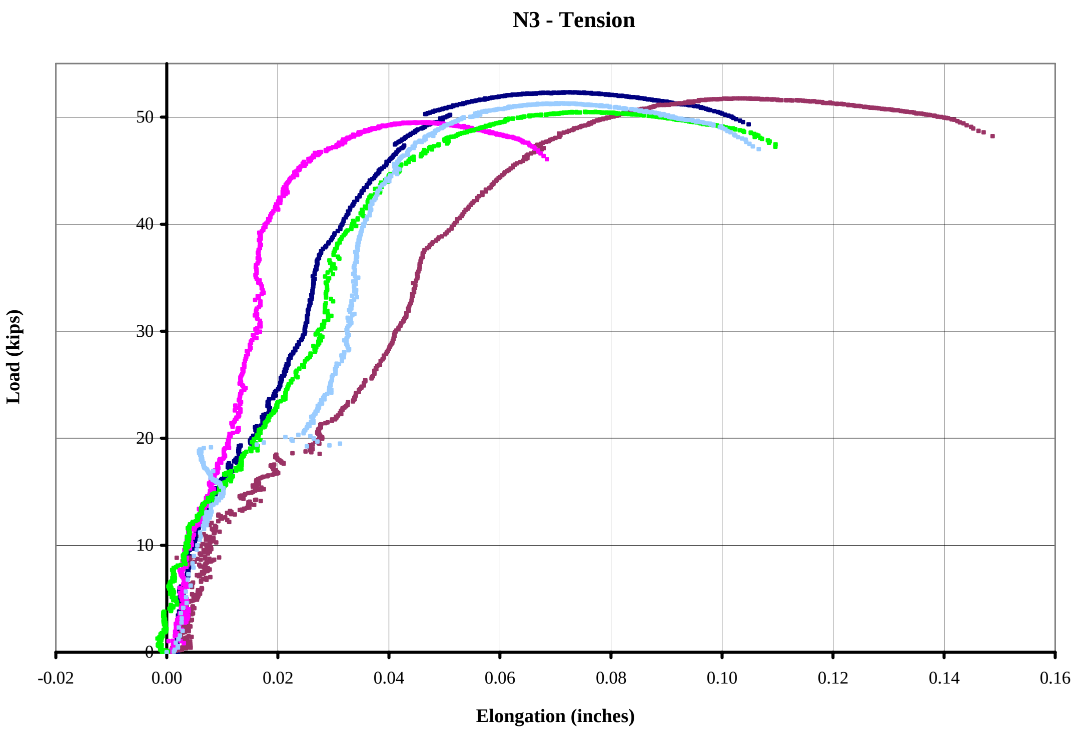

Figure A-23: Lot N3 – 3/4-inch A325 – Tension

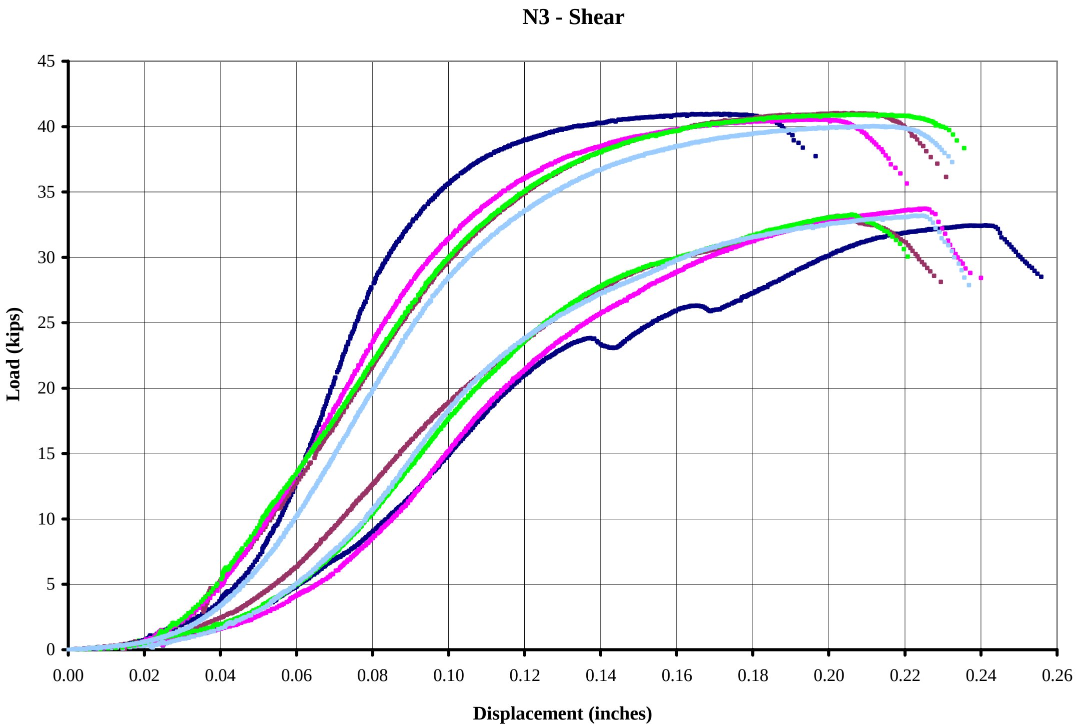

Figure A-24: Lot N3 – 3/4-inch A325 – Shear

T2

Bolt Properties:

Manufacturer:
Lot Number:
Size: 3/4"-10 x 3.5"
Grade: A325
Nominal Thread Length: 1 3/8 inches
Measured Thread Length: 1.4455 inches

Table A-13: Lot T2 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.525 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7375	50,988	8.30%	0.7411	40,805	0.7410	30,965
2	0.7385	49,950	6.88%	0.7412	40,985	0.7411	32,089
3	0.7360	49,240	9.72%	0.7410	40,924	0.7408	31,437
4	0.7335	49,784	6.78%	0.7412	41,375	0.7406	31,736
5	0.7340	50,109	8.75%	0.7412	41,292	0.7407	30,125

Note: The lever arm of the third LVDT was resting on the bolt head.

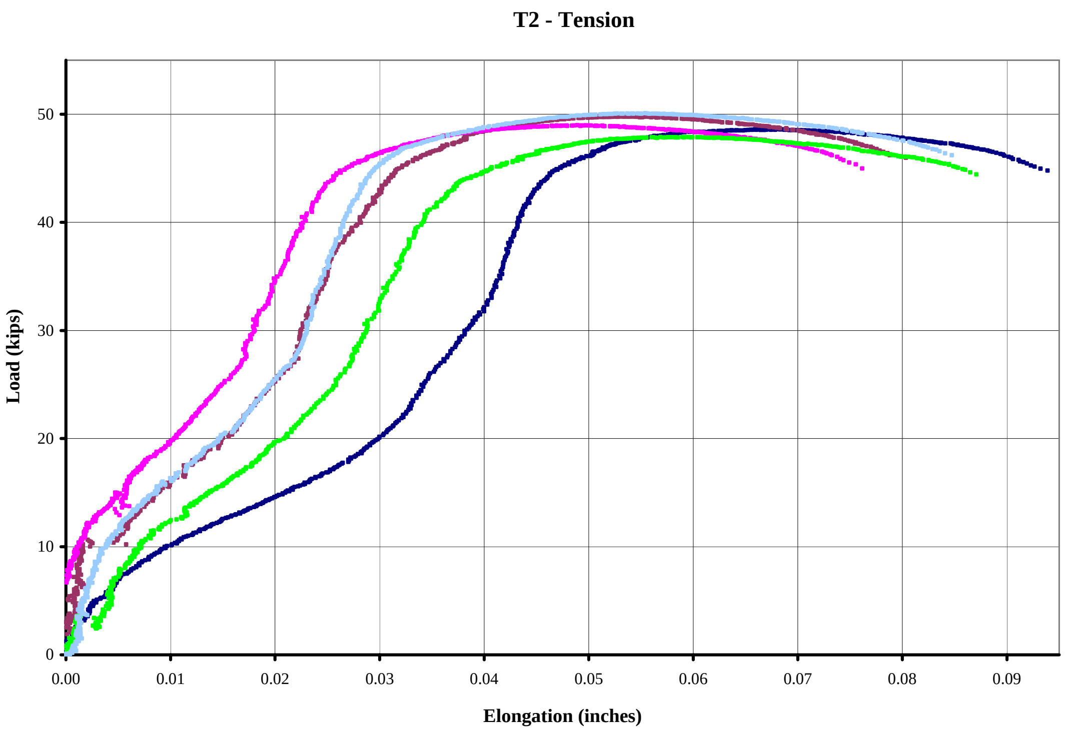

Figure A-25: Lot T2 – 3/4-inch A325 – Tension

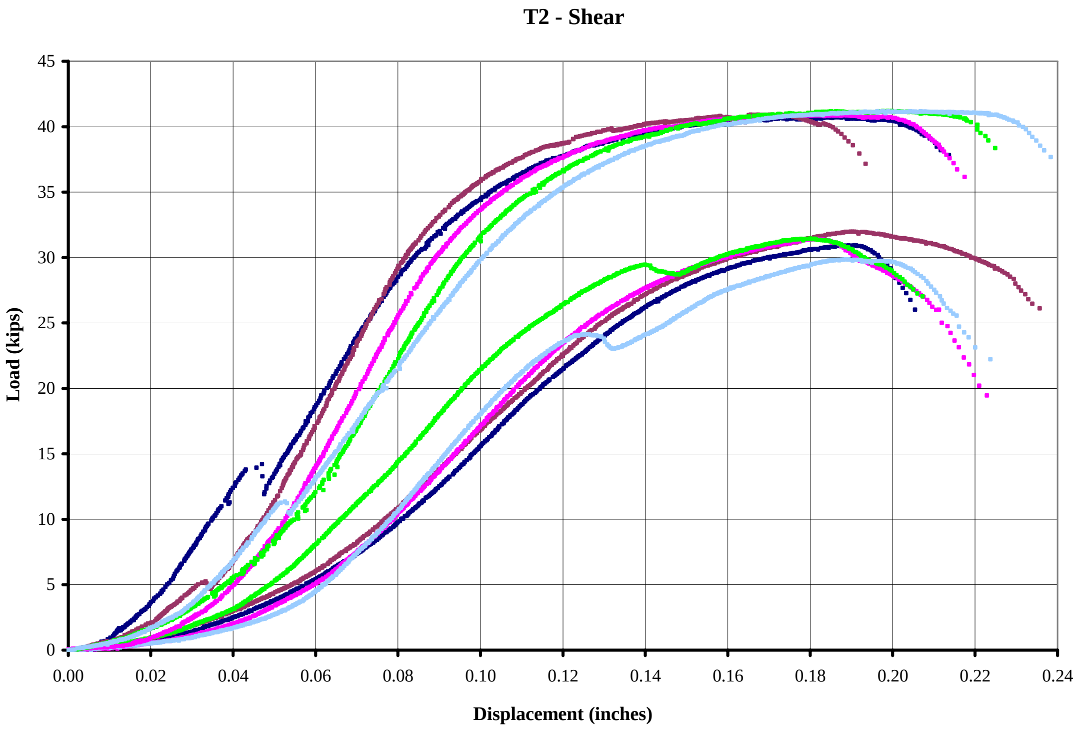

Figure A-26: Lot T2 – 3/4-inch A325 – Shear

T3

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.75"
Grade:	A325
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4555 inches

Table A-14: Lot T3 – 3/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7345	50,235	13.60%	0.7425	41,977	0.7414	30,777
2	0.7385	49,979	10.41%	0.7426	41,973	0.7413	30,893
3	0.7410	49,820	11.06%	0.7417	41,526	0.7418	32,273
4	0.7395	50,314	12.71%	0.7416	41,966	0.7415	31,347
5	0.7370	49,932	12.99%	0.7418	41,389	0.7413	33,081

Note: The lever arm of the third LVDT was resting on the bolt head.

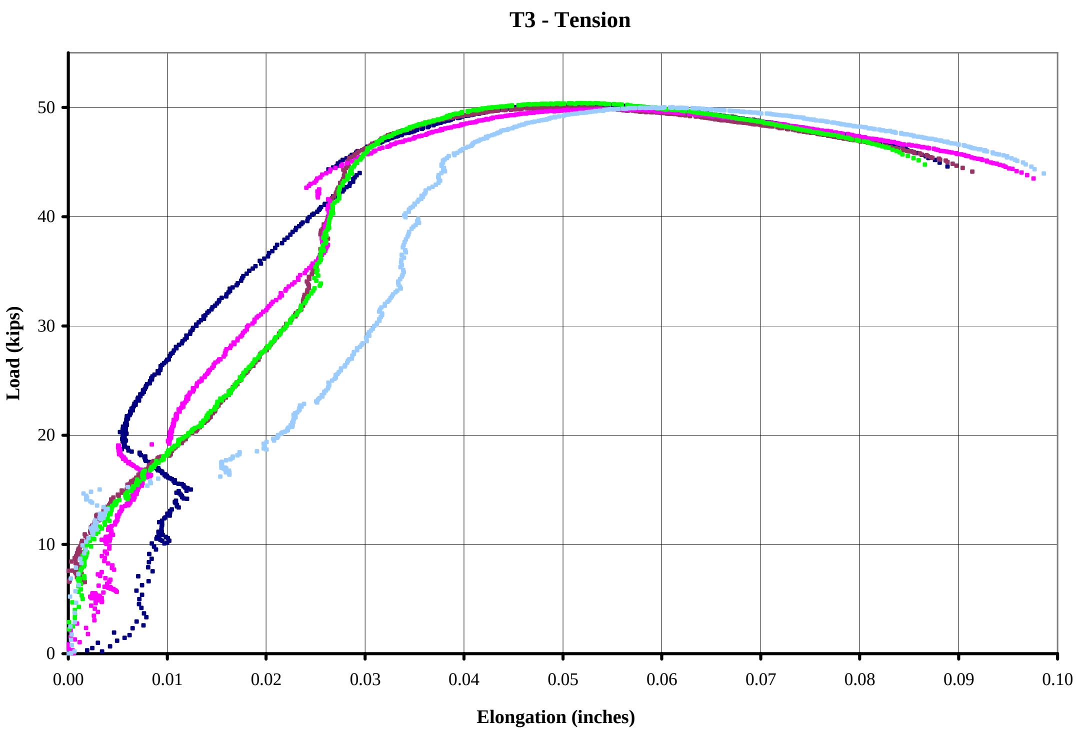

Figure A-27: Lot T3 – 3/4-inch A325 – Tension

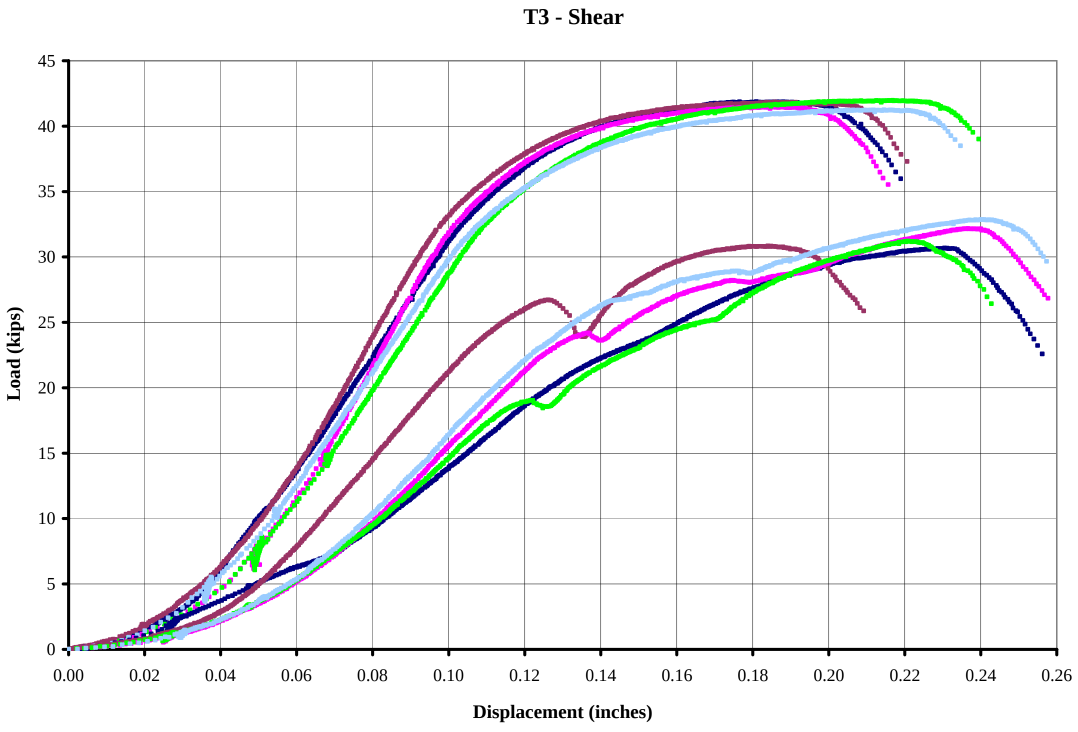

Figure A-28: Lot T3 – 3/4-inch A325 – Shear

B5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3.75"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5815 inches

Table A-15: Lot B5 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8672	66,826	15.33%	0.8680	53,363	0.8676	37,867
2	0.8678	66,942	12.68%	0.8677	52,556	0.8688	38,599
3	0.8660	66,394	9.93%	0.8683	52,405	0.8687	39,947
4	0.8678	67,558	10.12%	0.8687	52,740	0.8680	40,600
5	0.8682	66,769	10.94%	0.8688	53,158	0.8677	39,133

Note: The lever arm of the third LVDT was resting on the bolt head.

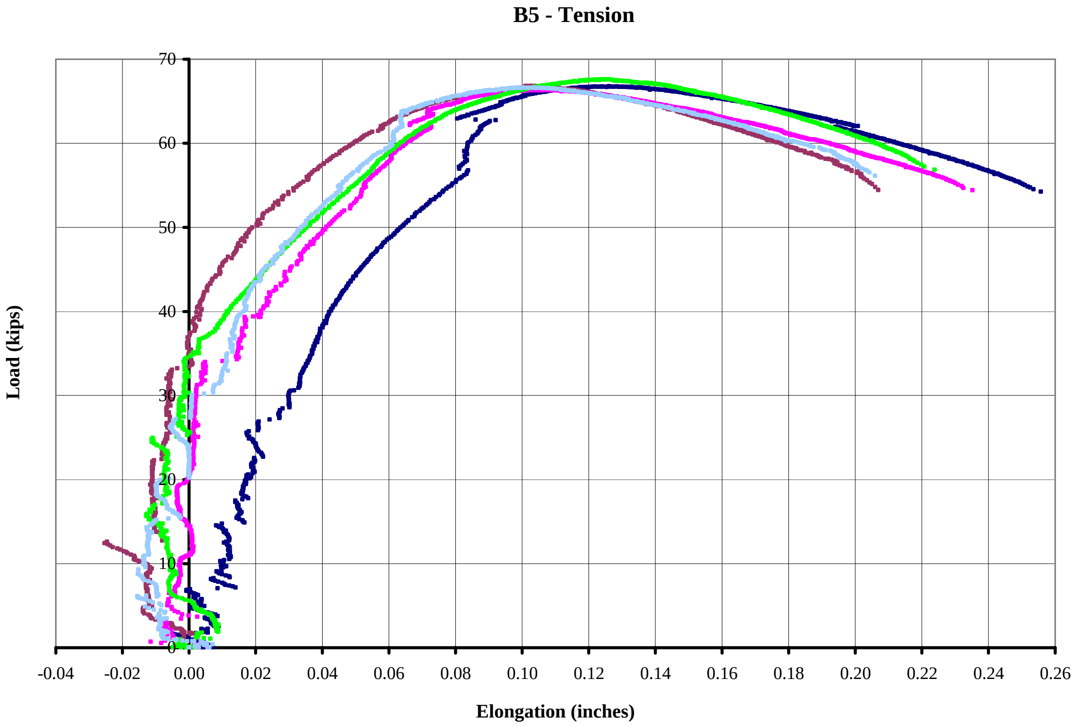

Figure A-29: Lot B5 – 7/8-inch A325 – Tension

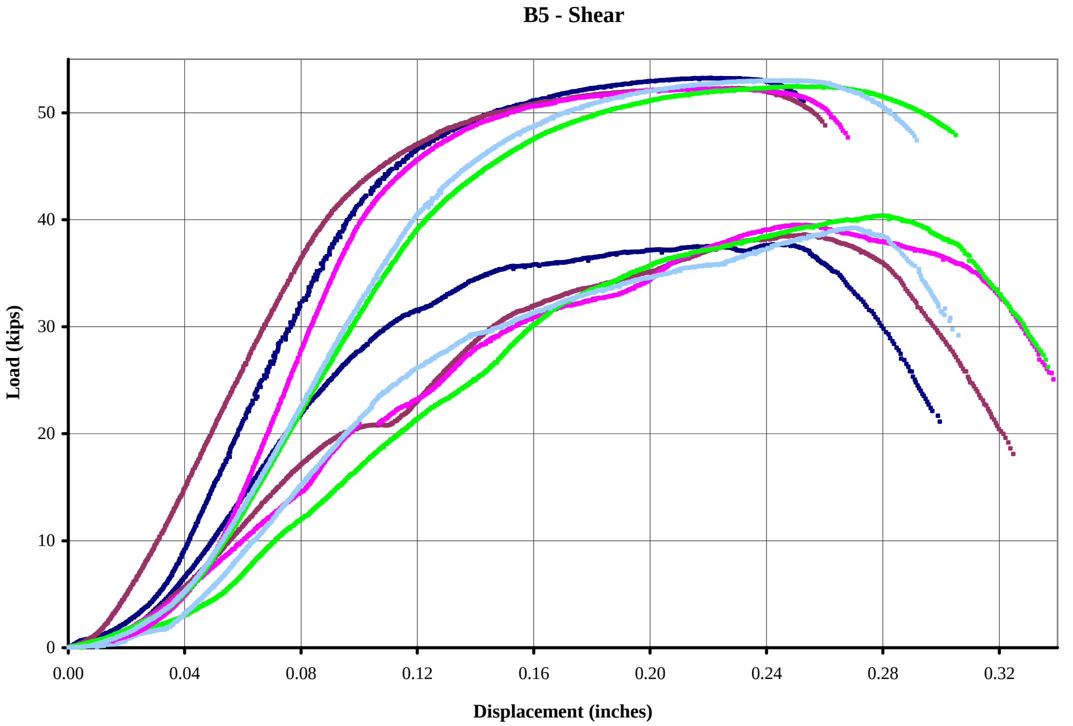

Figure A-30: Lot B5 – 7/8-inch A325 – Shear

B6

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.5"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5515 inches

Table A-16: Lot B6 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8676	67,717	13.76%	0.8666	52,570	0.8675	40,845
2	0.8664	66,769	13.25%	0.8674	51,950	0.8693	39,619
3	0.8680	66,816	17.05%	0.8663	52,322	0.8681	42,780
4	0.8688	66,289	18.14%	0.8667	51,824	0.8684	41,793
5	0.8686	67,969	13.89%	0.8663	52,275	0.8680	40,874

Note: The lever arm of the third LVDT was resting on the bolt head.

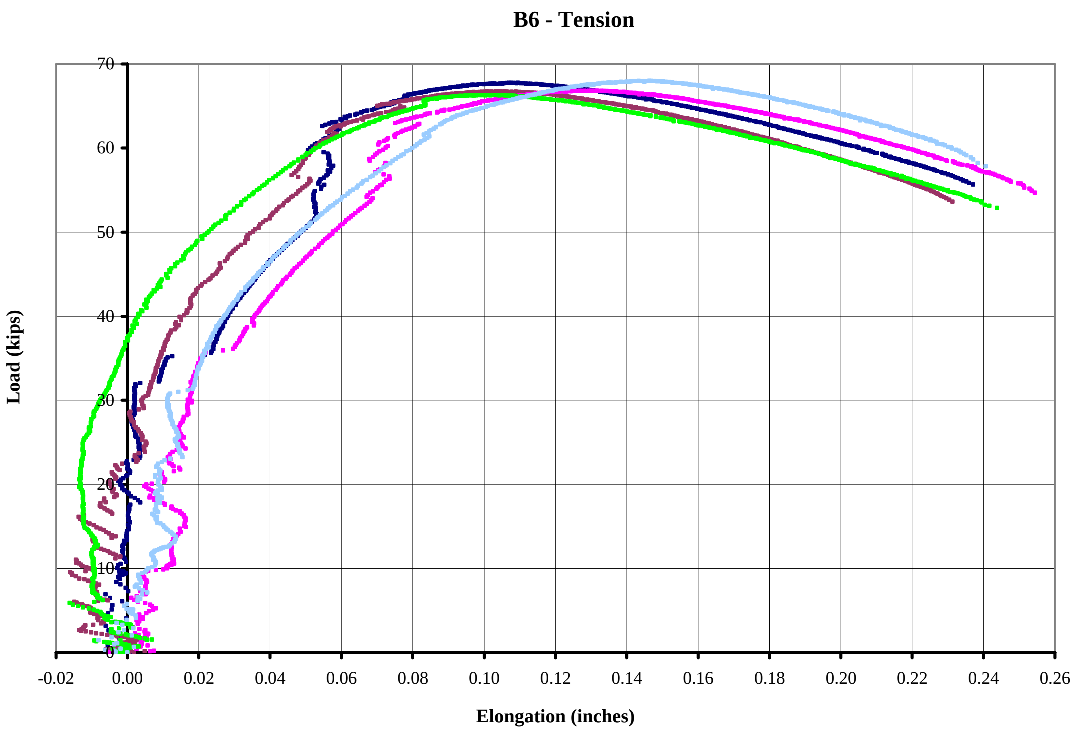

Figure A-31: Lot B6 – 7/8-inch A325 – Tension

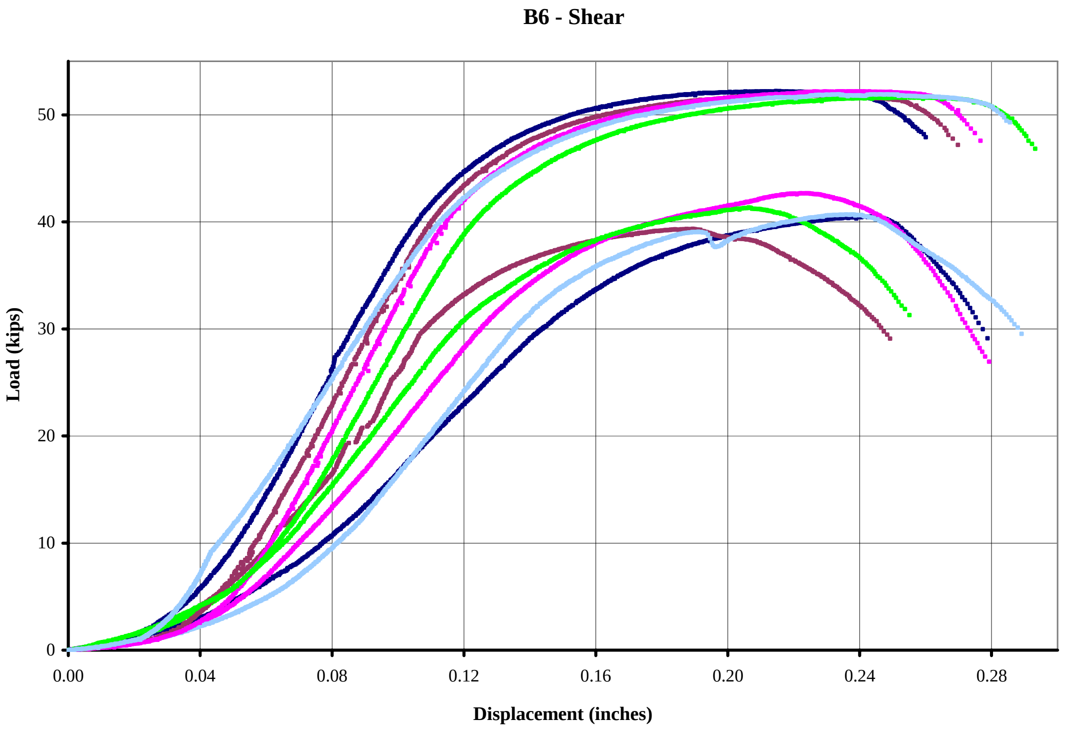

Figure A-32: Lot B6 – 7/8-inch A325 – Shear

B7

Bolt Properties:

Manufacturer:
Lot Number:
Size: 7/8"-9 x 4.75"
Grade: A325
Nominal Thread Length: 1 1/2 inches
Measured Thread Length: 1.5175 inches

Table A-17: Lot B7 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.7125 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8682	66,711	14.17%	0.8690	53,320	0.8687	41,328
2	0.8700	67,295	12.75%	0.8690	53,140	0.8687	41,778
3	0.8692	67,522	13.97%	0.8694	53,273	0.8694	41,249
4	0.8684	68,178	9.75%	0.8681	52,837	0.8694	40,340
5	0.8706	68,153	15.39%	0.8701	53,295	0.8688	38,105
6				0.8692	53,079		

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for X1 was not recorded for the Load versus Displacement graph due to technical problems.

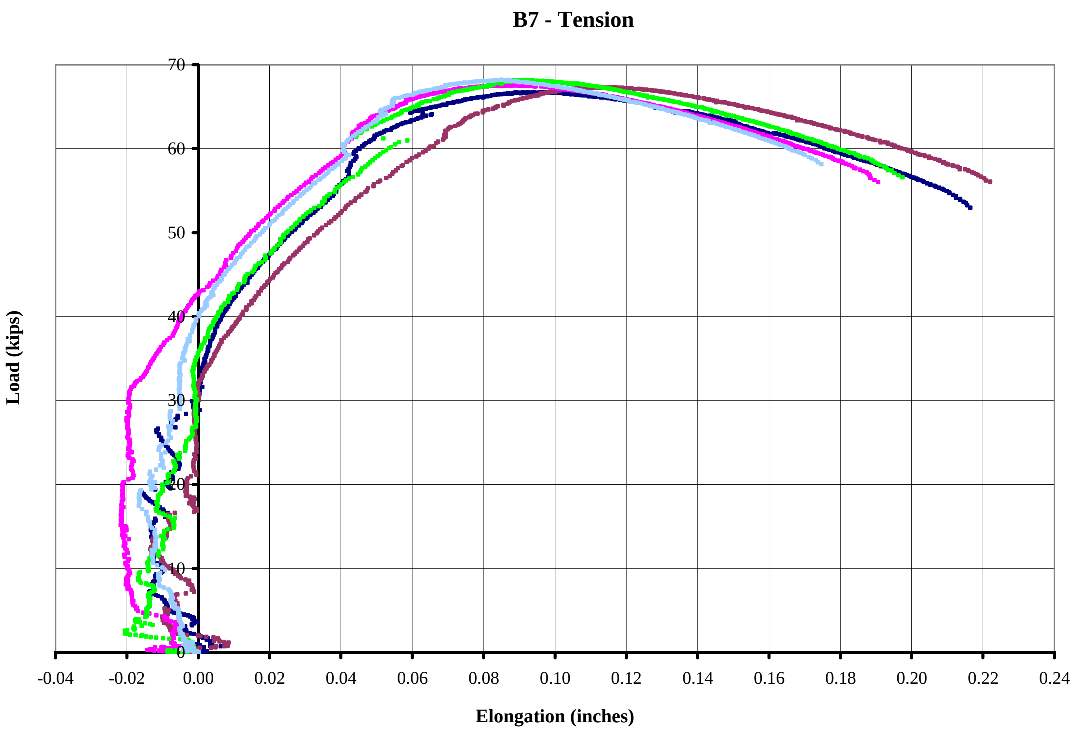

Figure A-33: Lot B7 – 7/8-inch A325 – Tension

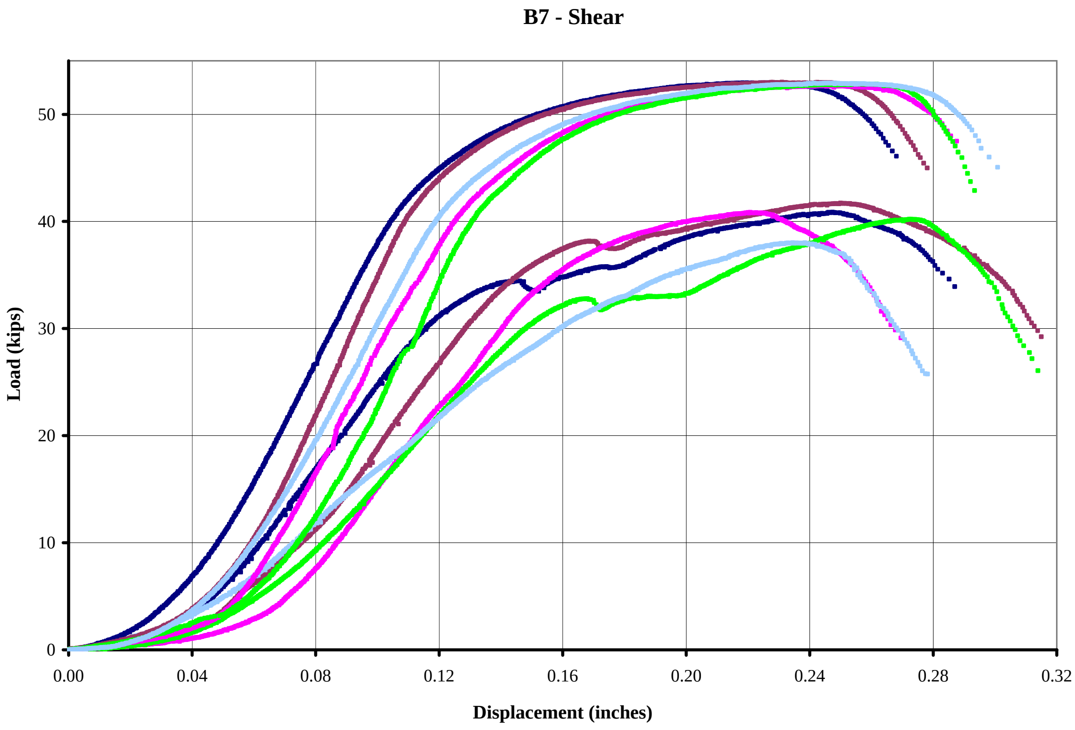

Figure A-34: Lot B7 – 7/8-inch A325 – Shear

L3

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5825 inches

Table A-18: Lot L3 – 7/8-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.45 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8713	67,194	6.51%	0.8712	52,268	0.8698	42,946
2	0.8706	65,651	7.61%	0.8701	53,129	0.8702	40,326
3	0.8719	66,495	7.08%	0.8700	53,007	0.8701	43,728
4	0.8716	66,913	8.25%	0.8703	54,679	0.8700	40,553
5	0.8710	66,048	9.67%	0.8702	52,650	0.8701	40,953

Note: The lever arm of the third LVDT was resting on the bolt head.

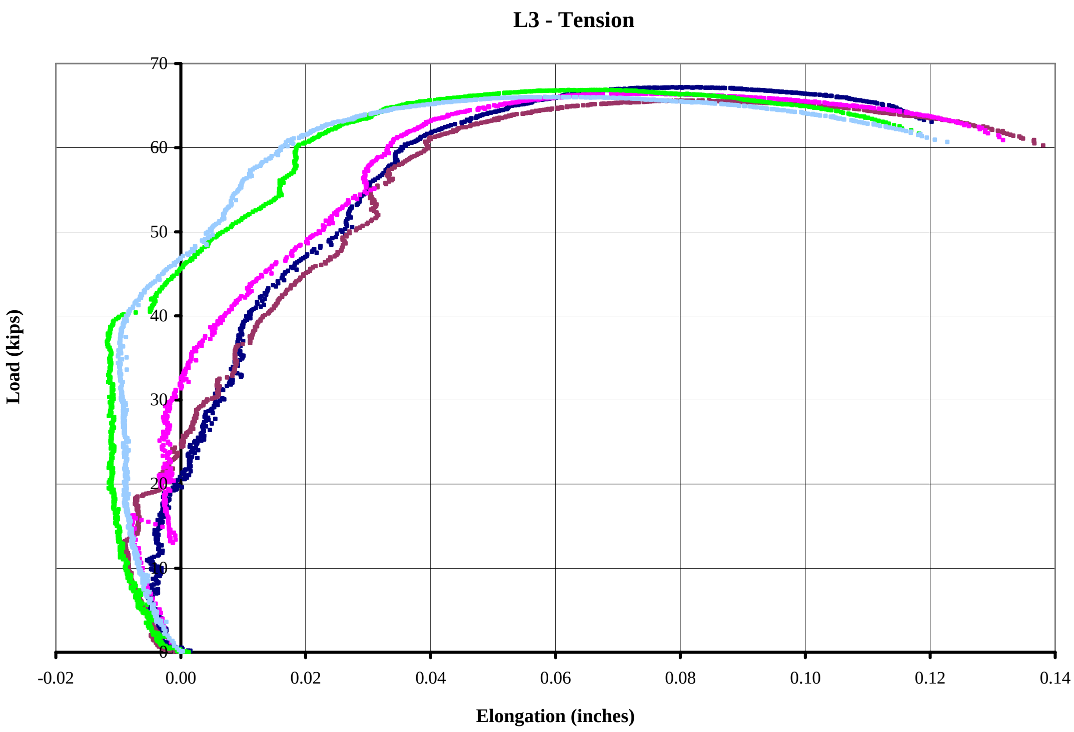

Figure A-35: Lot L3 – 7/8-inch A325 – Tension

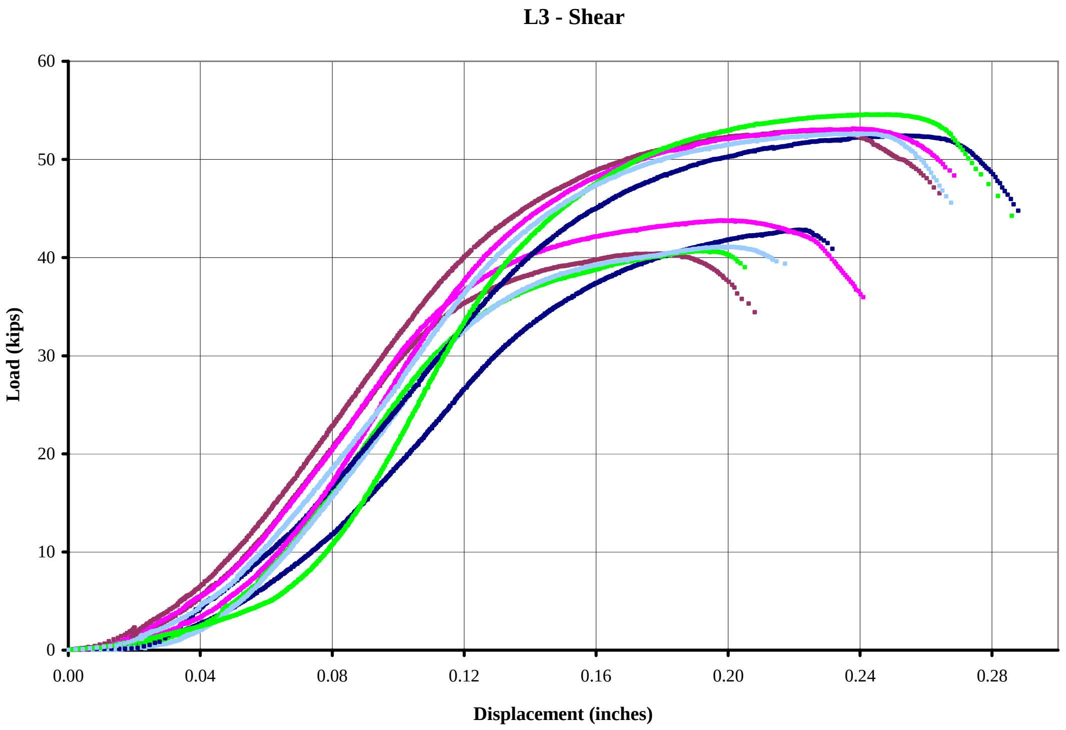

Figure A-36: Lot L3 – 7/8-inch A325 – Shear

L4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 5"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5435 inches

Table A-19: Lot L4 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8744	69,948	7.90%	0.8709	55,411	0.8710	43,209
2	0.8729	68,434	10.98%	0.8715	55,443	0.8727	41,721
3	0.8732	69,937	10.53%	0.8718	55,847	0.8704	39,742
4	0.8738	70,521	10.01%	0.8712	55,941	0.8721	43,927
5	0.8733	70,514	8.91%	0.8721	54,506	0.8714	41,768
6						0.8711	42,611

Note: The lever arm of the third LVDT was resting on the bolt head.

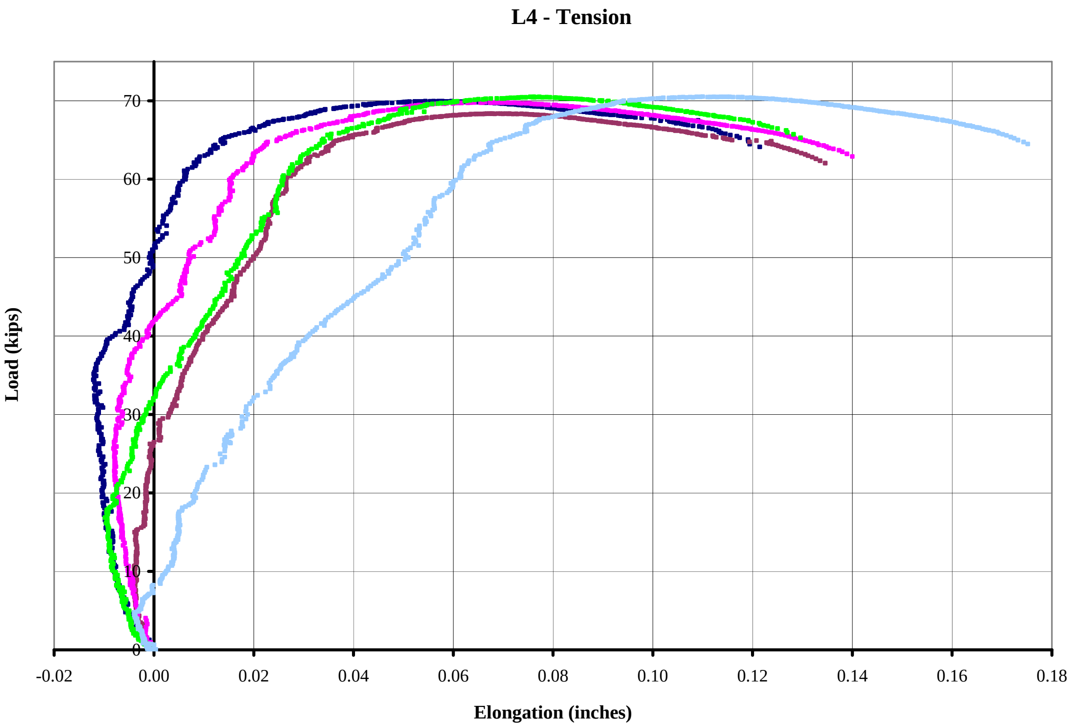

Figure A-37: Lot L4 – 7/8-inch A325 – Tension

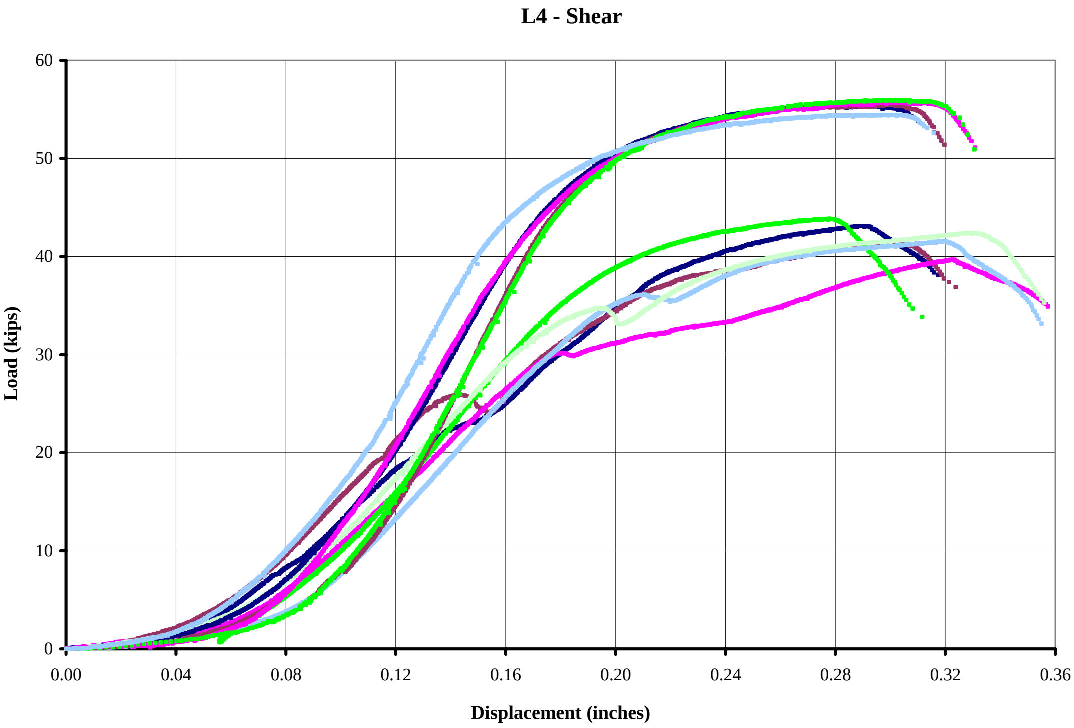

Figure A-38: Lot L4 – 7/8-inch A325 – Shear

N4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.25"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.4985 inches

Table A-20: Lot N4 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8716	68,726	12.18%	0.8699	54,600	0.8700	41,508
2	0.8724	68,513	12.98%	0.8695	54,182	0.8701	40,214
3	0.8719	69,595	12.78%	0.8700	54,142	0.8700	39,079
4	0.8717	69,011	12.05%	0.8695	53,771	0.8700	41,746
5	0.8715	69,829	13.85%	0.8696	54,697	0.8698	42,297

Note: The lever arm of the third LVDT was resting on the bolt head.

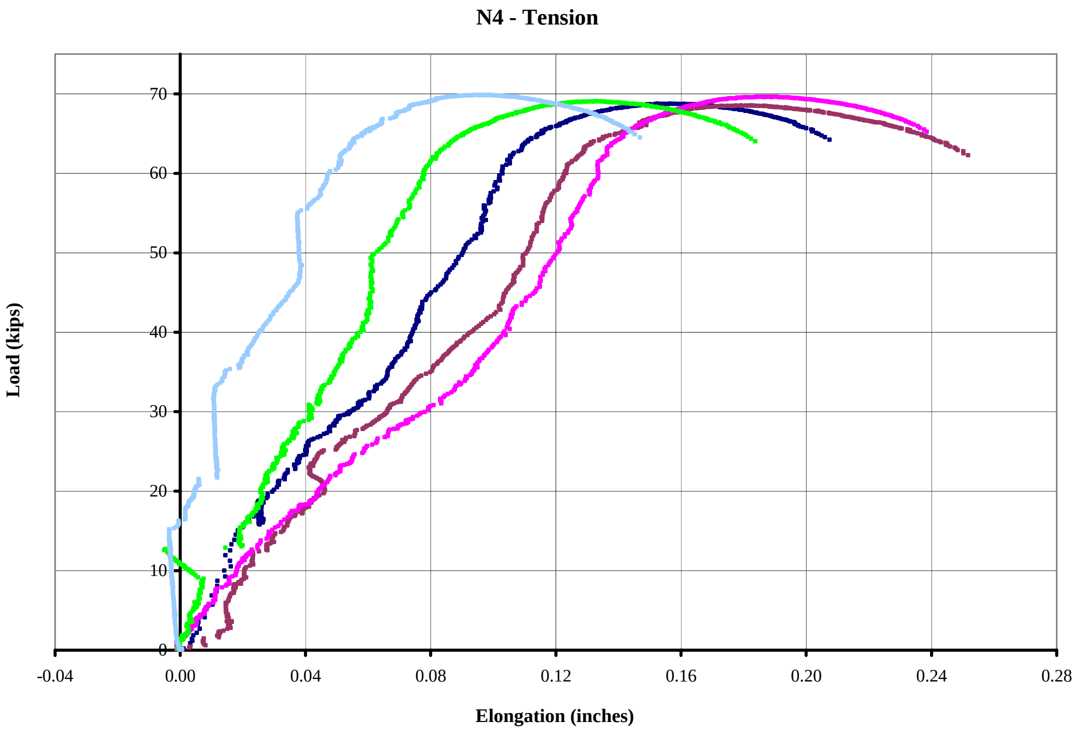

Figure A-39: Lot N4 – 7/8-inch A325 – Tension

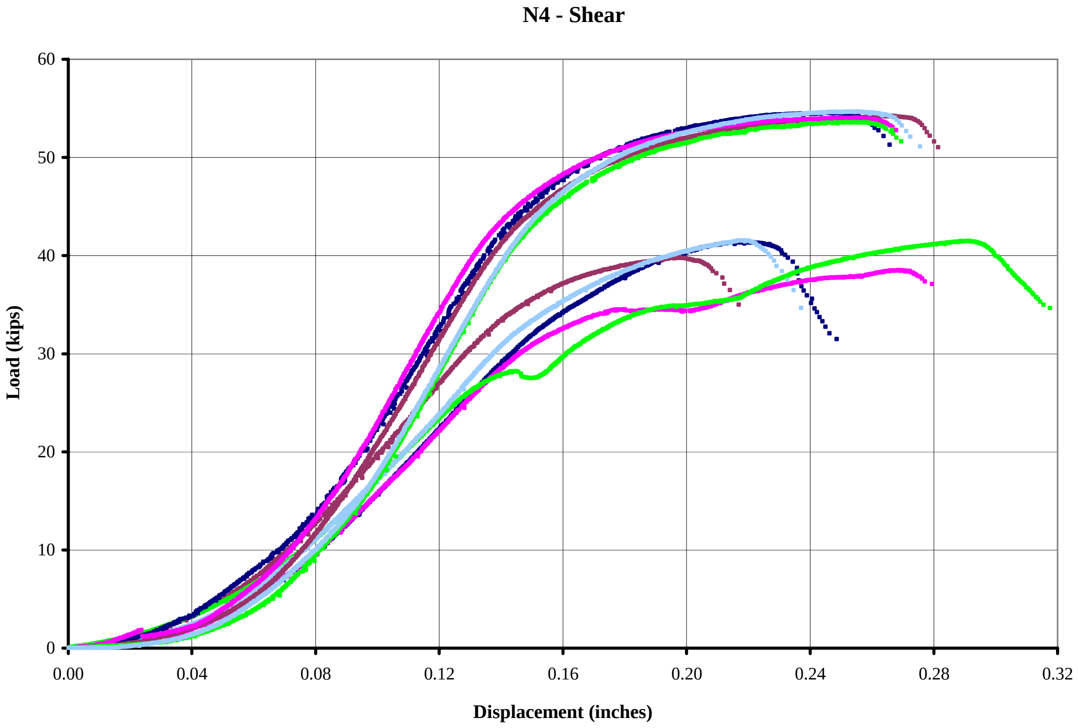

Figure A-40: Lot N4 – 7/8-inch A325 – Shear

N5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.25"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5240 inches

Table A-21: Lot N5 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8713	69,335	12.37%	0.8694	54,841	0.8694	40,138
2	0.8712	68,438	9.15%	0.8693	54,787	0.8692	42,452
3	0.8702	69,501	9.84%	0.8693	54,910	0.8694	42,853
4	0.8720	69,094	10.33%	0.8694	54,892	0.8688	47,474
5	0.8697	68,636	12.80%	0.8693	55,086	0.8695	45,033
6	0.8693	69,032	13.39%				

Note: The lever arm of the third LVDT was resting on the bolt head.

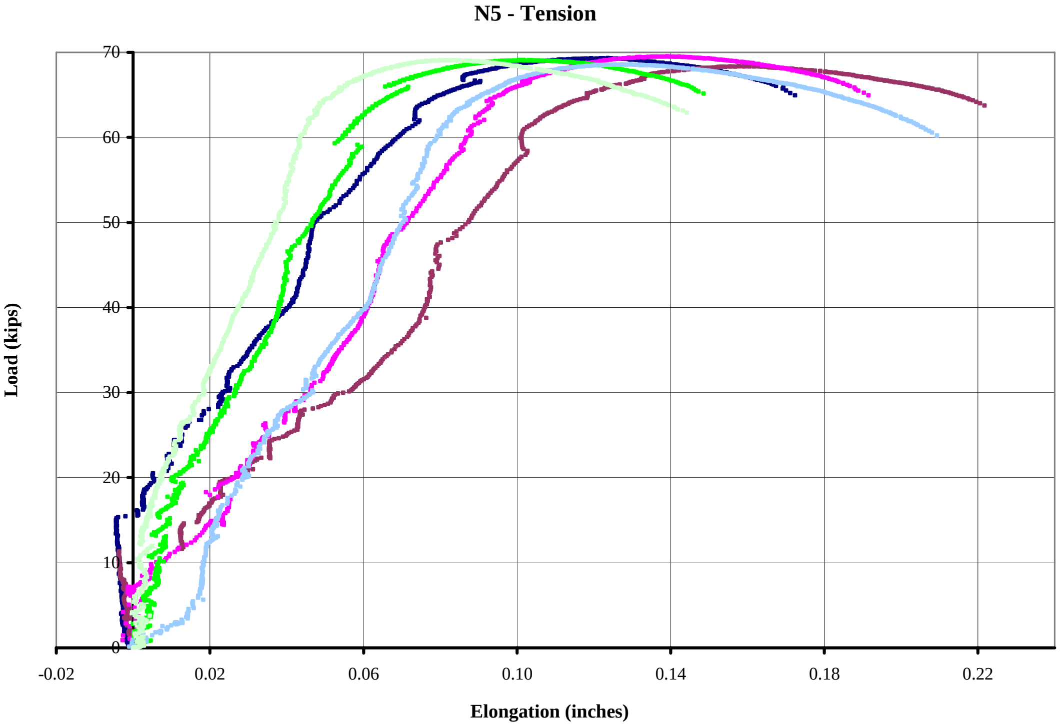

Figure A-41: Lot N5 – 7/8-inch A325 – Tension

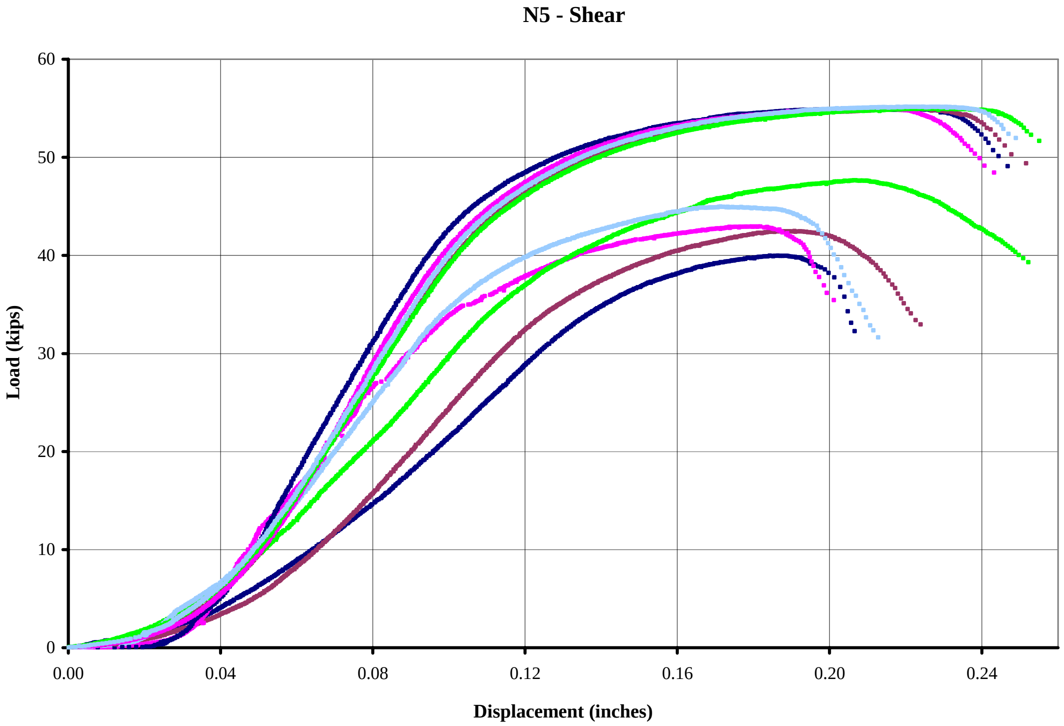

Figure A-42: Lot N5 – 7/8-inch A325 – Shear

T4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5850 inches

Table A-22: Lot T4 – 7/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8698	68,636	10.57%	0.8687	55,422	0.8693	40,304
2	0.8698	68,827	11.74%	0.8692	56,481	0.8695	42,568
3	0.8695	67,908	8.83%	0.8697	55,263	0.8696	44,168
4	0.8709	69,068	7.00%	0.8692	56,730	0.8692	42,788
5	0.8714	68,715	10.98%	0.8696	56,784	0.8687	44,976
6				0.8692	57,610		

Note: The lever arm of the third LVDT was resting on the bolt head.

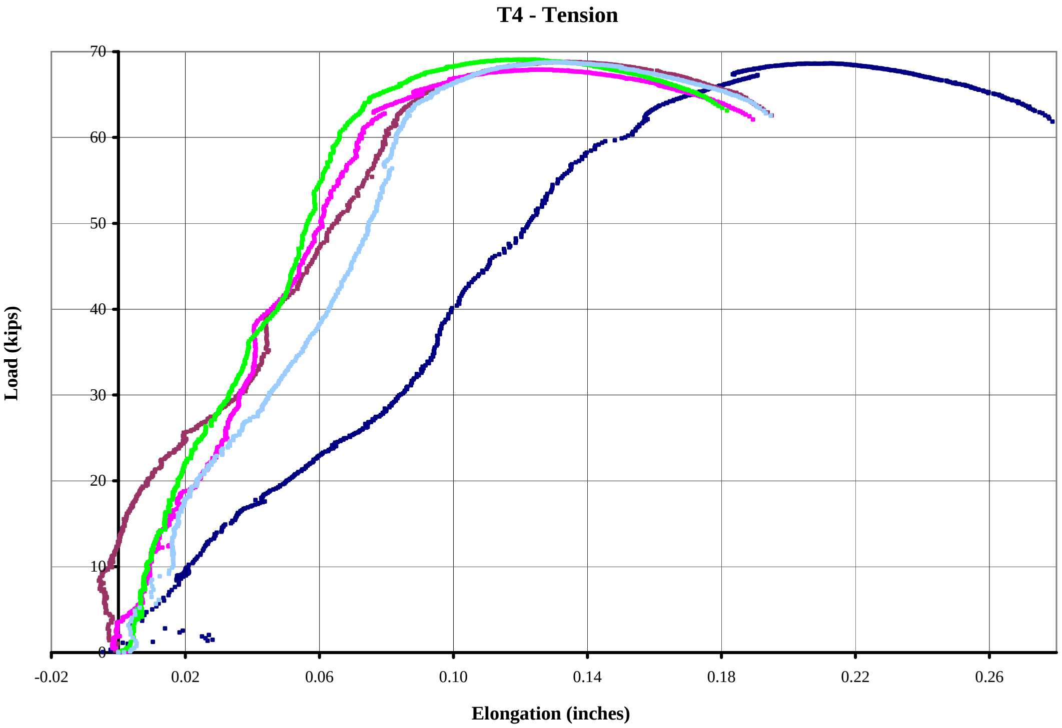

Figure A-43: Lot T4 – 7/8-inch A325 – Tension

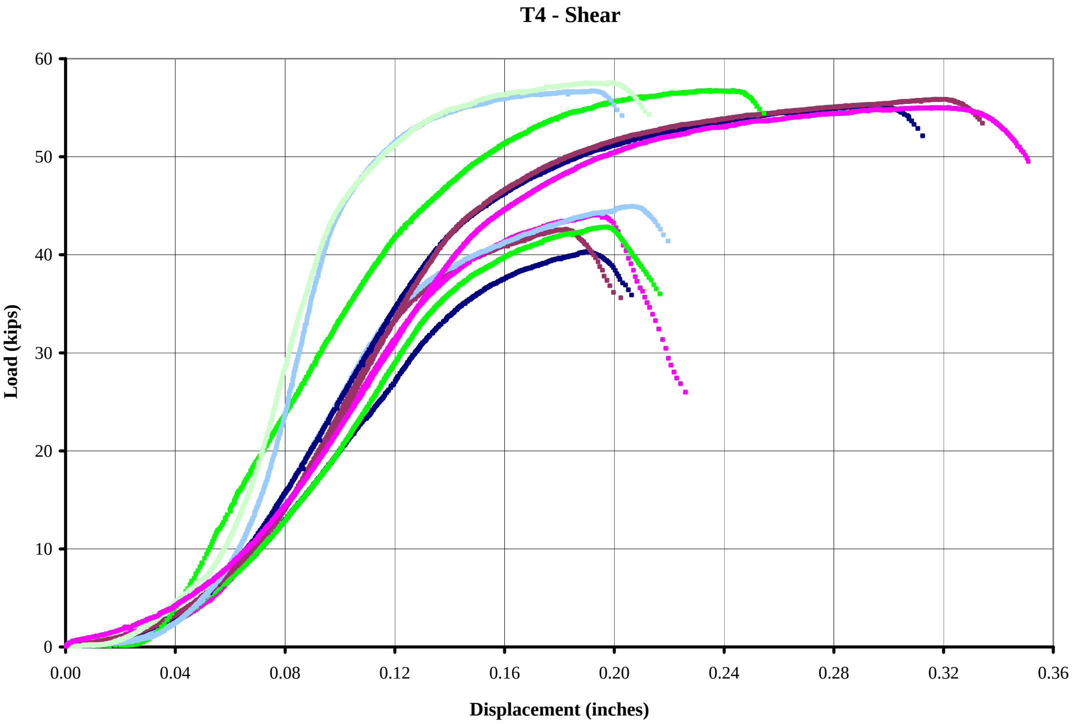

Figure A-44: Lot T4 – 7/8-inch A325 – Shear

T5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.25"
Grade:	A325
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.6205 inches

Table A-23: Lot T5 – 7/8-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8672	70,795	11.32%	0.8683	57,408	0.8673	43,372
2	0.8683	70,182	8.42%	0.8689	57,620	0.8670	43,656
3	0.8686	69,447	6.42%	0.8683	57,894	0.8684	43,310
4	0.8692	69,861	6.85%	0.8684	57,429	0.8682	42,063
5	0.8693	70,626	8.58%	0.8685	57,163	0.8685	41,187
6				0.8684	57,660		

Note: The lever arm of the third LVDT was resting on the bolt head.

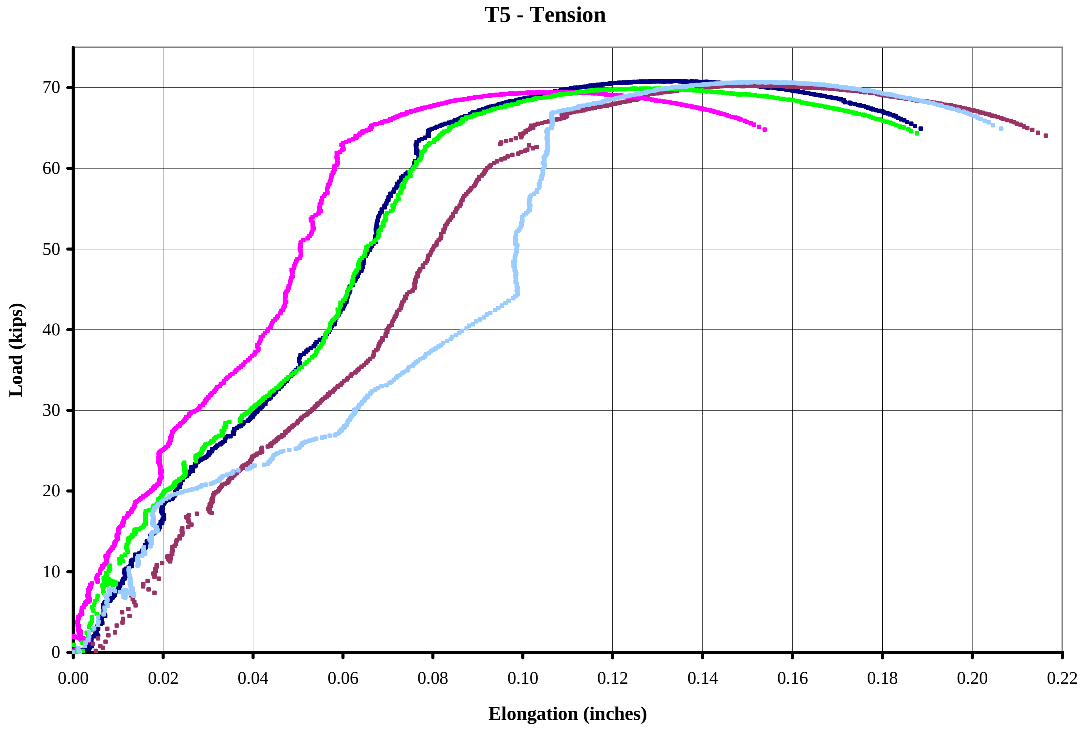

Figure A-45: Lot T5 – 7/8-inch A325 – Tension

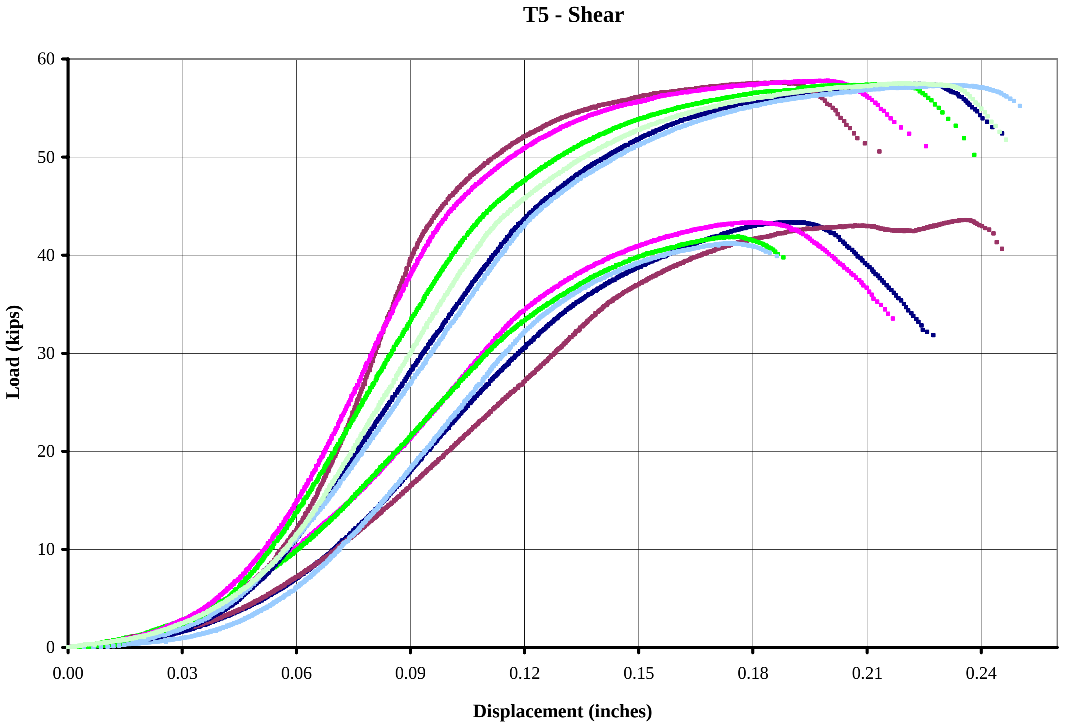

Figure A-46: Lot T5 – 7/8-inch A325 – Shear

B8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.25"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8415 inches

Table A-24: Lot B8 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.4875 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9888	87,459	9.31%	0.9893	68,409	0.9898	52,055
2	0.9880	86,709	7.36%	0.9897	68,701	0.9892	50,318
3	0.9898	89,312	6.60%	0.9895	68,023	0.9901	50,354
4	0.9890	87,989	9.34%	0.9899	68,124	0.9883	47,456
5	0.9886	87,956	9.96%	0.9890	68,513	0.9885	48,933
6	0.9880	88,378	9.15%			0.9893	46,111

Note: The lever arm of the third LVDT was resting on the bolt head.

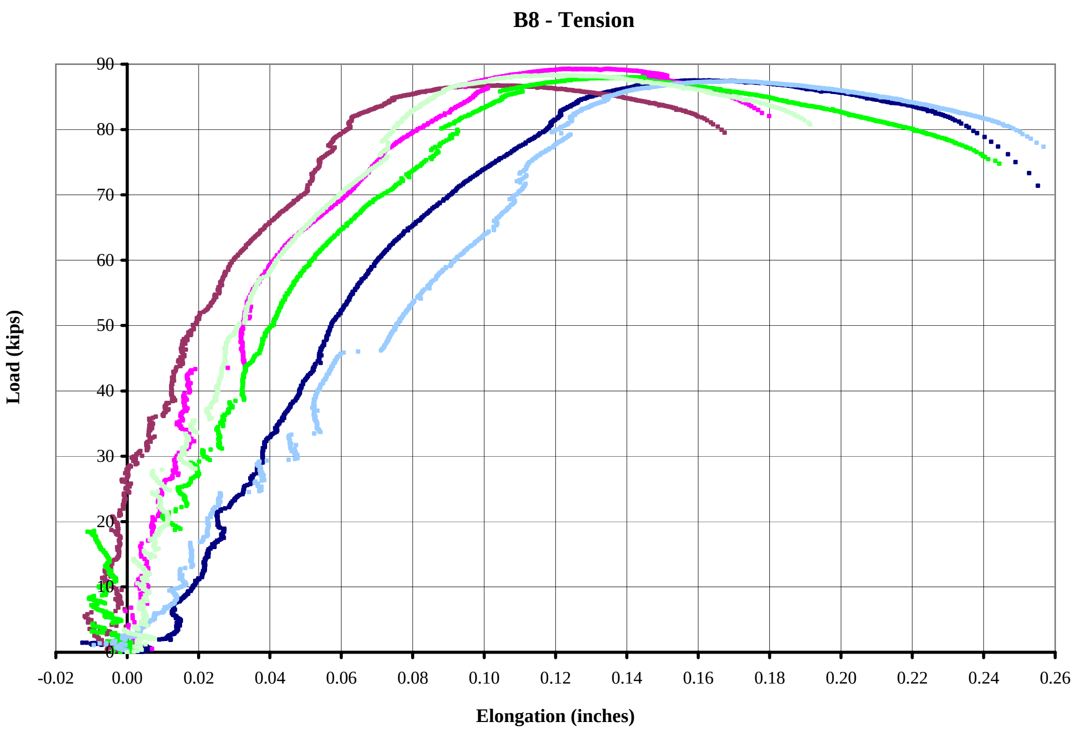

Figure A-47: Lot B8 – 1-inch A325 – Tension

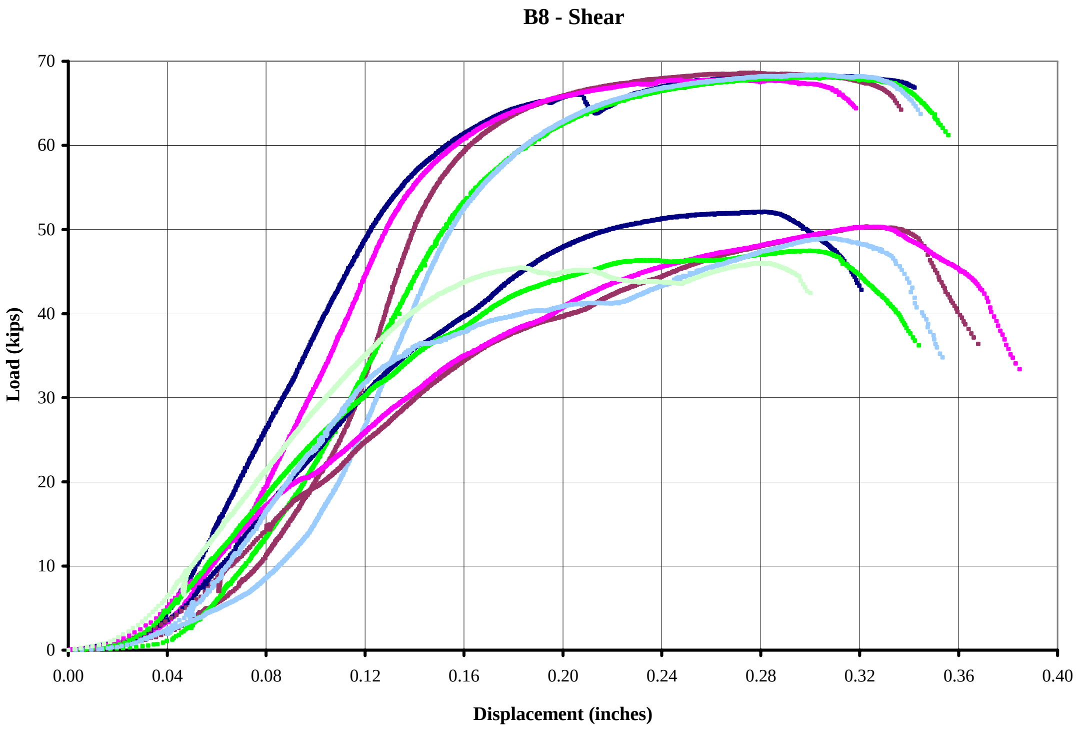

Figure A-48: Lot B8 – 1-inch A325 – Shear

B9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.5"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8130 inches

Table A-25: Lot B9 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.525 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9894	89,326	8.80%	0.9900	67,958	0.9901	53,392
2	0.9892	89,312	14.09%	0.9904	67,356	0.9906	52,697
3	0.9896	87,614	16.96%	0.9905	68,344	0.9905	52,264
4	0.9888	88,454	16.08%	0.9898	67,792	0.9899	49,853
5	0.9878	88,421	9.60%	0.9897	67,710	0.9893	51,168

Note: The lever arm of the third LVDT was resting on the bolt head.

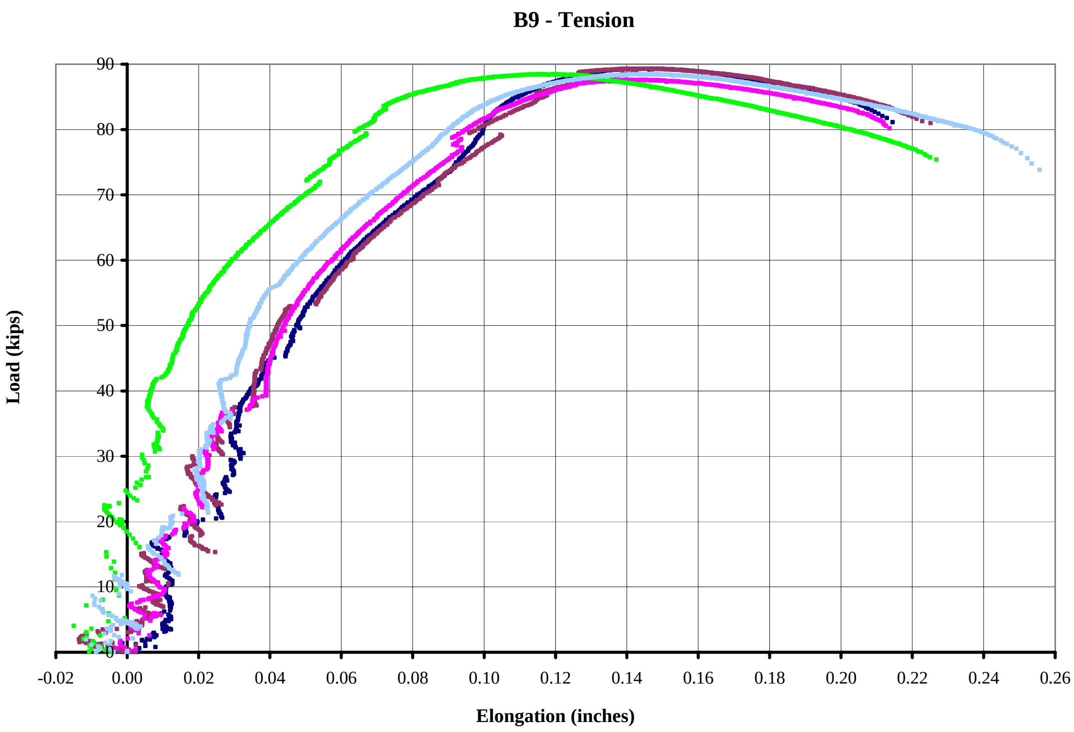

Figure A-49: Lot B9 – 1-inch A325 – Tension

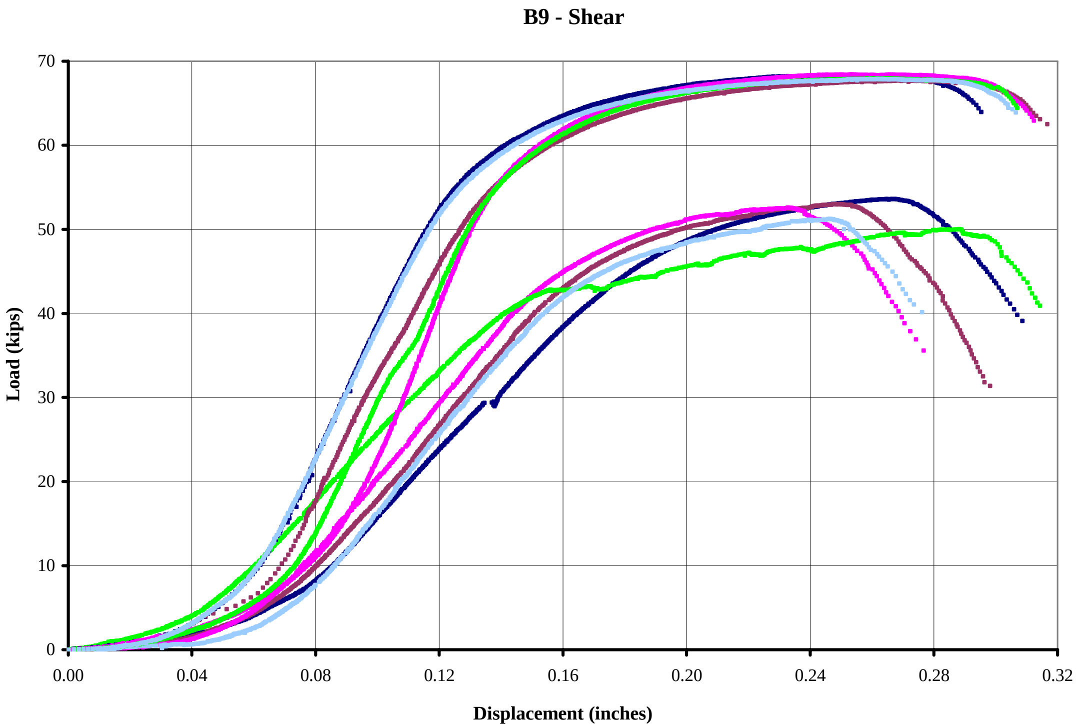

Figure A-50: Lot B9 – 1-inch A325 – Shear

B10

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8300 inches

Table A-26: Lot B10 – 1-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.6 in/min			Load Rate: 0.5 in/min		Load Rate: 0.5 in/min	
	Average Diameter (inches)	Failure Load (pounds)	Elongation	Average Diameter (inches)	Failure Load (pounds)	Average Diameter (inches)	Failure Load (pounds)
1	0.9910	88,785	10.55%	0.9917	68,683	0.9918	50,501
2	0.9904	87,686	10.44%	0.9922	68,095	0.9917	54,311
3	0.9906	88,811	14.10%	0.9918	68,423	0.9919	50,285
4	0.9922	87,574	12.10%	0.9918	68,946	0.9920	51,687
5	0.9900	88,501	12.79%	0.9913	67,317	0.9916	50,242

Note: The lever arm of the third LVDT was resting on the bolt head.

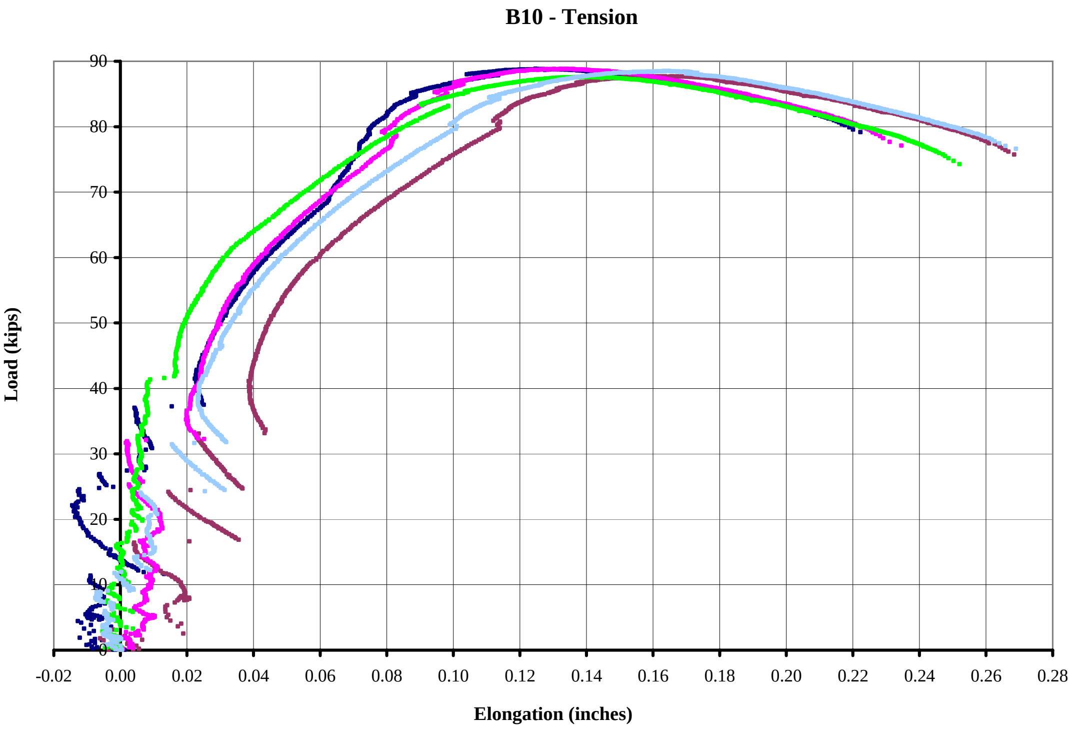

Figure A-51: Lot B10 – 1-inch A325 – Tension

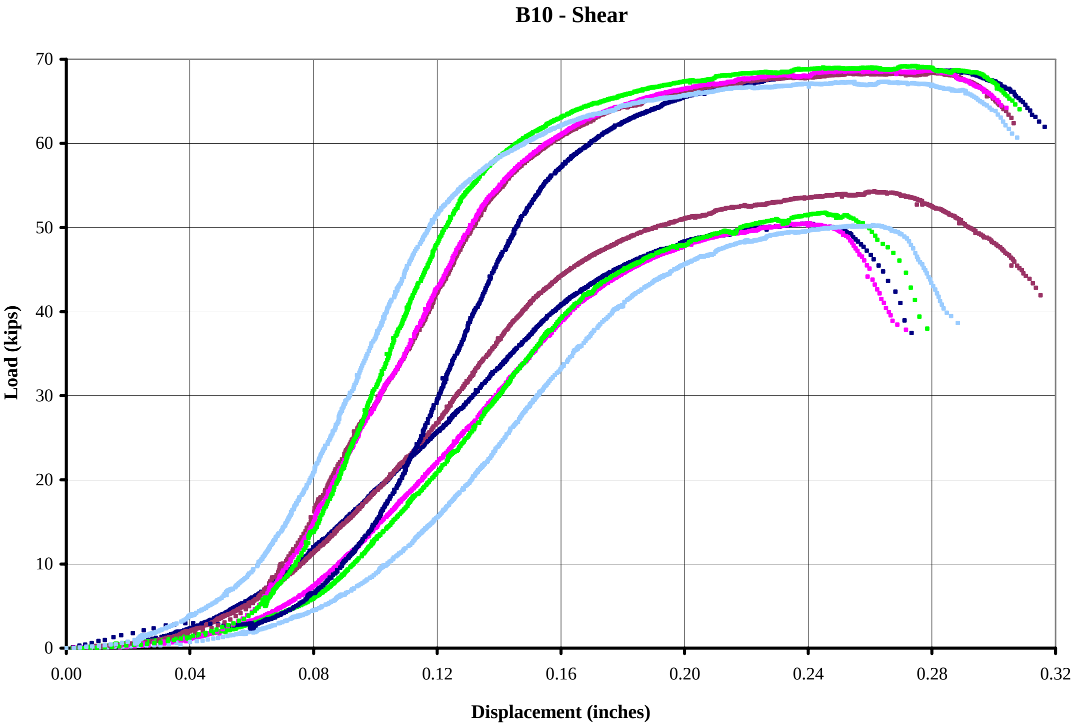

Figure A-52: Lot B10 – 1-inch A325 – Shear

B11

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4.75"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8480 inches

Table A-27: Lot B11 – 1-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.7125 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9898	85,347	11.63%	0.9925	65,904	0.9919	49,438
2	0.9939	84,611	12.45%	0.9920	65,280	0.9923	52,365
3	0.9938	85,624	11.85%	0.9921	65,734	0.9919	50,894
4	0.9916	85,217	12.99%	0.9902	65,421	0.9922	51,294
5	0.9932	85,195	11.20%	0.9925	64,574	0.9922	51,507

Note: The lever arm of the third LVDT was resting on the bolt head.

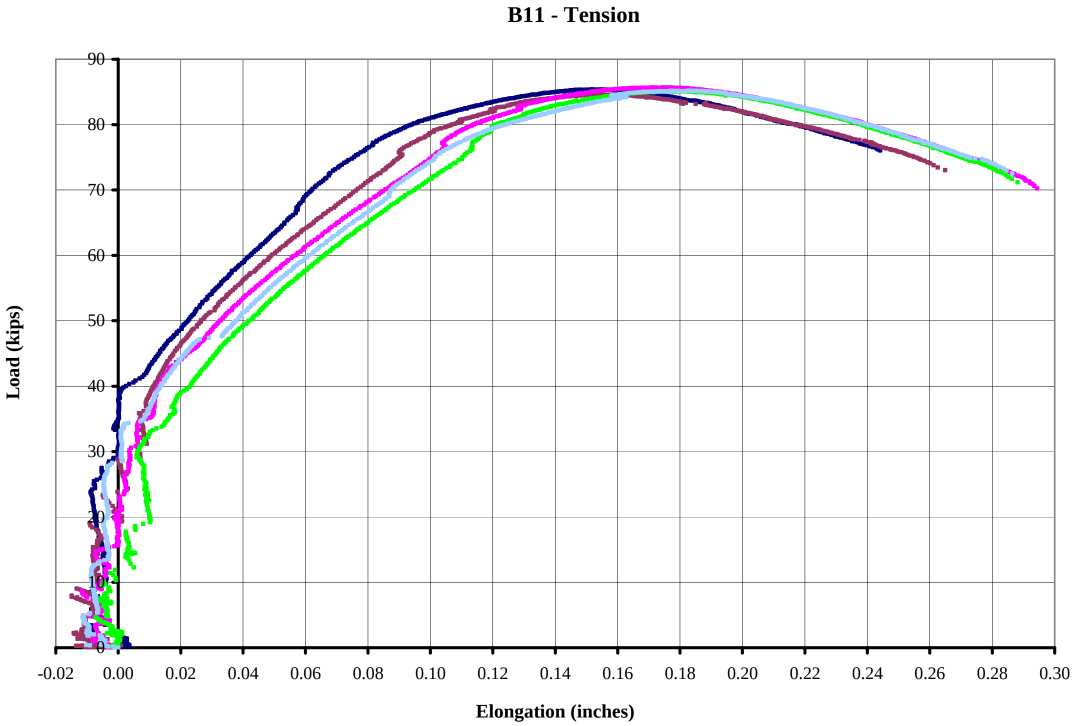

Figure A-53: Lot B11 – 1-inch A325 – Tension

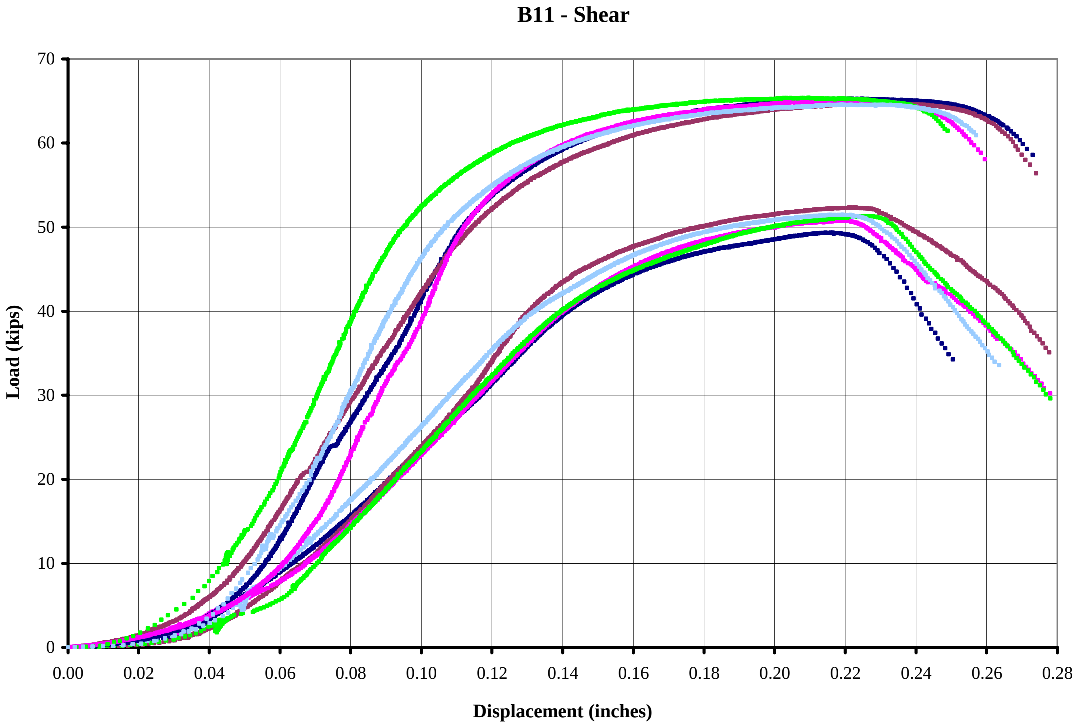

Figure A-54: Lot B11 – 1-inch A325 – Shear

L5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8545 inches

Table A-28: Lot L5 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.45 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9989	88,072	4.04%	0.9940	66,560	0.9962	52,516
2	0.9976	87,819	3.88%	0.9956	67,645	0.9960	51,532
3	0.9971	87,286	5.39%	0.9959	66,502	0.9962	53,122
4	0.9985	88,663	4.72%	0.9955	64,862	0.9959	54,578
5	0.9992	88,349	3.86%	0.9957	67,904	0.9960	51,759
6	1.0008	88,158	4.31%				
7	0.9980	87,942	4.88%				
8	0.9989	90,000	2.35%				
9	0.9969	87,690	3.86%				

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for T1 through T4 were not recorded for the Load versus
Elongation graph due to technical problems.

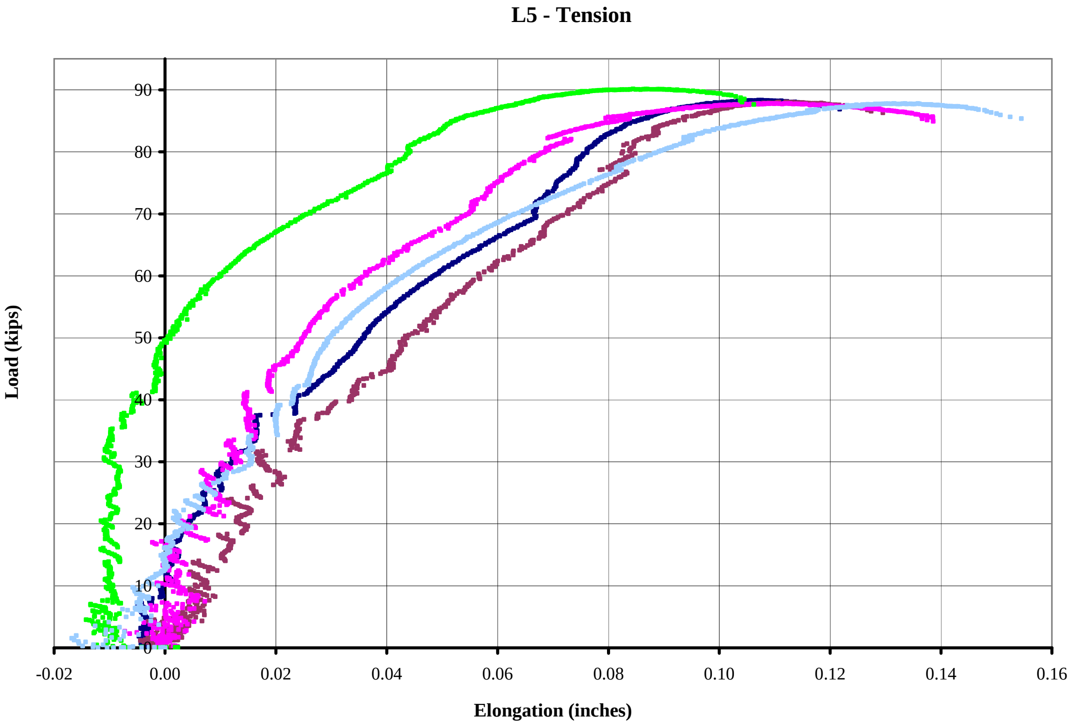

Figure A-55: Lot L5 – 1-inch A325 – Tension

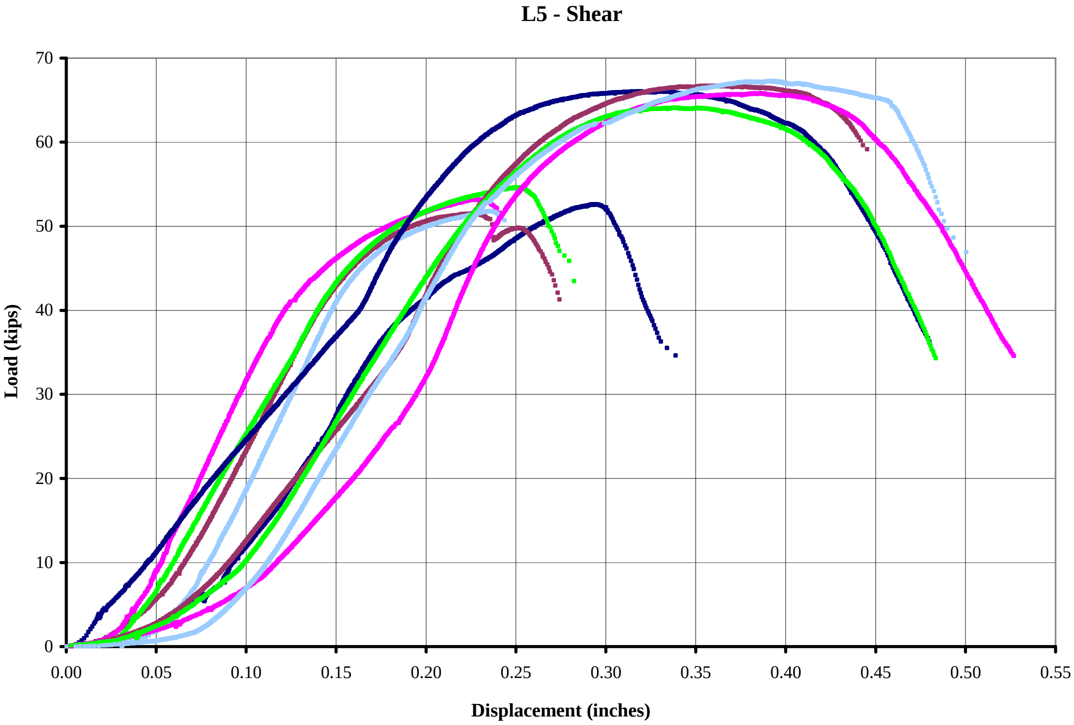

Figure A-56: Lot L5 – 1-inch A325 – Shear

L6

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 5"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8825 inches

Table A-29: Lot L6 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9952	89,229	7.01%	0.9932	69,548	0.9923	52,952
2	0.9941	88,273	4.83%	0.9926	69,865	0.9922	52,098
3	0.9943	88,227	7.97%	0.9913	68,989	0.9924	52,278
4	0.9961	89,232	7.12%	0.9920	69,151	0.9923	52,109
5	0.9942	88,998	6.06%	0.9920	68,986	0.9920	53,331

Note: The lever arm of the third LVDT was resting on the bolt head.

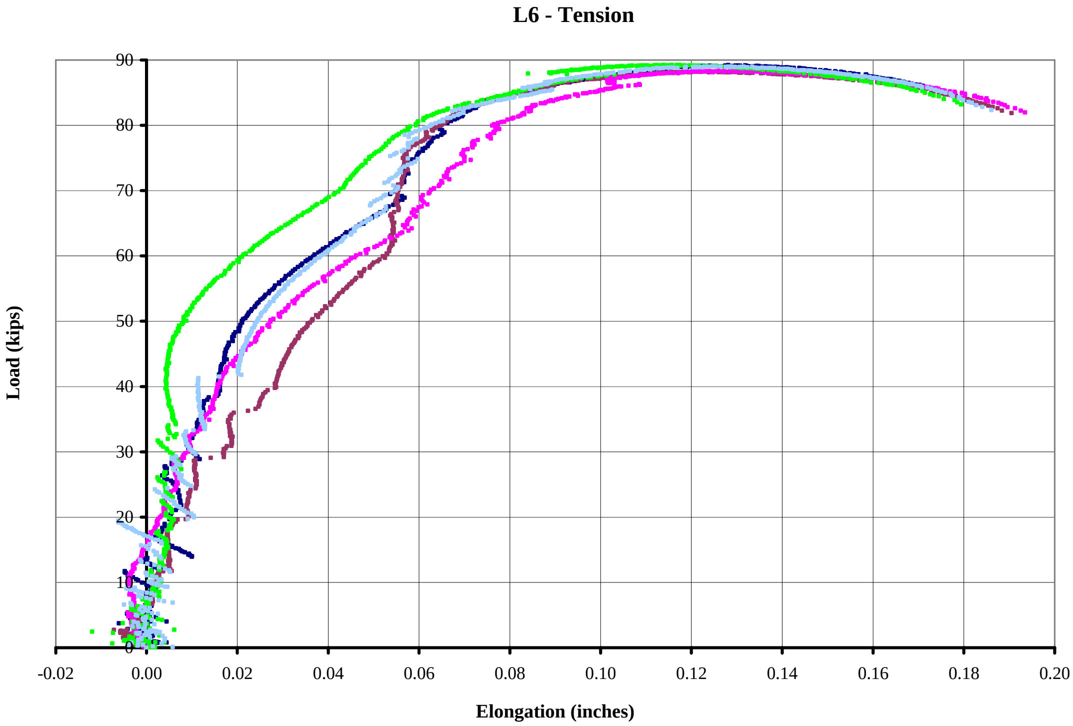

Figure A-57: Lot L6 – 1-inch A325 – Tension

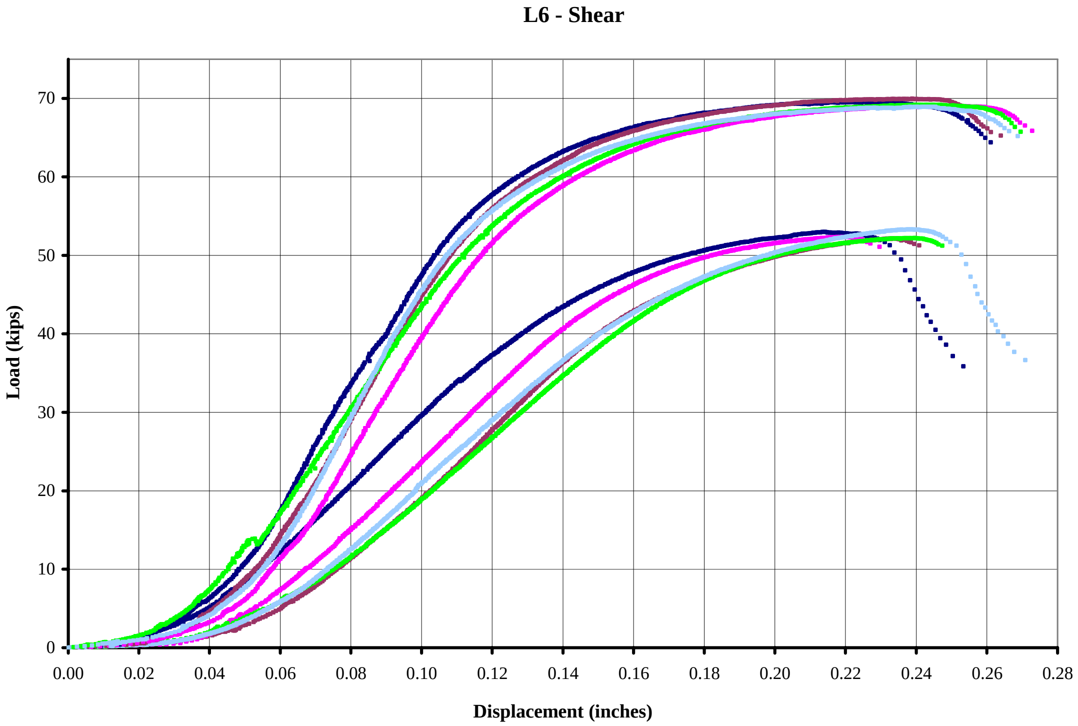

Figure A-58: Lot L6 – 1-inch A325 – Shear

N6

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8445 inches

Table A-30: Lot N6 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9942	81,583	5.31%	0.9950	68,895	0.9942	53,738
2	0.9943	88,082	5.34%	0.9942	68,899	0.9935	53,381
3	0.9956	85,148	6.13%	0.9943	67,360	0.9942	52,145
4	0.9973	83,833	7.56%	0.9938	69,400	0.9947	50,851
5	0.9955	87,653	7.32%	0.9939	66,996	0.9947	54,499

Note: The lever arm of the third LVDT was resting on the bolt head.

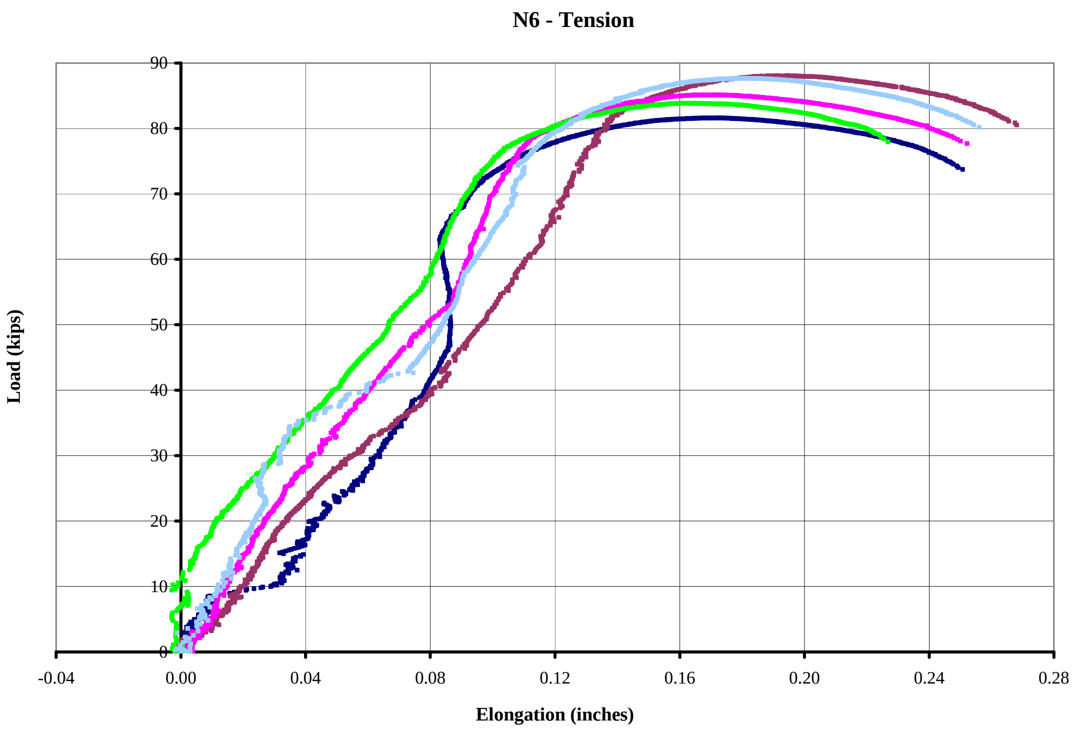

Figure A-59: Lot N6 – 1-inch A325 – Tension

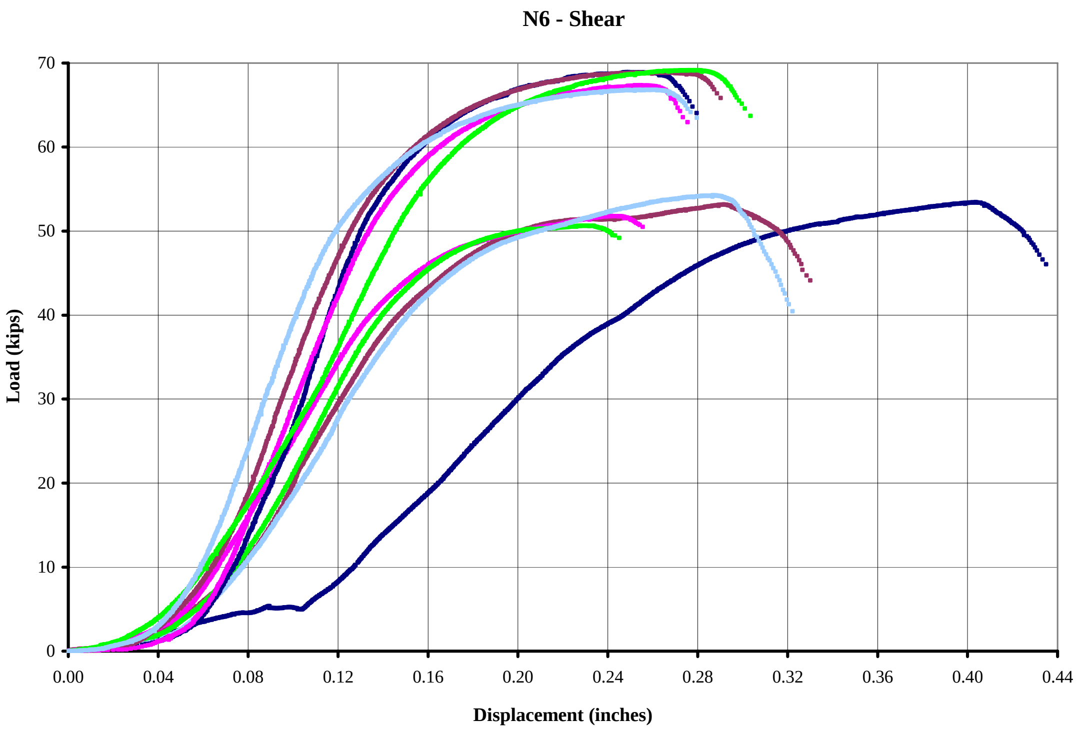

Figure A-60: Lot N6 – 1-inch A325 – Shear

N7

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4.5"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8720 inches

Table A-31: Lot N7 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9965	89,722	7.18%	0.9938	69,634	0.9936	50,404
2	0.9948	89,596	5.29%	0.9934	69,851	0.9938	54,542
3	0.9956	89,409	5.69%	0.9935	69,238	0.9933	55,022
4	0.9935	90,209	N/A	0.9935	69,584	0.9935	53,266
5	0.9973	89,809	3.93%	0.9939	69,079	0.9939	52,181

Note: The lever arm of the third LVDT was resting on the bolt head.

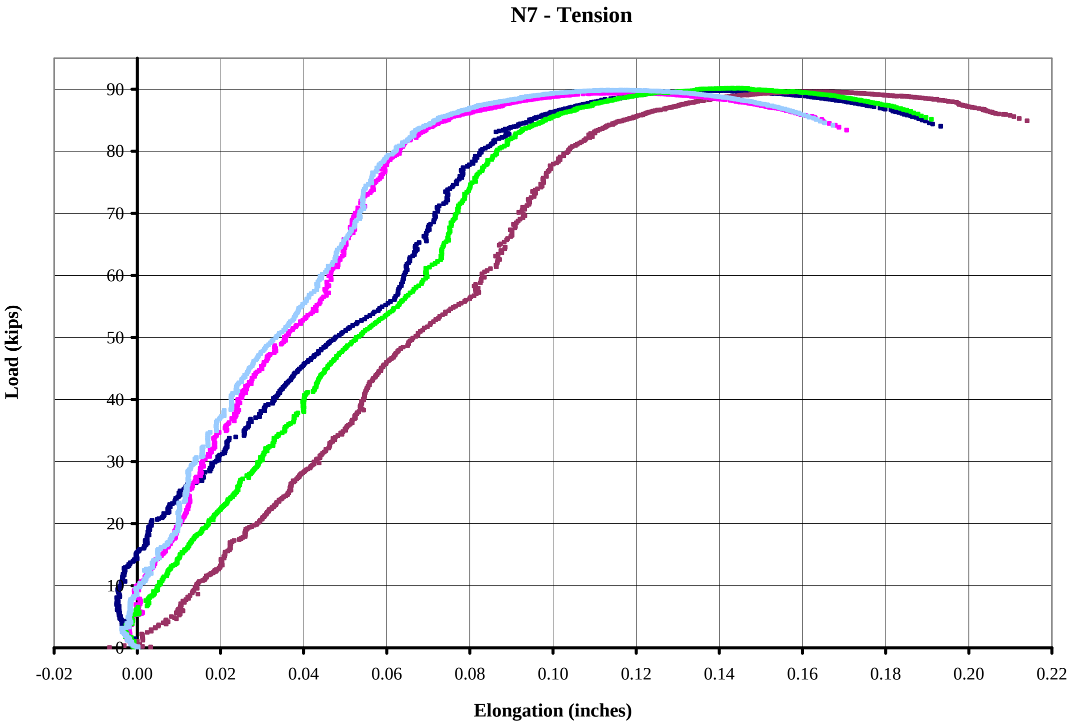

Figure A-61: Lot N7 – 1-inch A325 – Tension

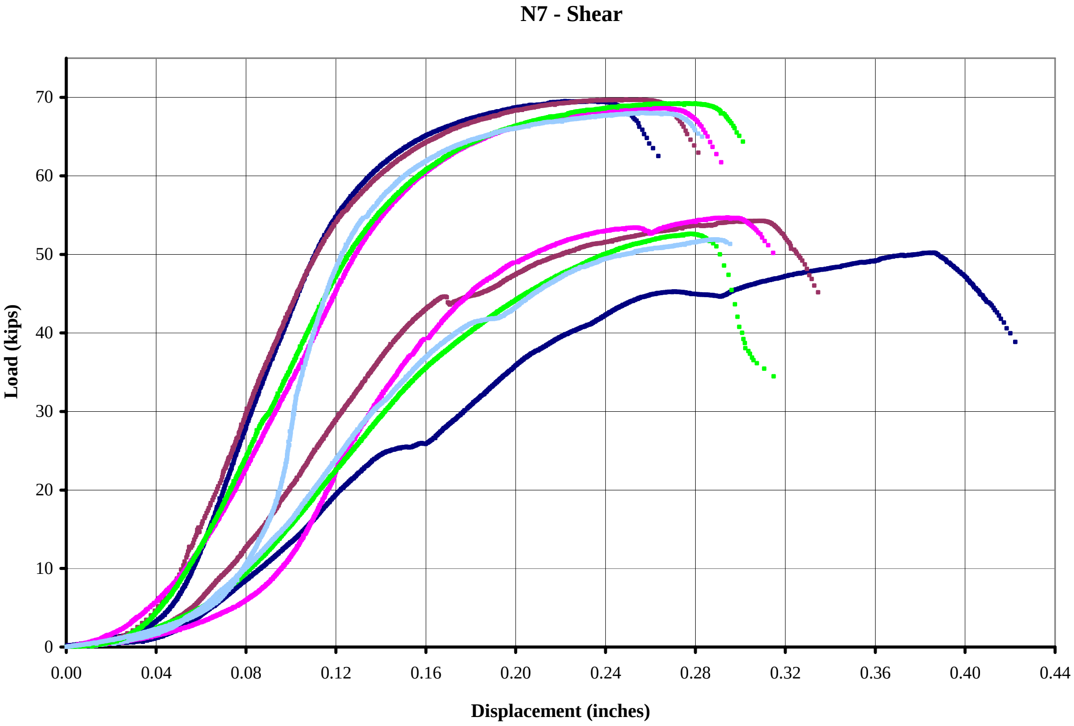

Figure A-62: Lot N7 – 1-inch A325 – Shear

T7

Bolt Properties:	
Manufacturer:	
Lot Number:	
Size:	1"-8 x 4.25"
Grade:	A325
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8435 inches

Table A-32: Lot T7 – 1-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9961	90,872	12.58%	0.9948	72,922	0.9937	55,501
2	0.9952	90,184	13.26%	0.9943	73,347	0.9939	56,438
3	0.9974	90,191	10.28%	0.9935	71,887	0.9941	56,265
4	0.9966	91,701	11.66%	0.9935	72,896	0.9935	54,913
5	0.9962	91,979	9.57%	0.9933	72,194	0.9936	53,363

Note: The lever arm of the third LVDT was resting on the bolt head.

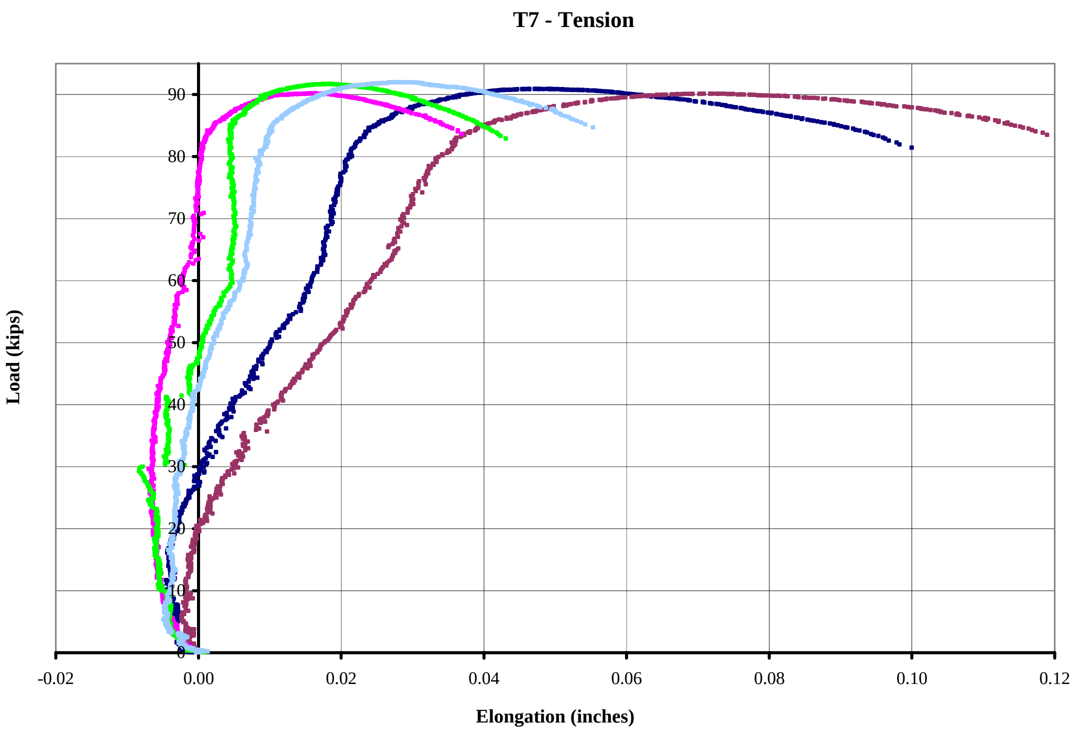

Figure A-63: Lot T7 – 1-inch A325 – Tension

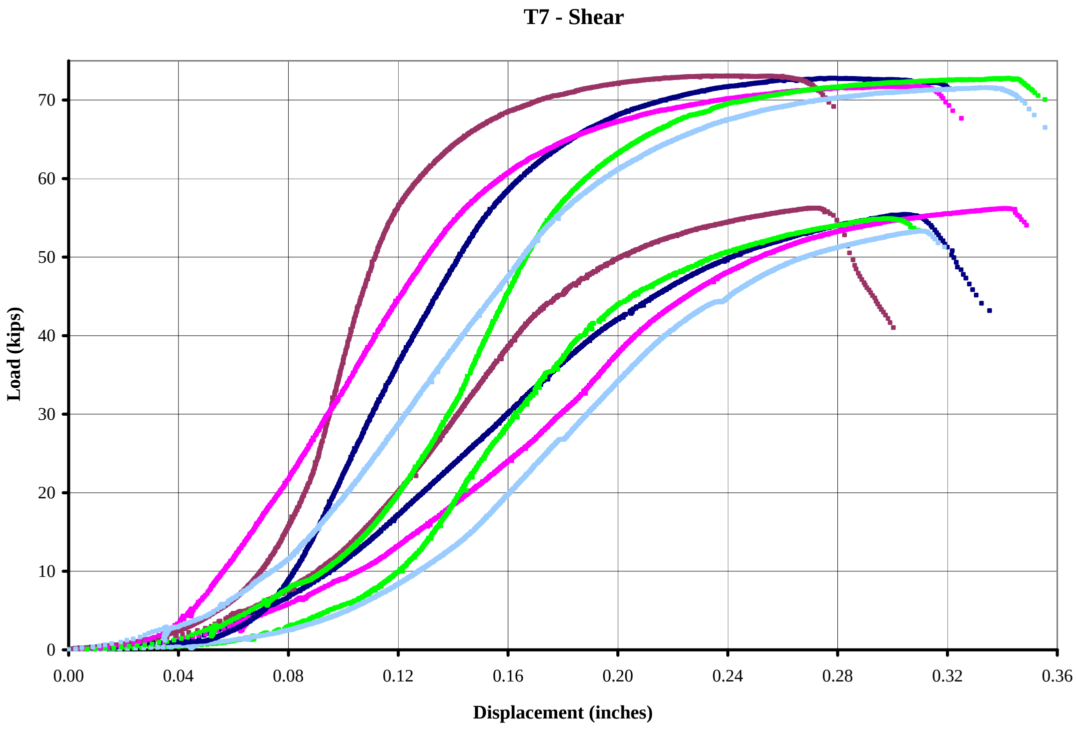

Figure A-64: Lot T7 – 1-inch A325 – Shear

F1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1475 inches

Table A-33: Lot F1 – 1-1/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1195	98,161	9.67%	1.1191	80,834	1.1180	58,705
2	1.1196	97,941	11.77%	1.1186	78,181	1.1180	62,173
3	1.1198	98,950	12.95%	1.1182	81,248	1.1188	61,740
4	1.1194	98,849	8.45%	1.1193	81,464	1.1188	62,609
5	1.1196	96,088	12.11%	1.1190	82,510	1.1191	62,851

Note: The lever arm of the third LVDT was resting on the angle.

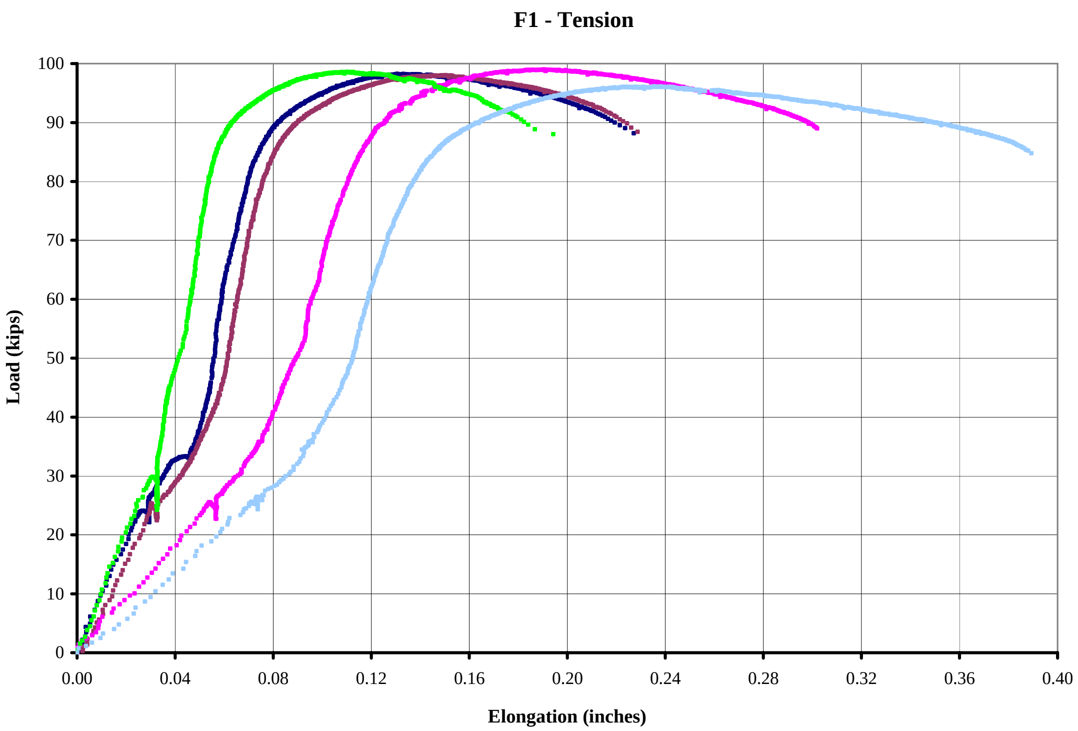

Figure A-65: Lot F1 – 1-1/8-inch A325 – Tension

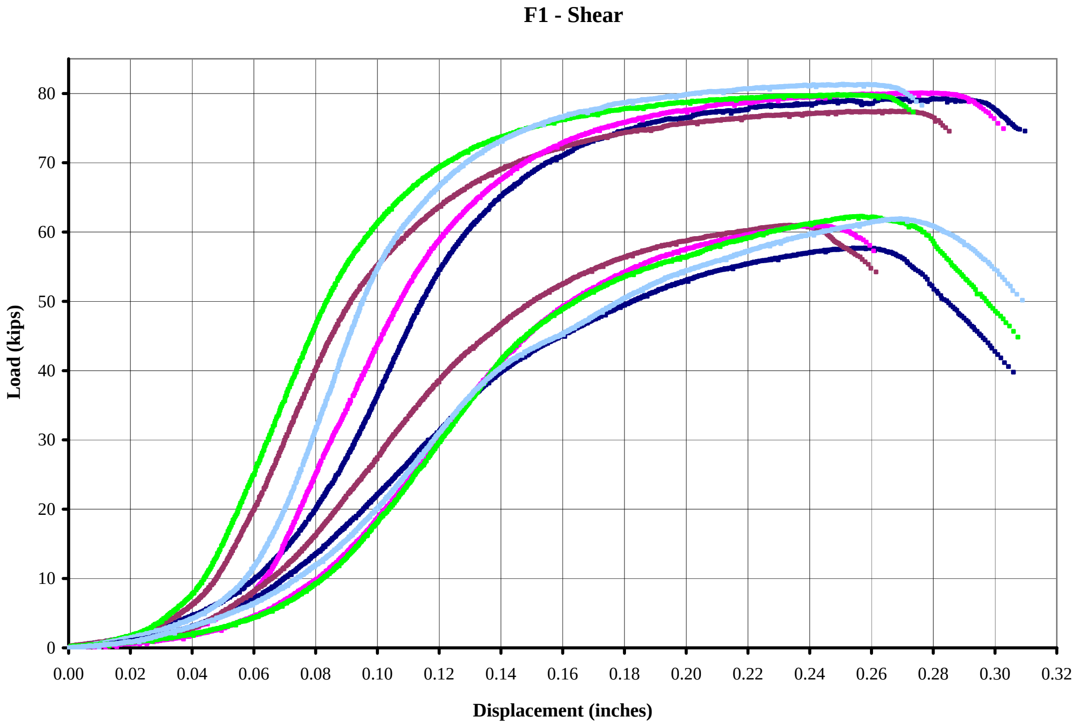

Figure A-66: Lot F1 – 1-1/8-inch A325 – Shear

L8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.25"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1580 inches

Table A-34: Lot L8 – 1-1/8-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.6375 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1186	101,729	5.07%	1.1194	82,427	1.1208	65,078
2	1.1195	101,657	6.36%	1.1205	81,299	1.1194	64,336
3	1.1196	100,453	5.88%	1.1193	81,392	1.1219	60,479
4	1.1200	101,106	5.67%	1.1205	80,848	1.1210	64,966
5	1.1198	99,199	6.49%	1.1201	80,801	1.1192	62,472
6						1.1213	63,478

Note: The lever arm of the third LVDT was resting on the angle.

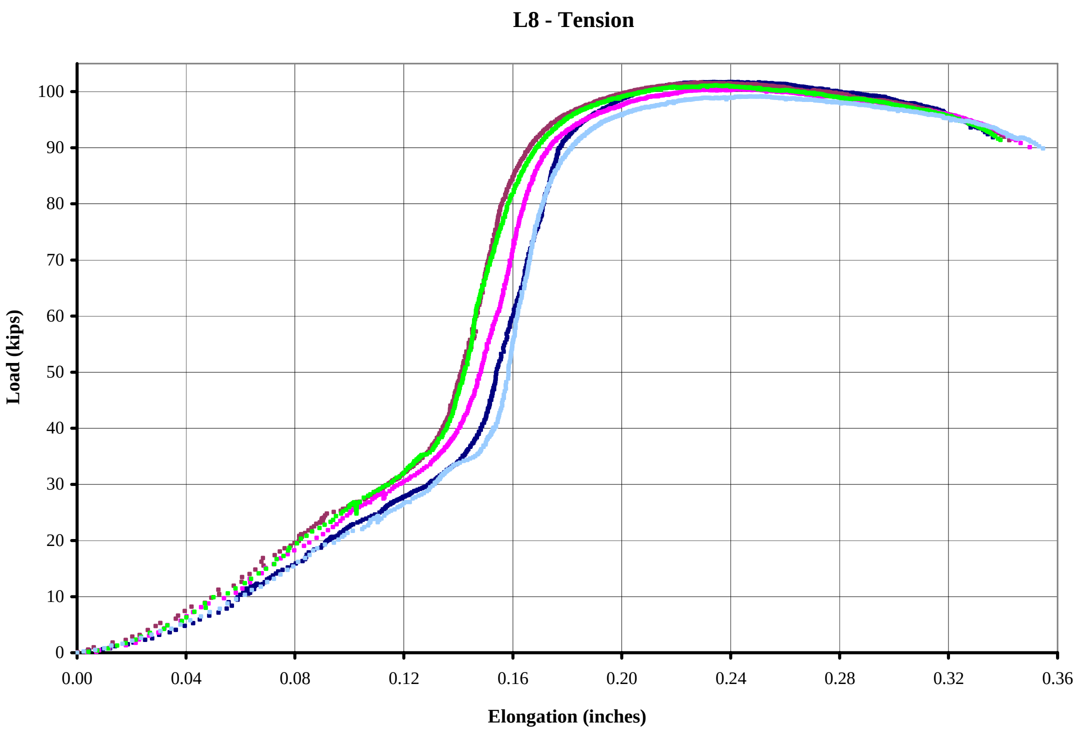

Figure A-67: Lot L8 – 1-1/8-inch A325 – Tension

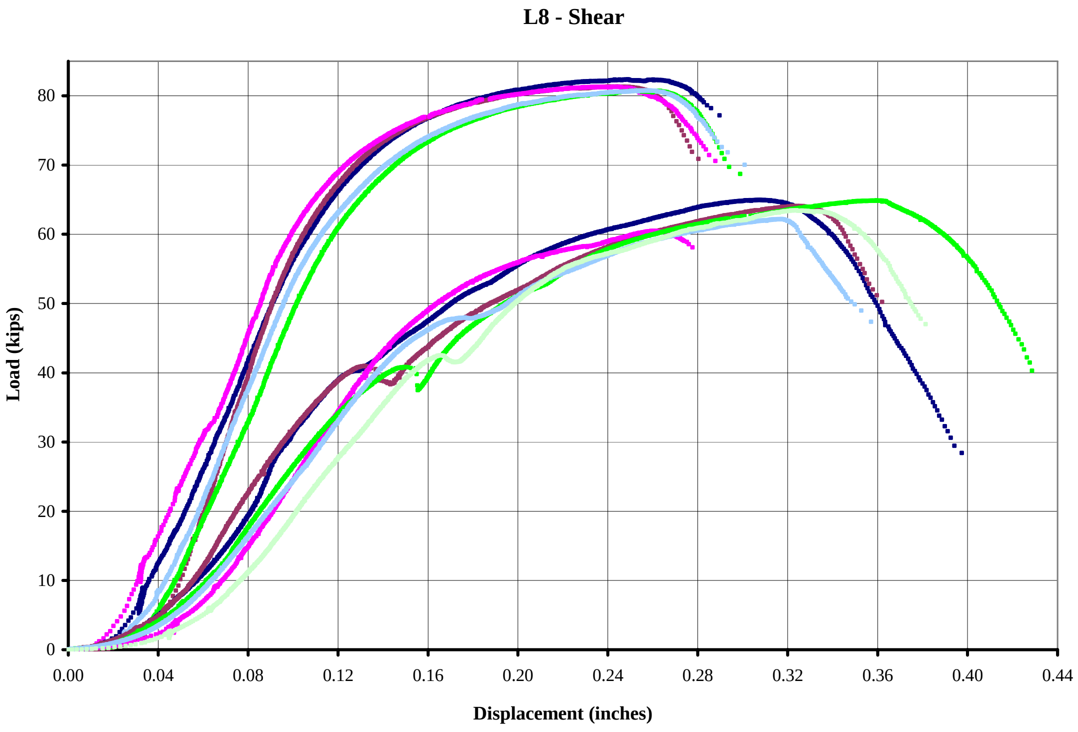

Figure A-68: Lot L8 – 1-1/8-inch A325 – Shear

N8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.5"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.0930 inches

Table A-35: Lot N8 – 1-1/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1181	105,626	5.84%	1.1188	86,442	1.1187	66,488
2	1.1189	105,795	9.84%	1.1186	85,177	1.1187	65,186
3	1.1180	107,435	5.79%	1.1186	85,188	1.1193	67,735
4	1.1186	107,738	7.77%	1.1169	84,820	1.1154	64,000
5	1.1189	105,240	6.35%	1.1188	85,898	1.1192	66,430
6	1.1184	105,543	5.84%				

Note: The lever arm of the third LVDT was resting on the angle.
Data for T6 was not recorded for the Load versus Elongation graph
due to technical problems.

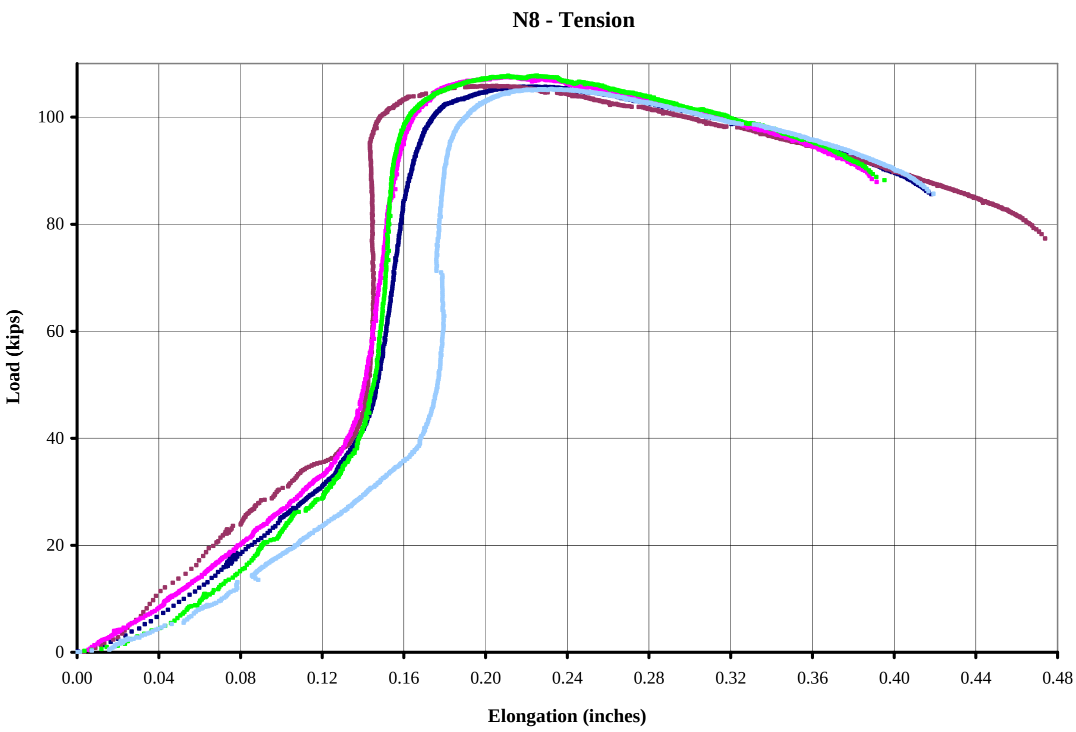

Figure A-69: Lot N8 – 1-1/8-inch A325 – Tension

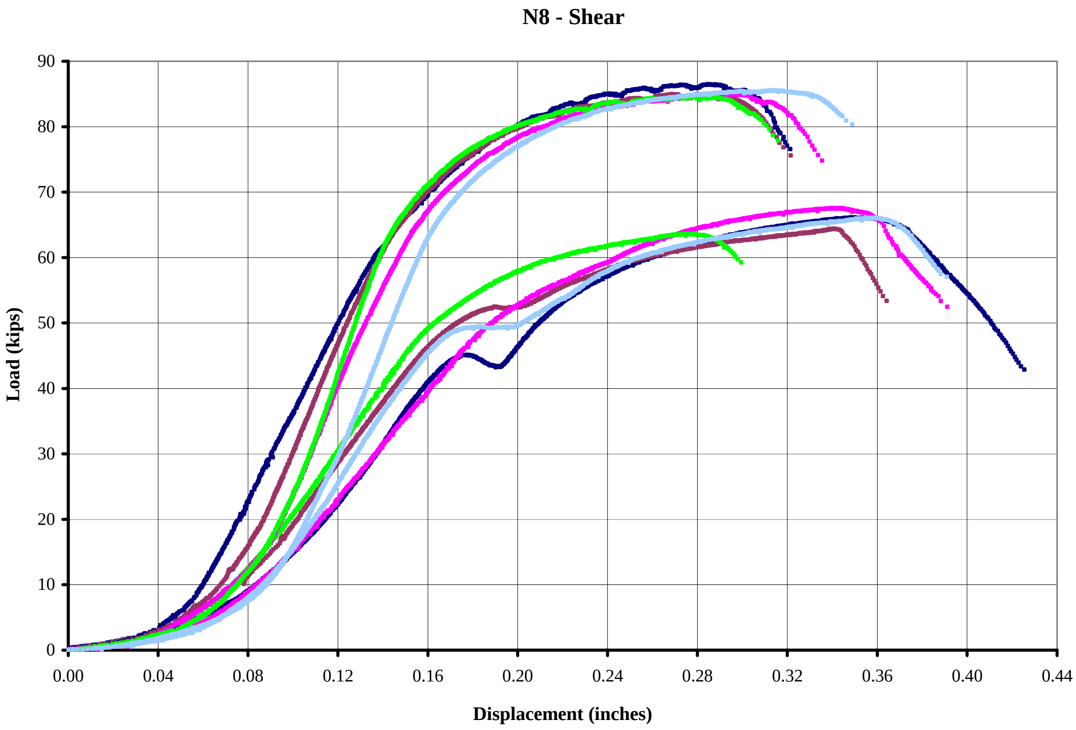

Figure A-70: Lot N8 – 1-1/8-inch A325 – Shear

T8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.25"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1505 inches

Table A-36: Lot T8 – 1-1/8-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1187	101,470	6.63%	1.1202	82,582	1.1188	63,925
2	1.1192	100,327	7.73%	1.1194	83,400	1.1188	65,309
3	1.1194	98,550	7.27%	1.1197	82,066	1.1181	59,340
4	1.1195	100,839	4.65%	1.1204	82,074	1.1189	63,027
5	1.1187	100,493	7.23%	1.1182	80,801	1.1190	63,492

Note: The lever arm of the third LVDT was resting on the angle.

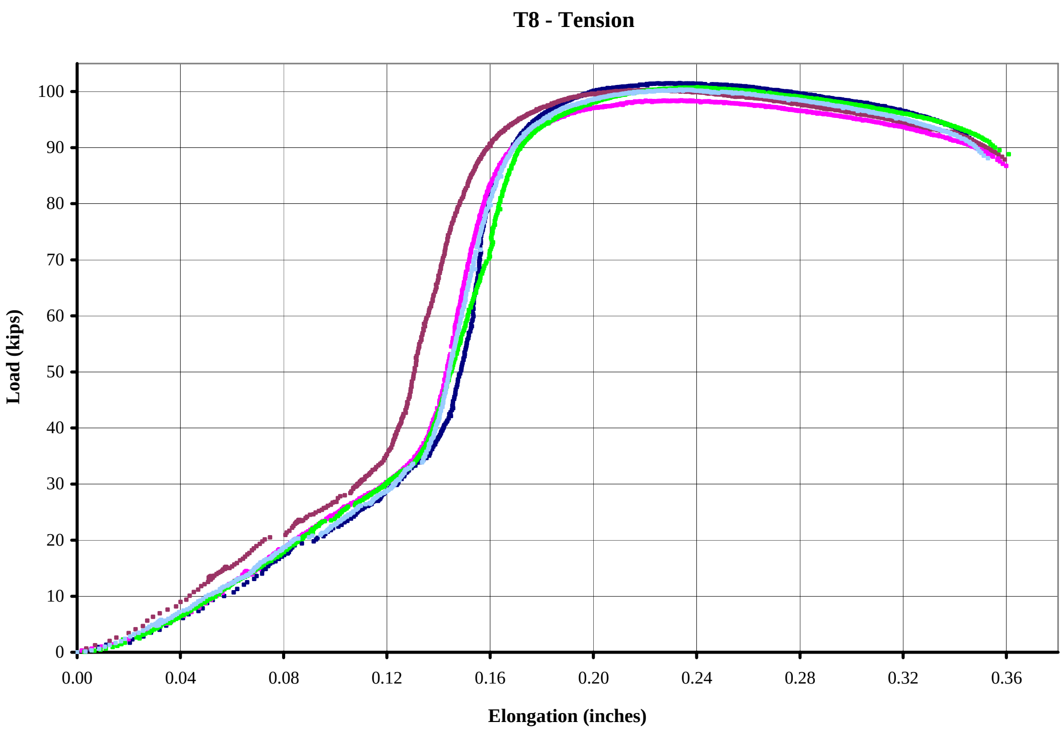

Figure A-71: Lot T8 – 1-1/8-inch A325 – Tension

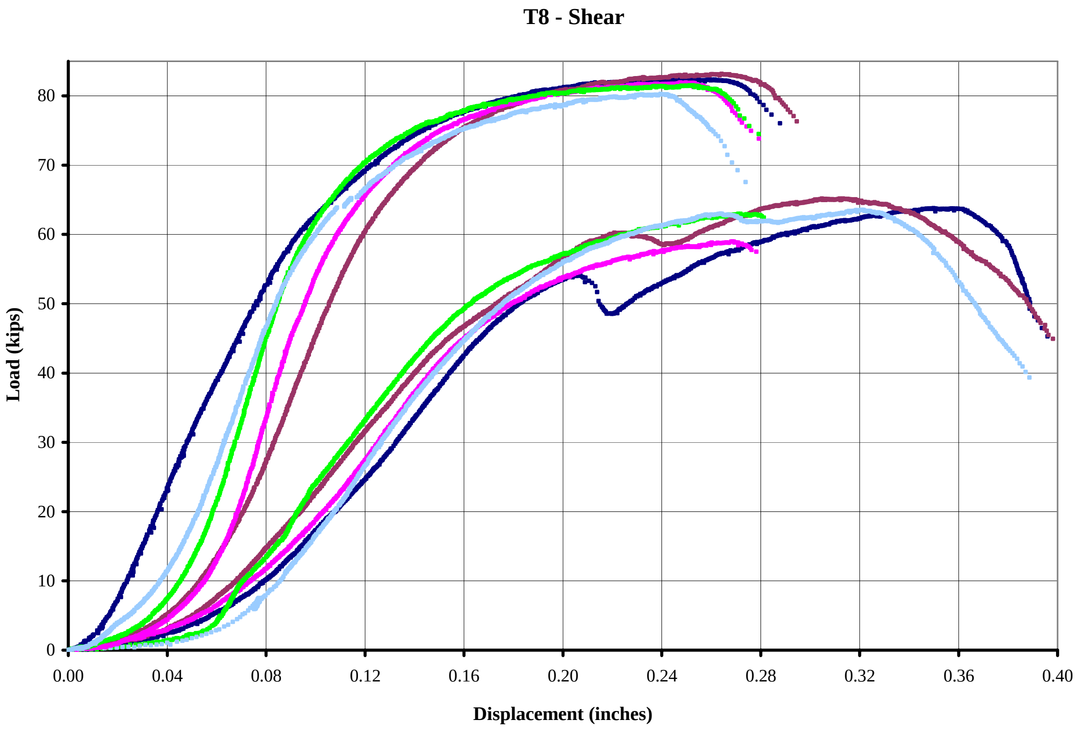

Figure A-72: Lot T8 – 1-1/8-inch A325 – Shear

C3

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.75"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1220 inches

Table A-37: Lot C3 – 1-1/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.7125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2438	127,669	2.56%	1.2443	98,709	1.2444	78,350
2	1.2441	129,473	5.14%	1.2434	98,298	1.2445	74,807
3	1.2435	126,644	3.62%	1.2446	99,563	1.2448	75,823
4	1.2451	126,312	5.26%	1.2444	99,267	1.2435	75,899
5	1.2456	125,475	5.16%	1.2438	99,448	1.2441	76,112

Note: The lever arm of the third LVDT was resting on the angle.

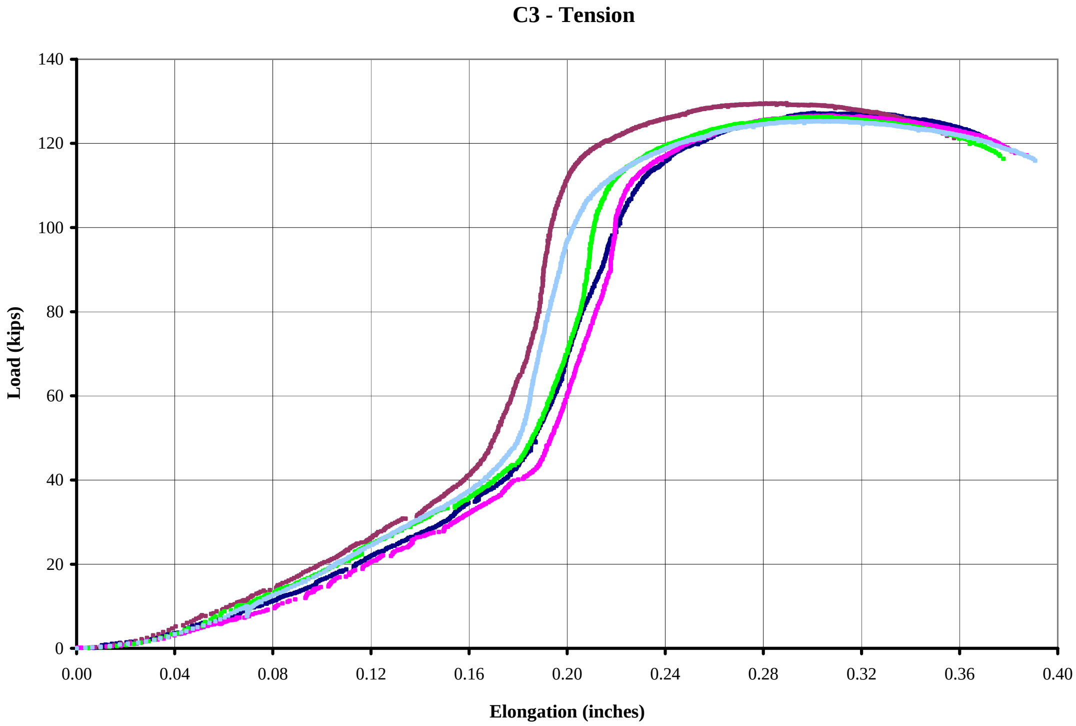

Figure A-73: Lot C3 – 1-1/4-inch A325 – Tension

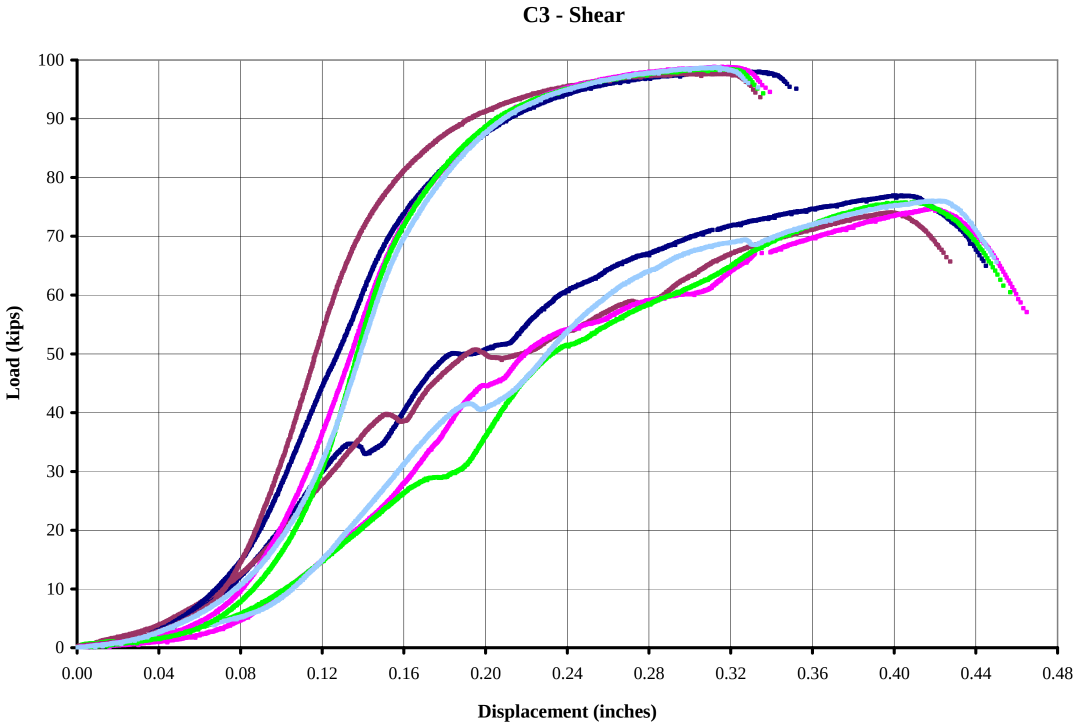

Figure A-74: Lot C3 – 1-1/4-inch A325 – Shear

C4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 5"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.0820 inches

Table A-38: Lot C4 – 1-1/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2438	135,506	7.71%	1.2432	99,458	1.2417	79,594
2	1.2436	133,918	6.13%	1.2433	101,124	1.2426	82,784
3	1.2432	134,019	4.48%	1.2423	97,800	1.2429	78,329
4	1.2434	128,174	6.78%	1.2429	100,403	1.2422	79,511
5	1.2427	136,270	6.36%	1.2426	100,514	1.2431	76,883

Note: The lever arm of the third LVDT was resting on the angle.

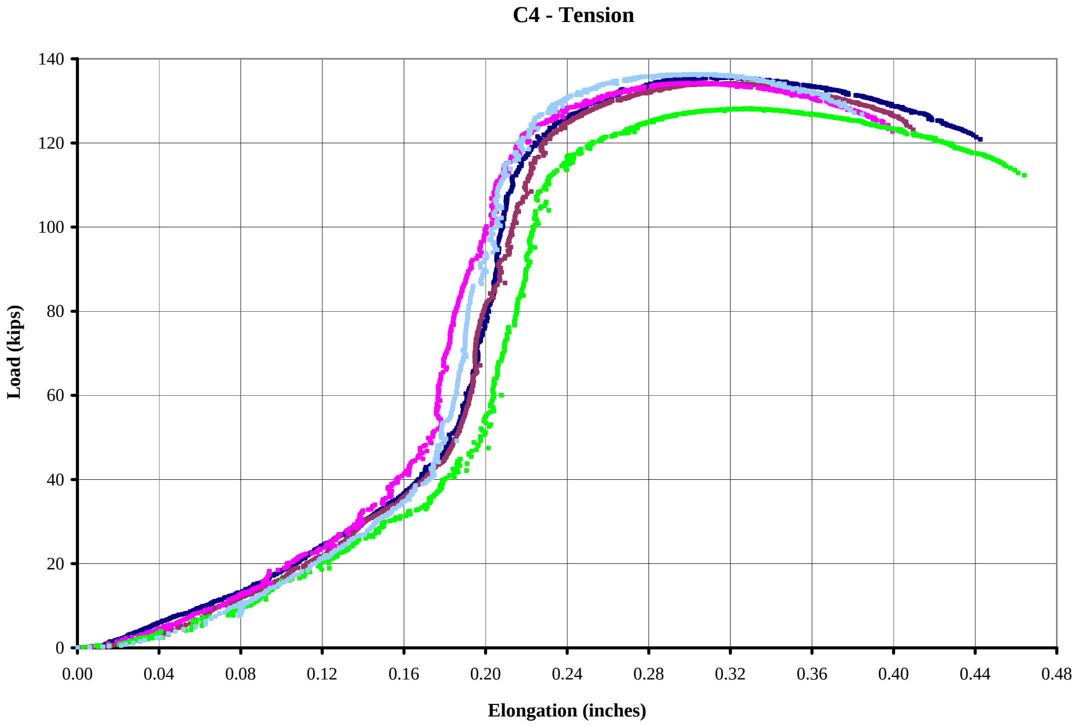

Figure A-75: Lot C4 – 1-1/4-inch A325 – Tension

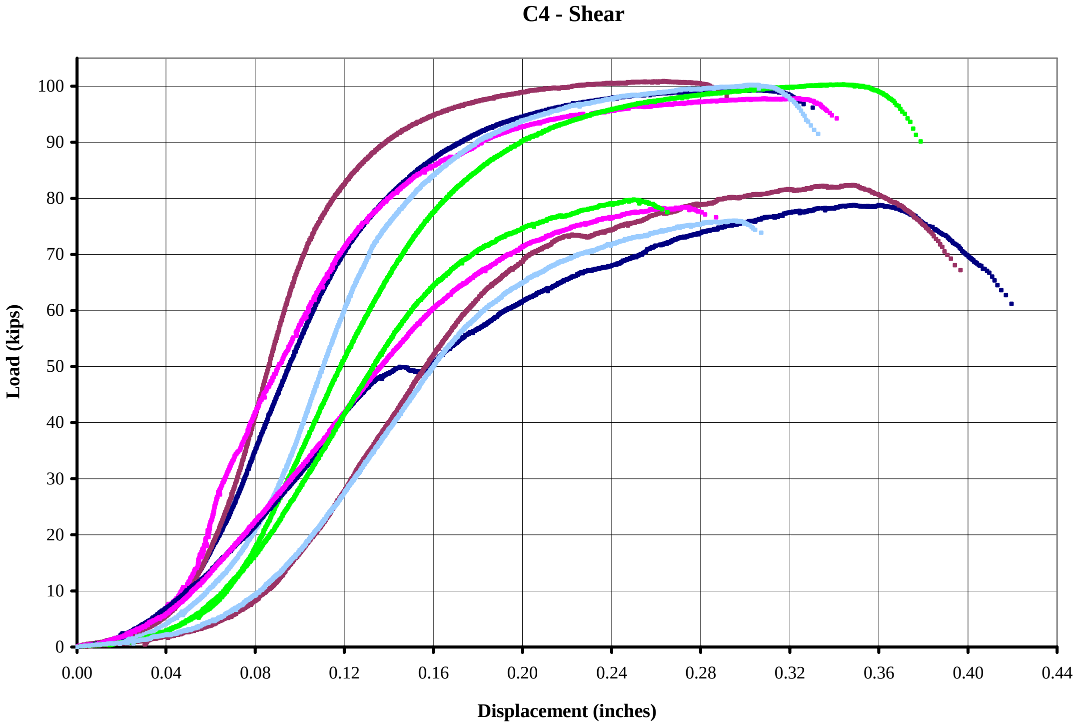

Figure A-76: Lot C4 – 1-1/4-inch A325 – Shear

N9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.5"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1130 inches

Table A-39: Lot N9 – 1-1/4-inch A325 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate:	0.675 in/min		**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2442	121,189	8.37%	1.2427	92,202	1.2444	74,176
2	1.2442	117,985	10.13%	1.2427	92,386	1.2444	71,761
3	1.2447	123,166	4.39%	1.2433	95,410	1.2446	71,905
4	1.2437	117,797	9.13%	1.2438	94,888	1.2419	70,460
5	1.2440	121,867	6.22%	1.2425	95,486	1.2433	75,585

Note: The lever arm of the third LVDT was resting on the angle.

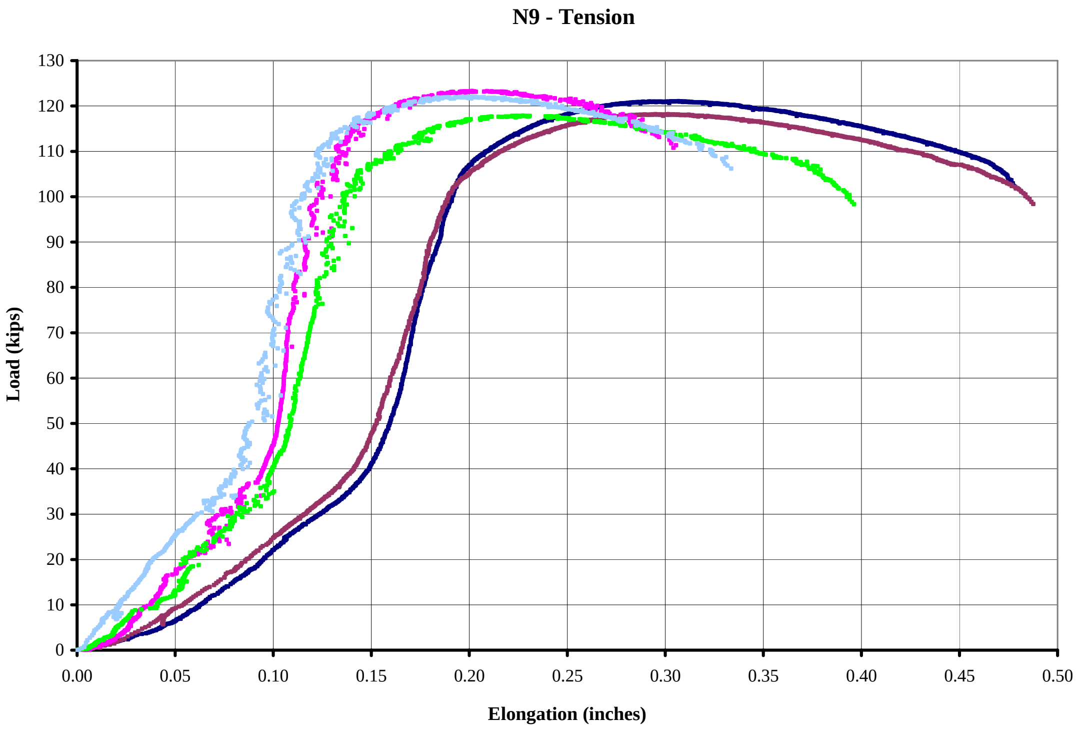

Figure A-77: Lot N9 – 1-1/4-inch A325 – Tension

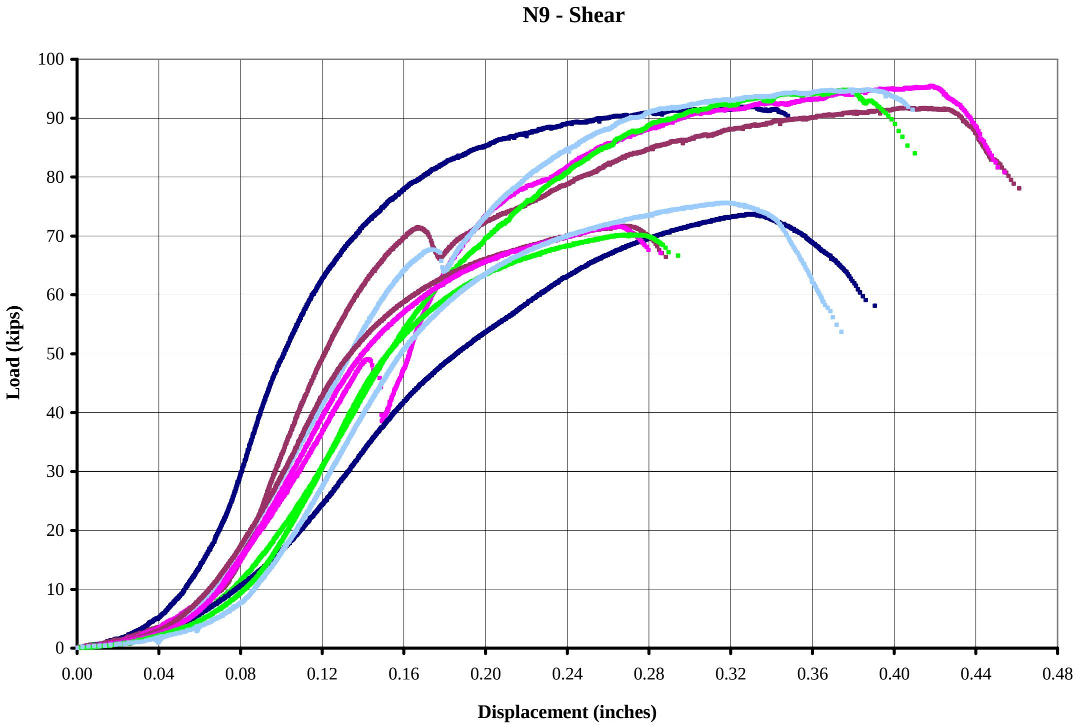

Figure A-78: Lot N9 – 1-1/4-inch A325 – Shear

T9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.5"
Grade:	A325
Nominal Thread Length:	2 inches
Measured Thread Length:	2.2075 inches

Table A-40: Lot T9 – 1-1/4-inch A325 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2439	127,409	5.54%	1.2433	99,361	1.2432	76,818
2	1.2442	126,053	6.08%	1.2435	98,723	1.2425	77,254
3	1.2435	127,395	7.71%	1.2430	100,042	1.2433	75,733
4	1.2440	129,300	4.80%	1.2419	100,161	1.2428	74,728
5	1.2440	128,795	4.91%	1.2426	99,592	1.2429	78,112
6	1.2439	128,824	5.80%	1.2421	100,583		
7				1.2430	101,744		
8				1.2426	100,587		

Note: The lever arm of the third LVDT was resting on the angle.
Data for T1 was not recorded for the Load versus Elongation graph due to technical problems.
Data for X1, X2, and X4 were not recorded for the Load versus Displacement graph due to technical problems.

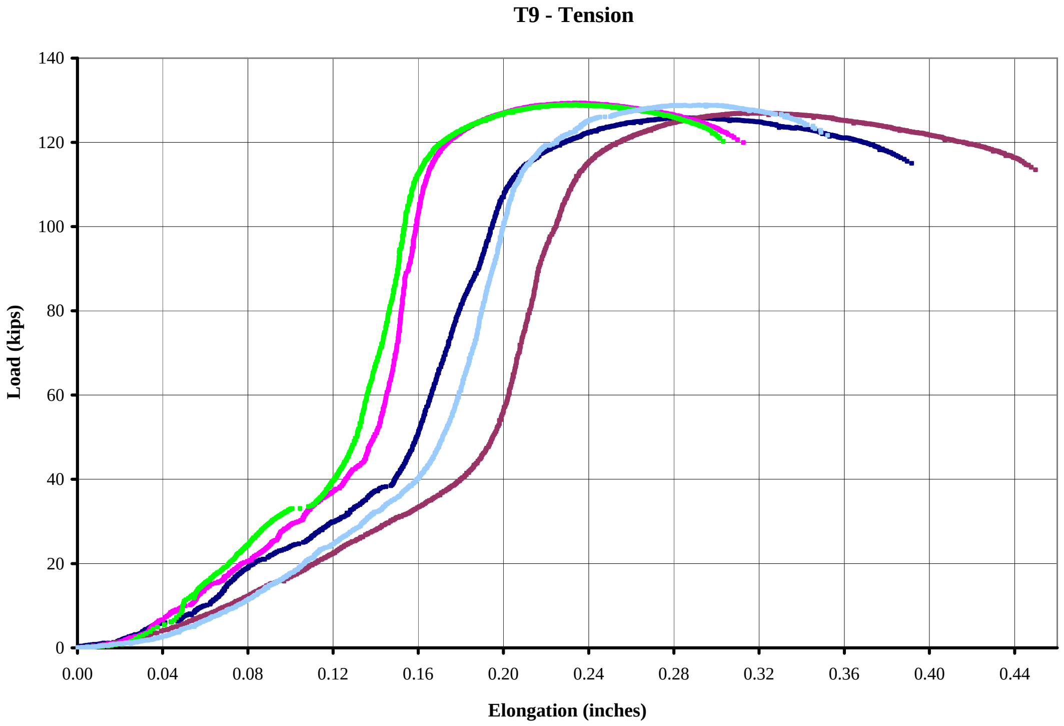

Figure A-79: Lot T9 – 1-1/4-inch A325 – Tension

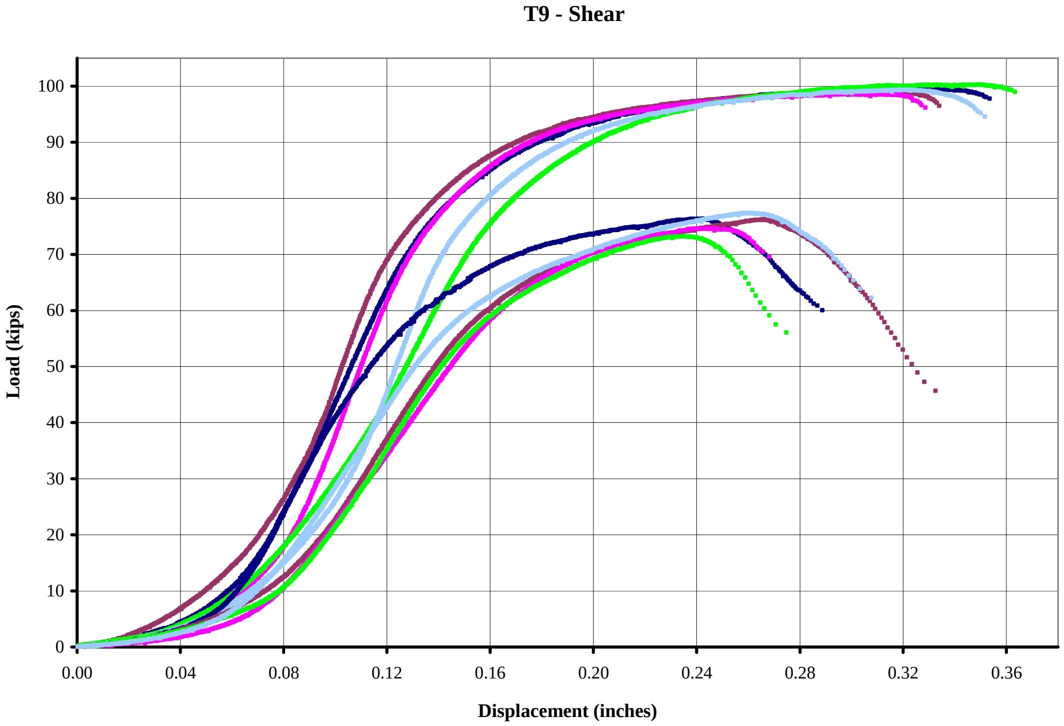

Figure A-80: Lot T9 – 1-1/4-inch A325 – Shear

U1

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 2.75"
Grade:	F1852
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.3325 inches

Table A-41: Lot U1 – 5/8-inch F1852 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate:		0.4125 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6224	33,661	14.18%	0.6226	28,582	0.6225	21,136
2	0.6227	34,771	16.06%	0.6226	28,373	0.6228	22,574
3	0.6222	34,634	14.45%	0.6227	28,445	0.6224	21,562
4	0.6228	34,512	11.33%	0.6225	28,788	0.6229	20,390
5	0.6231	34,804	10.62%	0.6228	28,445	0.6224	21,638

Note: The lever arm of the third LVDT was resting on the bolt head.

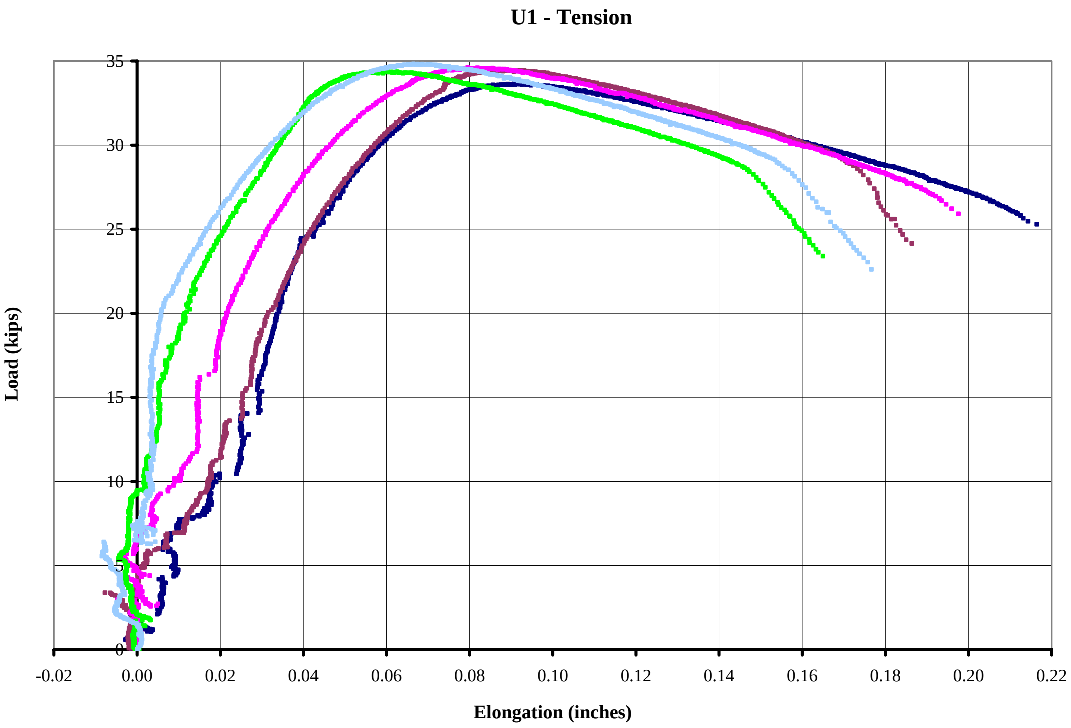

Figure A-81: Lot U1 – 5/8-inch F1852 – Tension

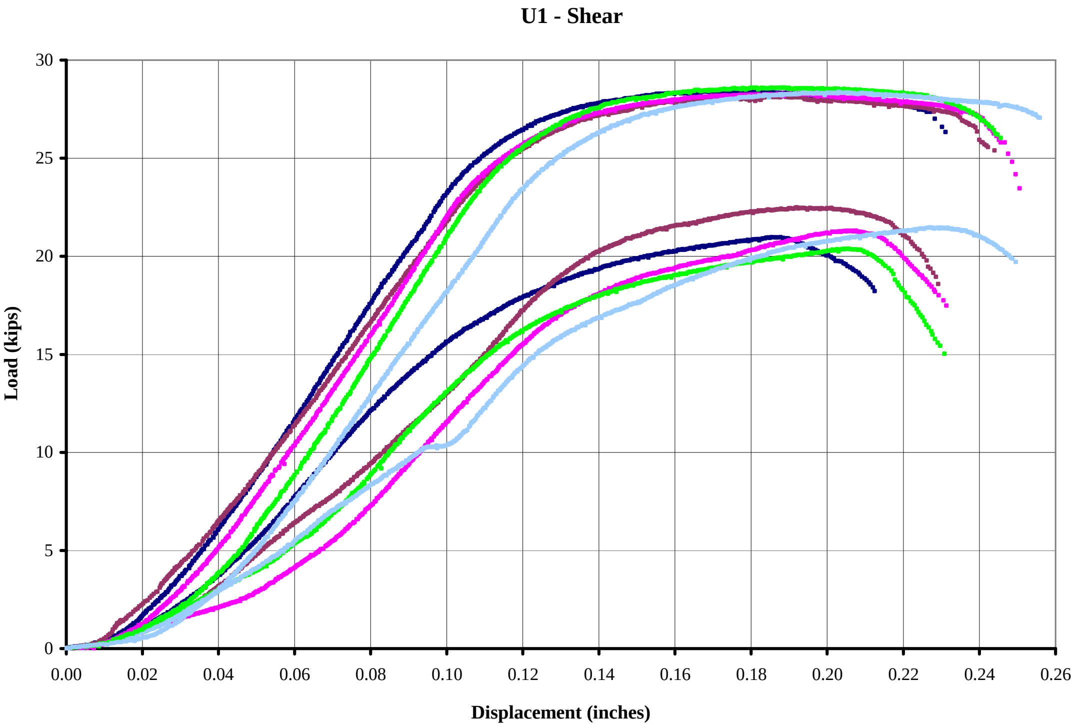

Figure A-82: Lot U1 – 5/8-inch F1852 – Shear

U2

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.75"
Grade:	F1852
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4360 inches

Table A-42: Lot U2 – 3/4-inch F1852 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7325	49,845	18.25%	0.7430	41,209	0.7431	31,286
2	0.7335	49,420	16.33%	0.7425	40,870	0.7435	31,386
3	0.7315	49,701	20.93%	0.7426	40,719	0.7433	31,177
4	0.7350	49,546	21.31%	0.7432	41,357	0.7432	31,448
5	0.7320	49,528	18.70%	0.7428	41,162	0.7430	30,056
6	0.7345	49,492	19.67%				
7	0.7305	49,571	21.94%				
8	0.7315	49,539	20.33%				

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for T7 and T8 were not recorded for the Load versus Elongation graph due to technical problems.

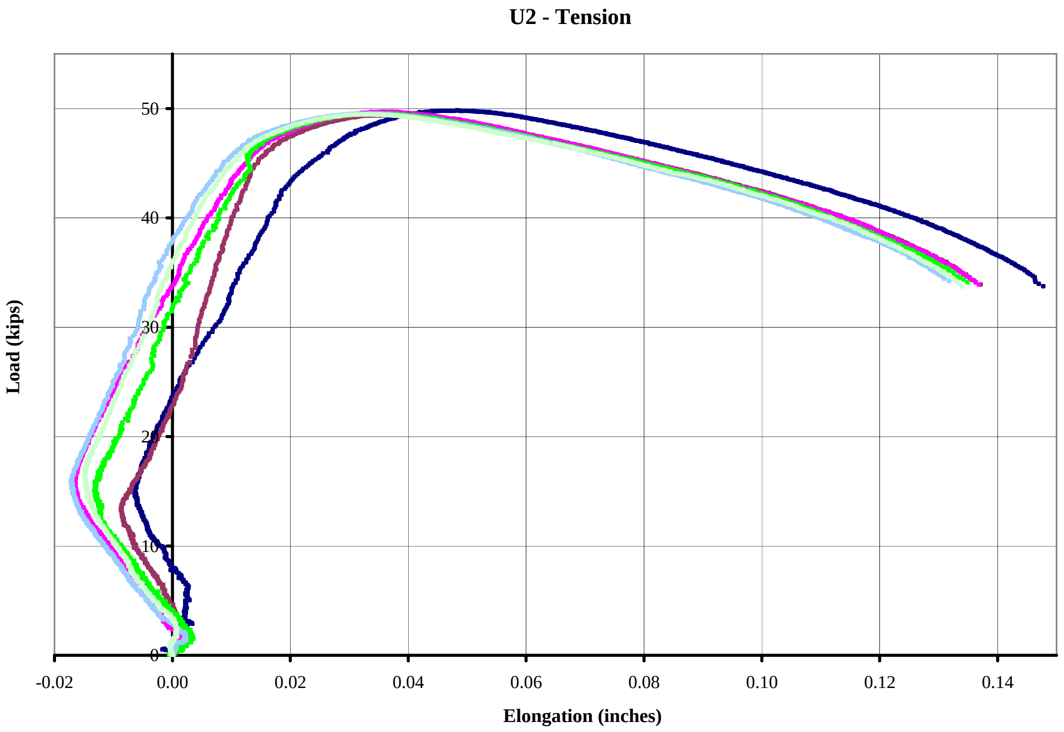

Figure A-83: Lot U2 – 3/4-inch F1852 – Tension

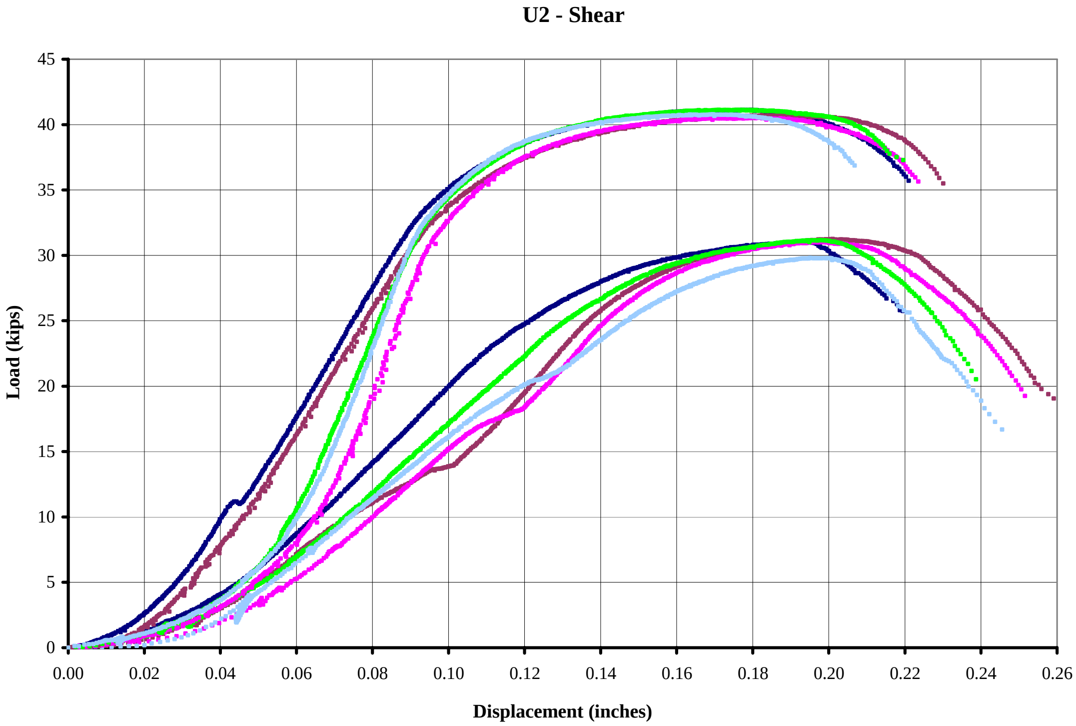

Figure A-84: Lot U2 – 3/4-inch F1852 – Shear

U3

Bolt Properties:

Manufacturer:
Lot Number:
Size: 7/8"-9 x 3.5"
Grade: F1852
Nominal Thread Length: 1 1/2 inches
Measured Thread Length: 1.5375 inches

Table A-43: Lot U3 – 7/8-inch F1852 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.525 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8716	71,213	21.98%	0.8718	56,514	0.8715	43,635
2	0.8719	71,008	17.27%	0.8717	57,018	0.8717	45,477
3	0.8719	70,298	16.59%	0.8715	56,124	0.8721	44,435
4	0.8720	72,071	18.70%	0.8719	57,278	0.8717	43,411
5	0.8723	71,152	14.93%	0.8715	56,193	0.8715	43,790

Note: The lever arm of the third LVDT was resting on the bolt head.

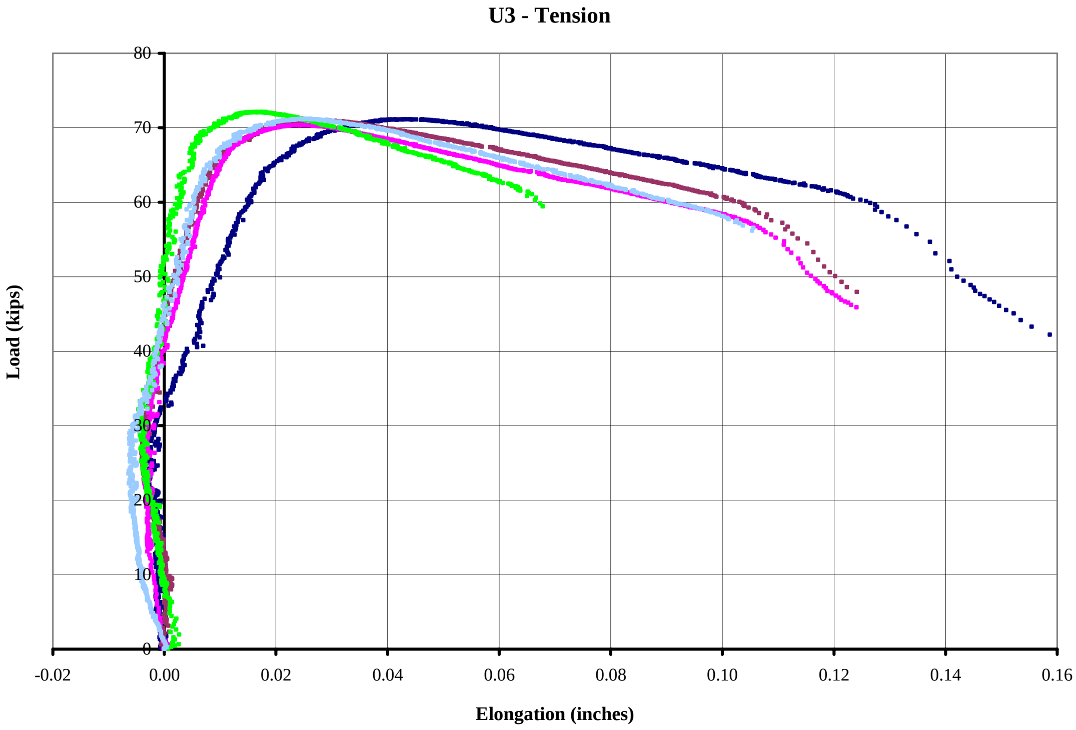

Figure A-85: Lot U3 – 7/8-inch F1852 – Tension

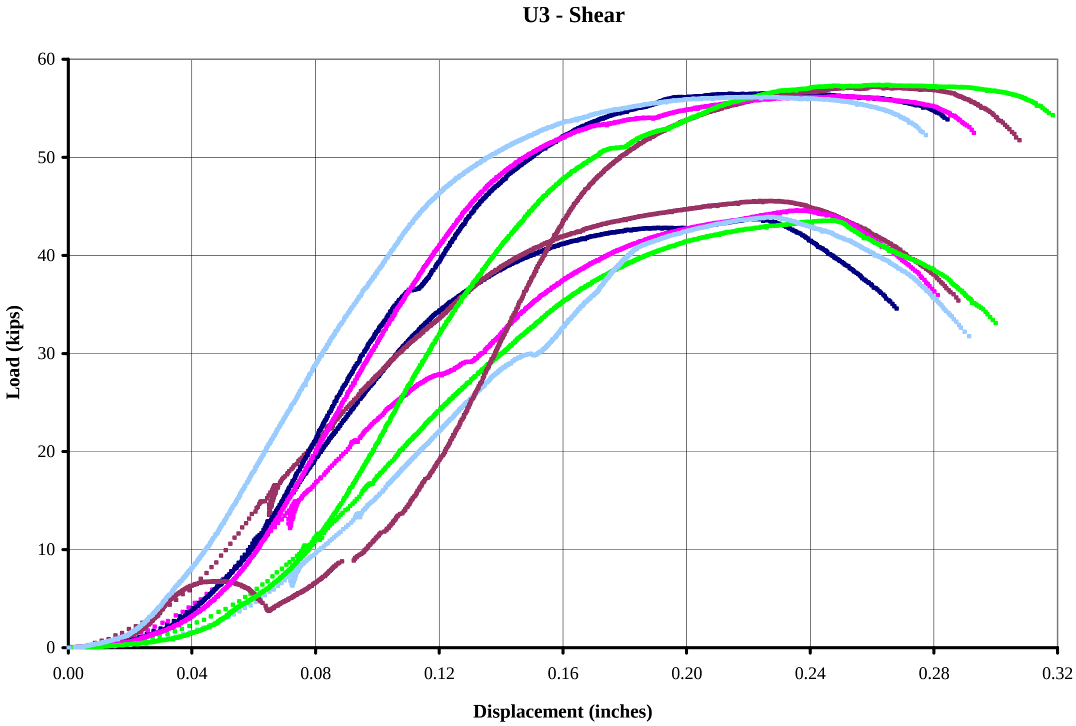

Figure A-86: Lot U3 – 7/8-inch F1852 – Shear

U5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.25"
Grade:	F1852
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.7265 inches

Table A-44: Lot U5 – 1-inch F1852 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.4875 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9974	92,325	11.38%	0.9920	73,246	0.9931	56,463
2	0.9957	89,506	14.89%	0.9918	73,603	0.9938	57,451
3	0.9967	92,520	12.74%	0.9918	71,289	0.9929	56,481
4	0.9972	92,873	13.09%	0.9922	72,309	0.9945	56,402
5	0.9967	92,448	13.26%	0.9919	71,664	0.9936	55,750

Note: The lever arm of the third LVDT was resting on the bolt head.

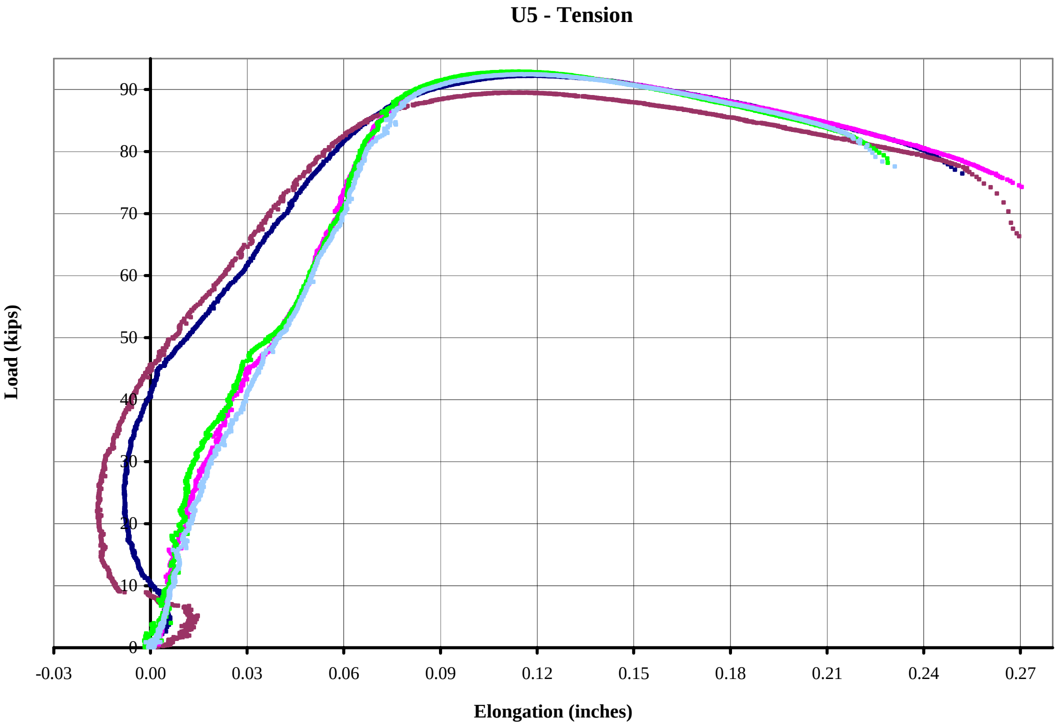

Figure A-87: Lot U5 – 1-inch F1852 – Tension

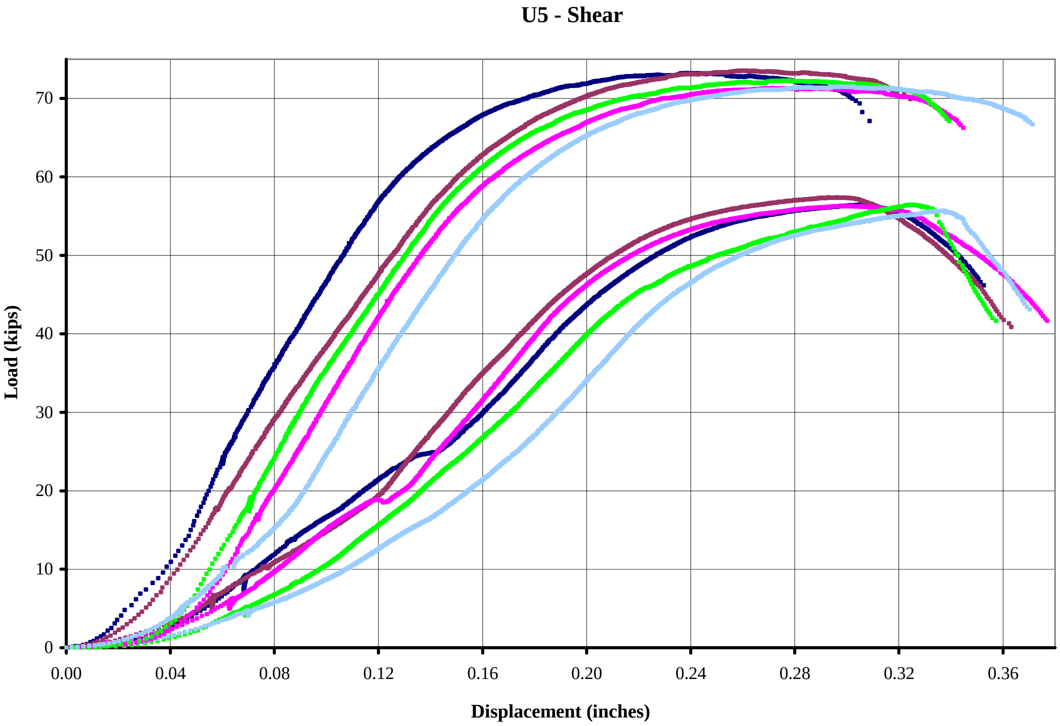

Figure A-88: Lot U5 – 1-inch F1852 – Shear

U6

Bolt Properties:

Manufacturer:
Lot Number:
Size: 1-1/8"-7 x 4.5"
Grade: F1852
Nominal Thread Length: 2 inches
Measured Thread Length: 2.0760 inches

Table A-45: Lot U6 – 1-1/8-inch F1852 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1097	104,454	2.26%	1.1112	80,279	1.1117	63,298
2	1.1101	105,482	5.31%	1.1112	79,893	1.1112	64,541
3	1.1104	104,332	8.01%	1.1113	80,398	1.1112	64,624
4	1.1101	103,391	8.07%	1.1110	79,295	1.1109	65,868
5	1.1102	105,831	5.73%	1.1114	80,480	1.1119	63,824

Note: The lever arm of the third LVDT was resting on the angle.

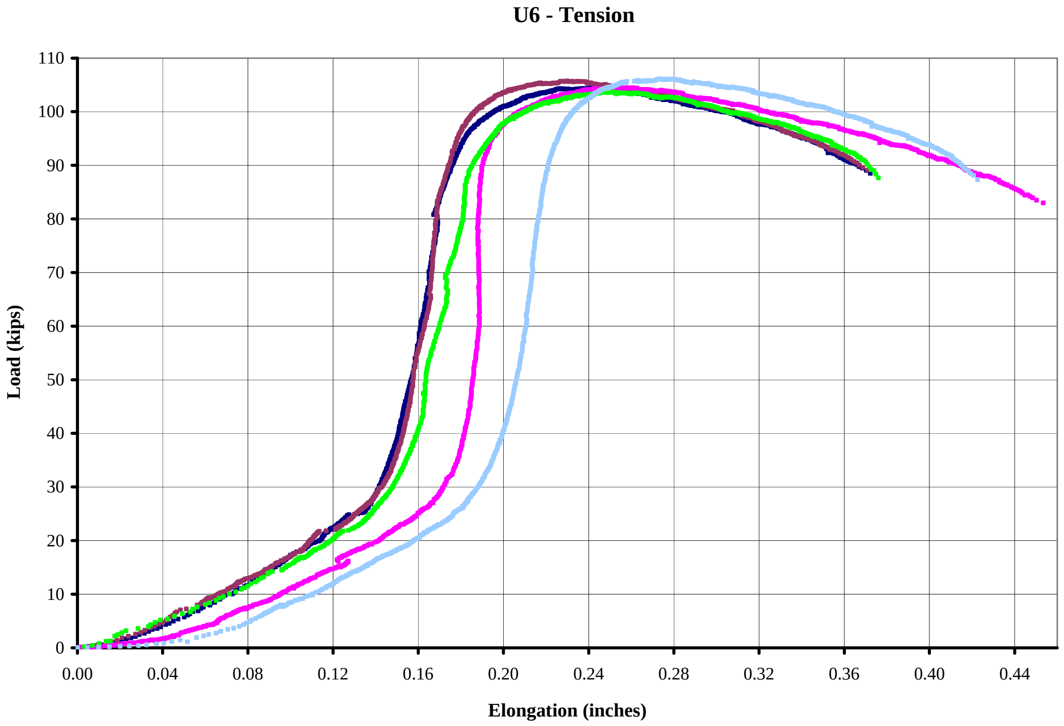

Figure A-89: Lot U6 – 1-1/8-inch F1852 – Tension

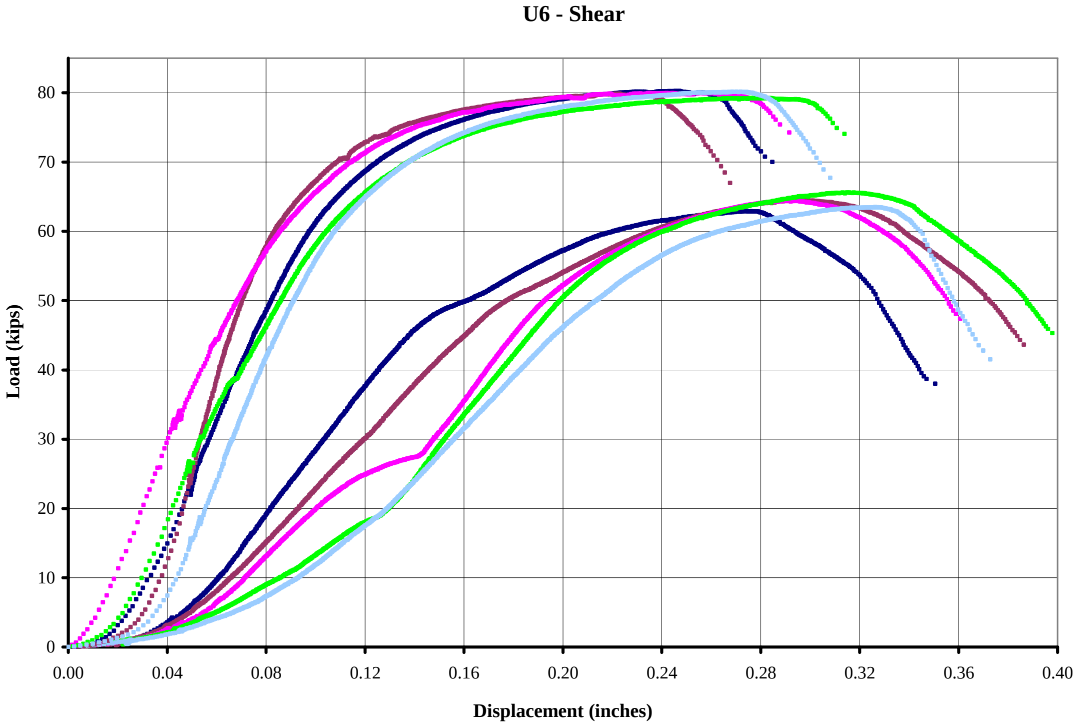

Figure A-90: Lot U6 – 1-1/8-inch F1852 – Shear

C5

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 4.5"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2840 inches

Table A-46: Lot C5 – 5/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6214	36,126	11.21%	0.6213	30,280	0.6213	24,541
2	0.6214	35,957	11.06%	0.6214	29,891	0.6209	25,286
3	0.6219	36,112	9.50%	0.6213	29,588	0.6216	25,565
4	0.6215	35,813	10.75%	0.6212	29,606	0.6217	24,899
5	0.6214	36,501	9.19%	0.6215	30,056	0.6204	24,210

Note: The lever arm of the third LVDT was resting on the angle.

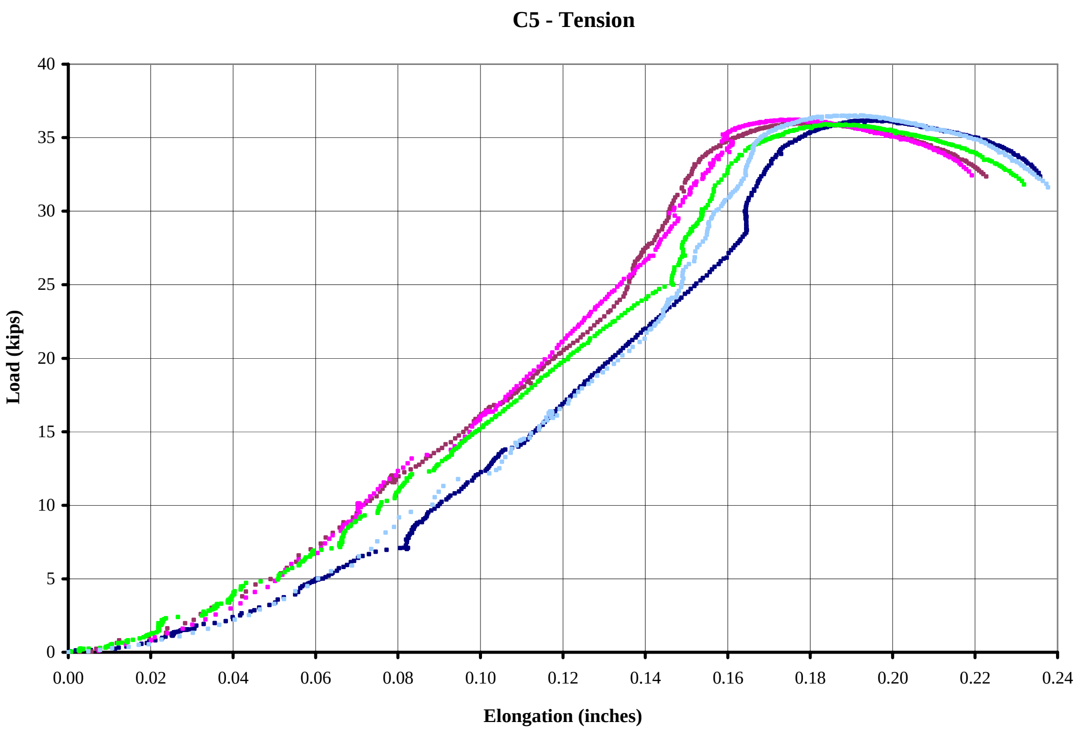

Figure A-91: Lot C5 – 5/8-inch A490 – Tension

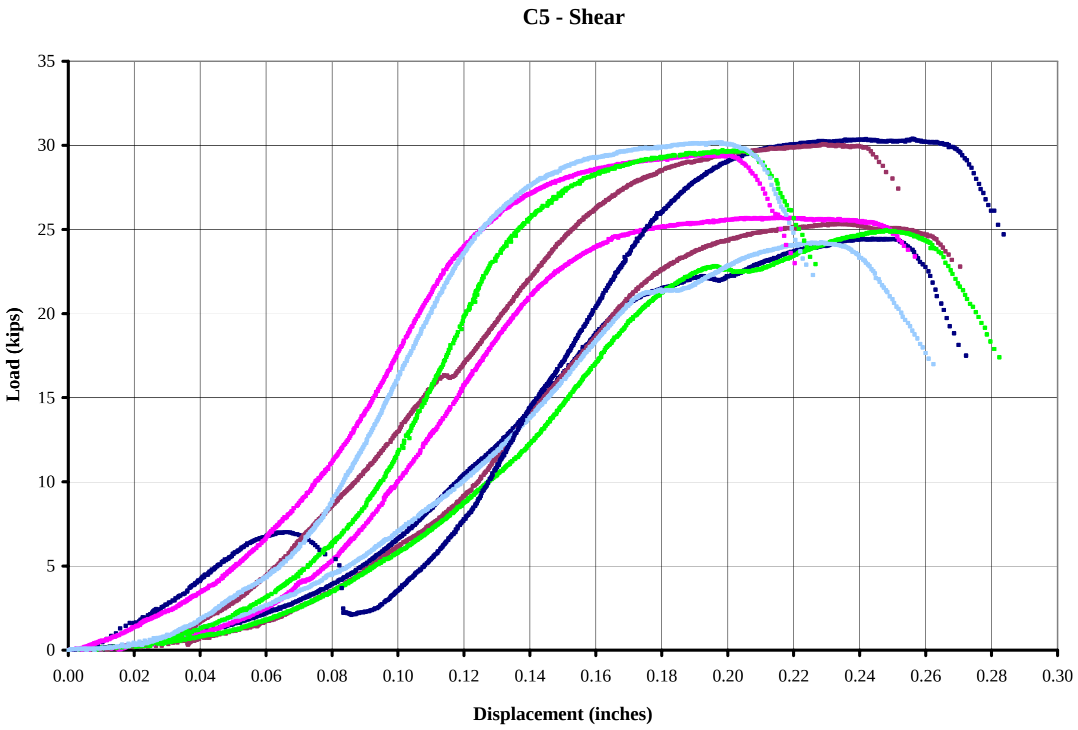

Figure A-92: Lot C5 – 5/8-inch A490 – Shear

C6

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 5"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.3370 inches

Table A-47: Lot C6 – 5/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6185	36,599	6.96%	0.6194	30,320	0.6196	22,667
2	0.6191	36,116	6.66%	0.6193	29,555	0.6170	23,070
3	0.6195	36,267	6.36%	0.6173	29,858	0.6192	22,035
4	0.6194	36,202	6.62%	0.6193	29,743	0.6196	22,544
5	0.6194	35,798	4.71%	0.6190	29,674	0.6197	23,254

Note: The lever arm of the third LVDT was resting on the angle.

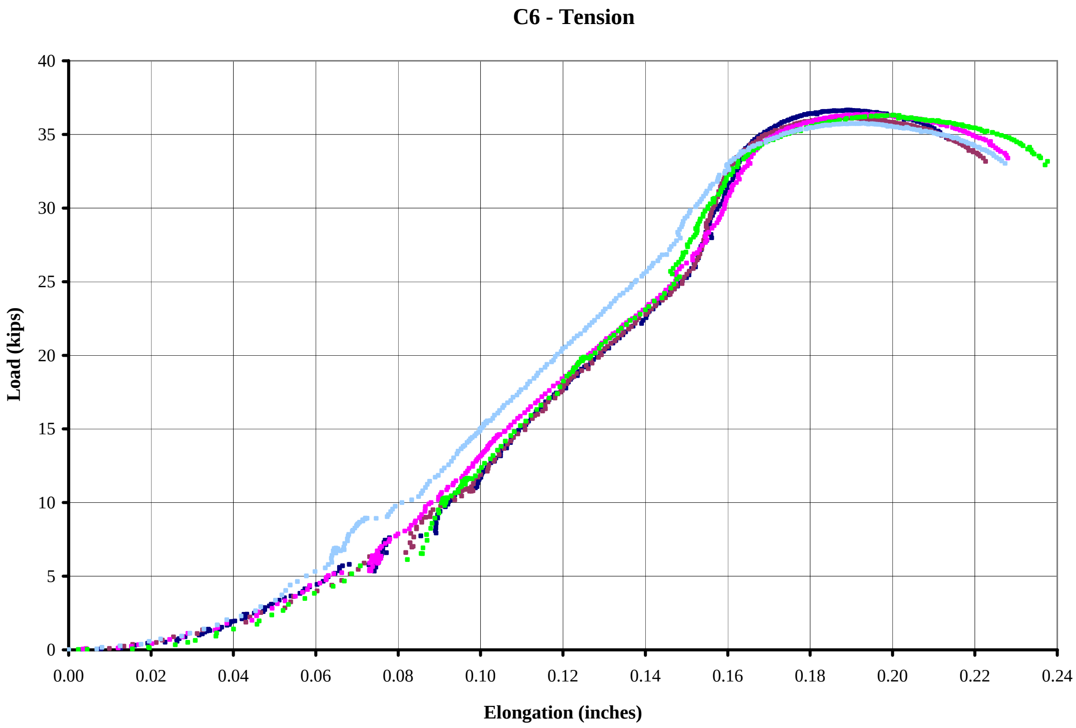

Figure A-93: Lot C6 – 5/8-inch A490 – Tension

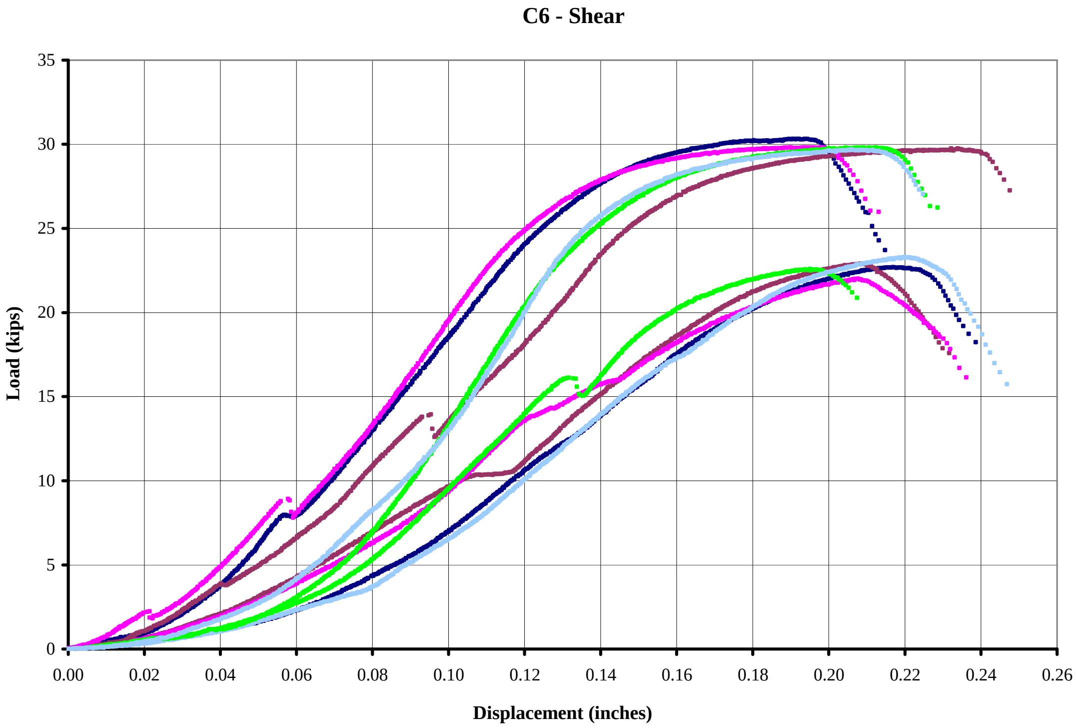

Figure A-94: Lot C6 – 5/8-inch A490 – Shear

L9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.3065 inches

Table A-48: Lot L9 – 5/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.45 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6206	36,372	5.47%	0.6195	28,809	0.6197	21,873
2	0.6207	36,231	8.19%	0.6188	29,664	0.6187	20,079
3	0.6203	36,501	5.32%	0.6194	29,530	0.6198	22,132
4	0.6203	36,130	7.00%	0.6196	29,620	0.6196	21,470
5	0.6202	36,296	4.86%	0.6199	29,541	0.6194	21,355

Note: The lever arm of the third LVDT was resting on the bolt head.

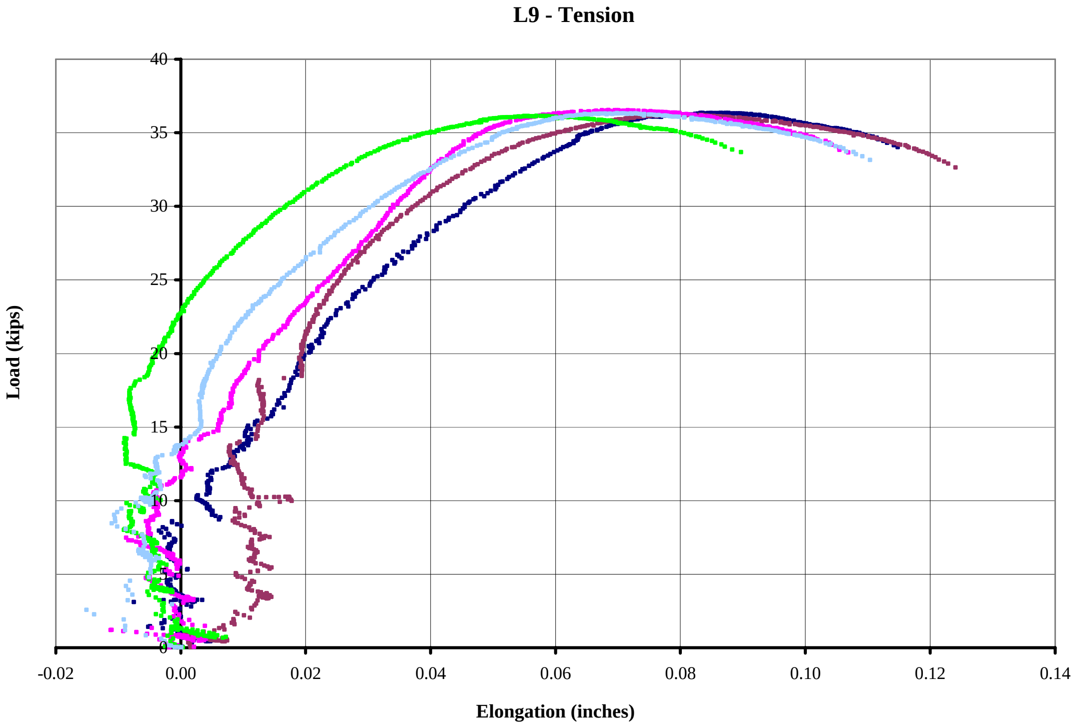

Figure A-95: Lot L9 – 5/8-inch A490 – Tension

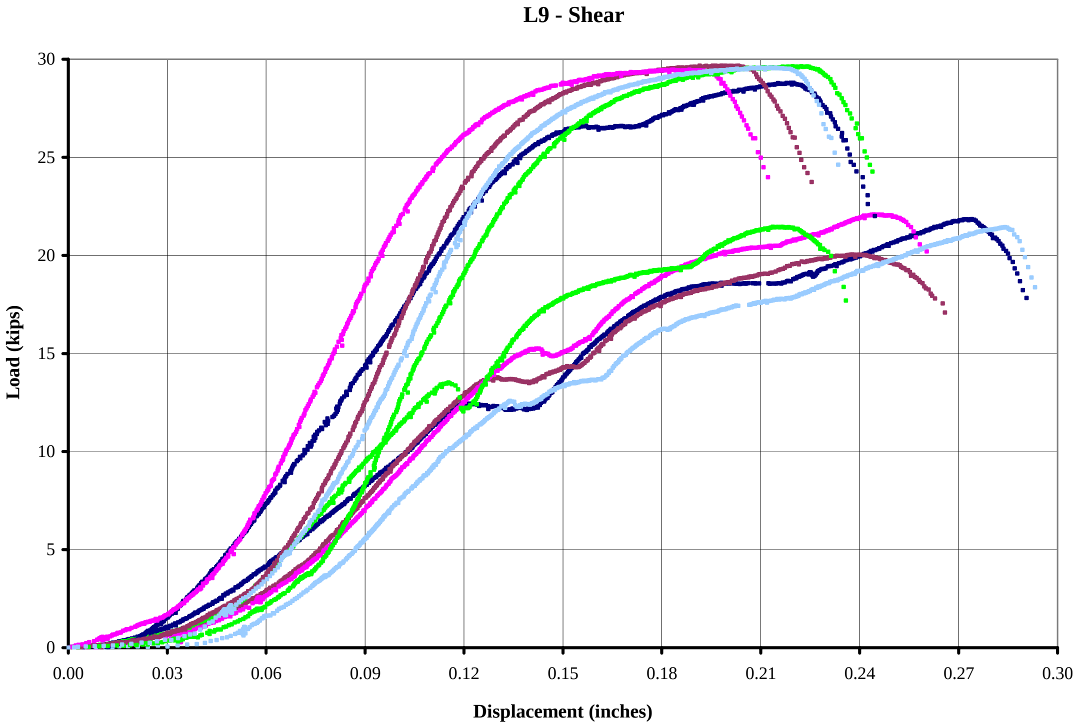

Figure A-96: Lot L9 – 5/8-inch A490 – Shear

N10

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3.5"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2895 inches

Table A-49: Lot N10 – 5/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.525 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6228	38,199	6.13%	0.6208	30,727	0.6209	22,459
2	0.6221	38,116	7.02%	0.6207	30,903	0.6209	22,451
3	0.6230	38,062	6.67%	0.6206	30,918	0.6211	23,827
4	0.6220	38,152	7.33%	0.6210	30,907	0.6209	21,855
5	0.6223	37,803	7.75%	0.6210	30,503	0.6211	23,713

Note: The lever arm of the third LVDT was resting on the bolt head.

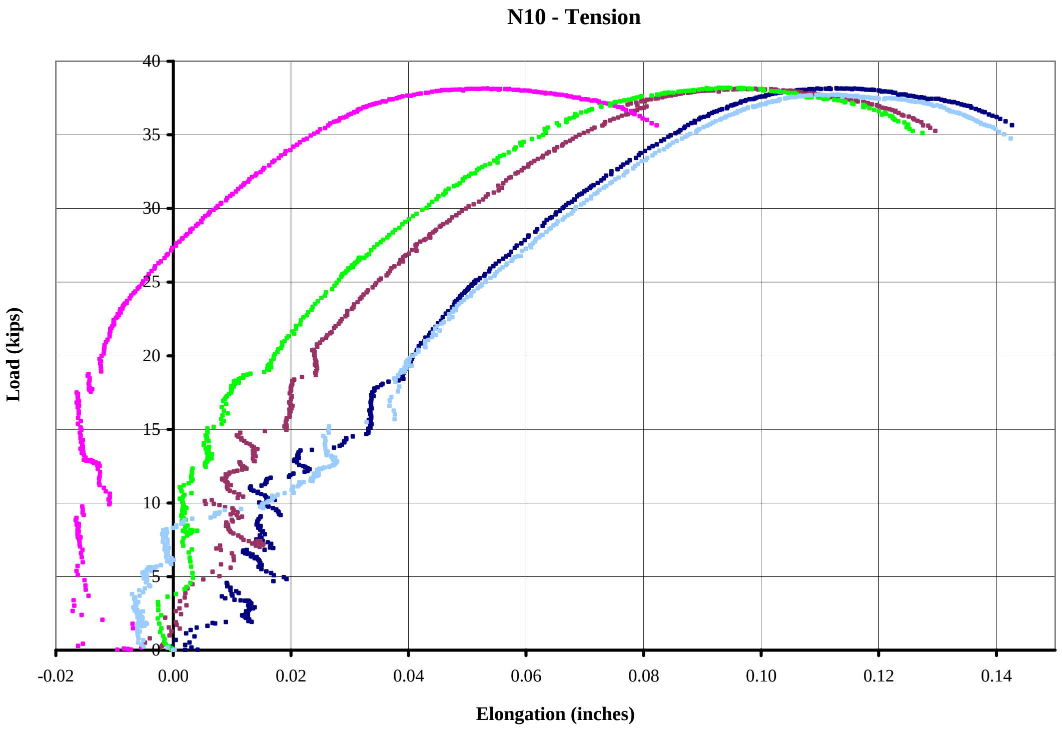

Figure A-97: Lot N10 – 5/8-inch A490 – Tension

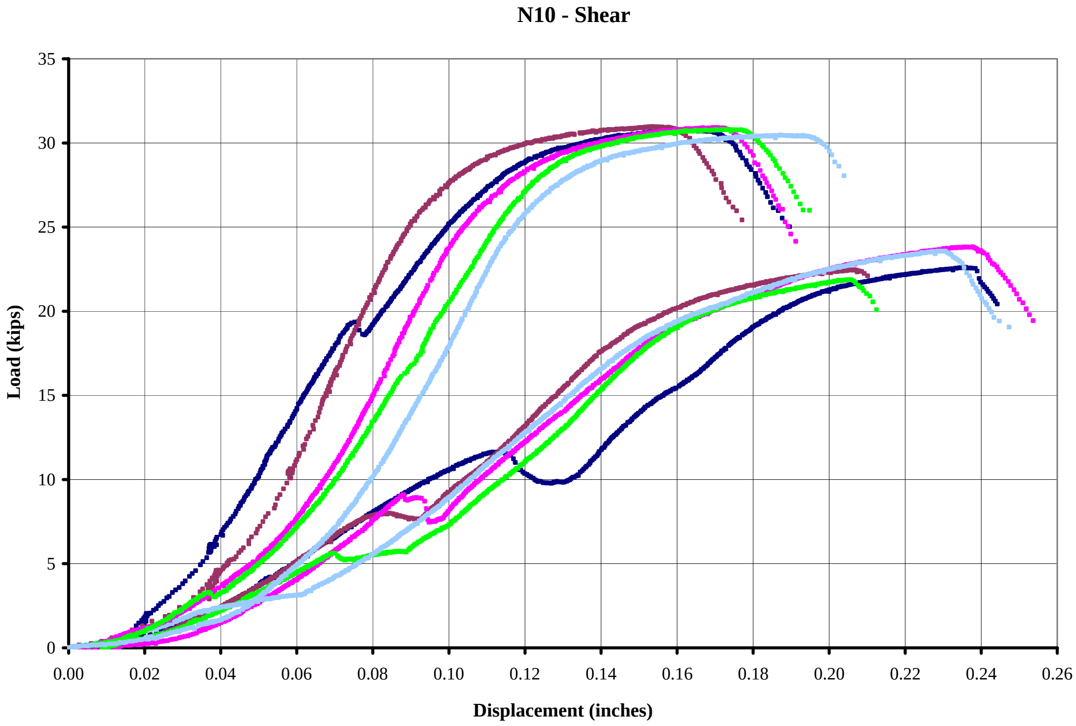

Figure A-98: Lot N10 – 5/8-inch A490 – Shear

N11

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3.75"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2660 inches

Table A-50: Lot N11 – 5/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.5625 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.6213	38,408	9.83%	0.6211	30,129	0.6208	23,051
2	0.6215	38,387	9.40%	0.6205	30,305	0.6206	22,508
3	0.6214	38,588	8.81%	0.6208	30,637	0.6208	23,319
4	0.6216	38,098	7.31%	0.6205	30,572	0.6208	21,622
5	0.6225	38,289	8.29%	0.6205	30,662	0.6208	22,668

Note: The lever arm of the third LVDT was resting on the bolt head.

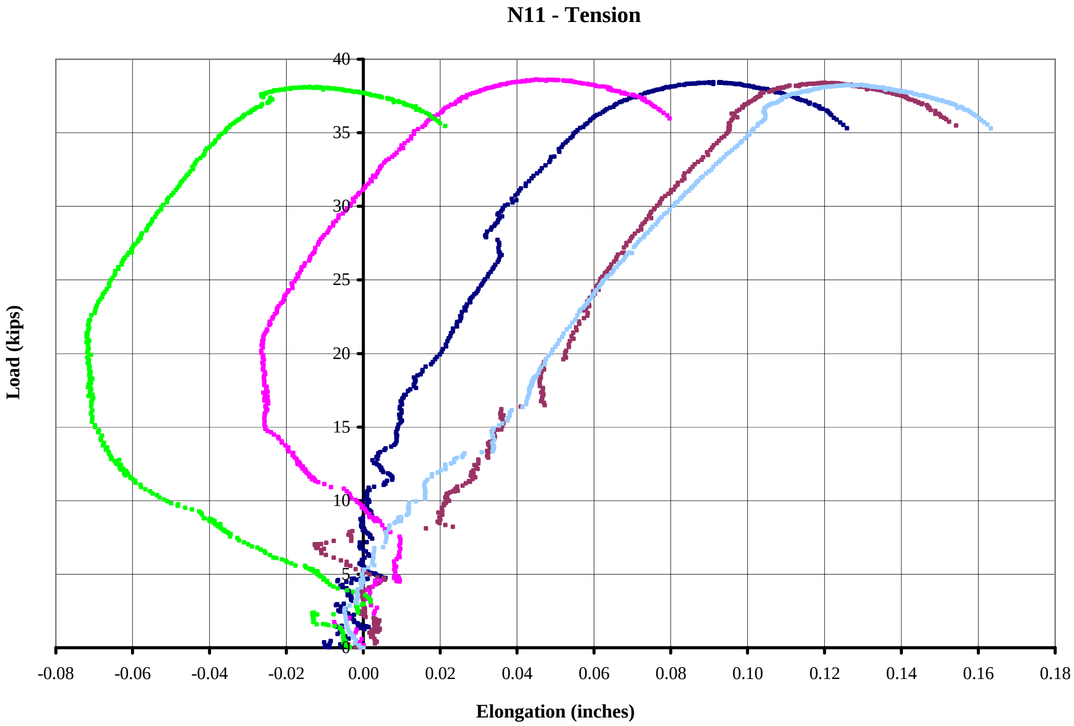

Figure A-99: Lot N11 – 5/8-inch A490 – Tension

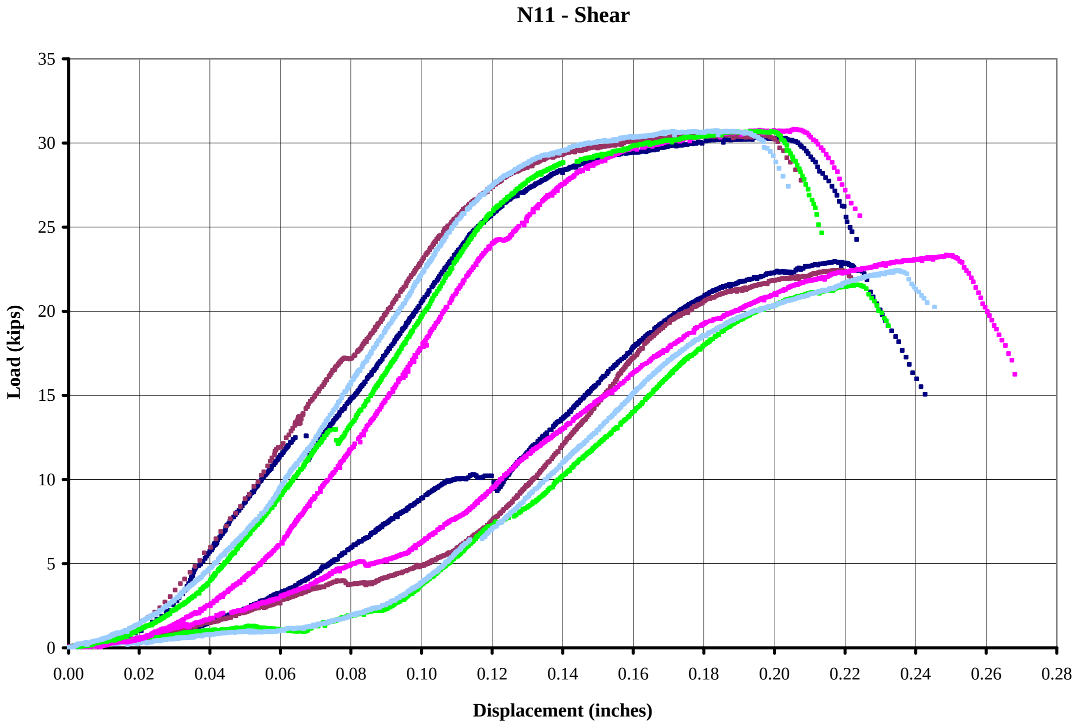

Figure A-100: Lot N11 – 5/8-inch A490 – Shear

T10

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	5/8"-11 x 3"
Grade:	A490
Nominal Thread Length:	1 1/4 inches
Measured Thread Length:	1.2470 inches

Table A-51: Lot T10 – 5/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.45 in/min			Load Rate: 0.5 in/min		Load Rate: 0.5 in/min	
	Average Diameter (inches)	Failure Load (pounds)	Elongation	Average Diameter (inches)	Failure Load (pounds)	Average Diameter (inches)	Failure Load (pounds)
1	0.6188	36,292	12.27%	0.6200	29,501	0.6196	23,325
2	0.6197	36,123	13.75%	0.6199	29,462	0.6196	23,796
3	0.6204	36,357	10.79%	0.6198	29,577	0.6196	22,886
4	0.6197	36,170	12.55%	0.6177	29,137	0.6204	22,093
5	0.6204	36,357	13.67%	0.6197	29,408	0.6204	22,409

Note: The lever arm of the third LVDT was resting on the bolt head.

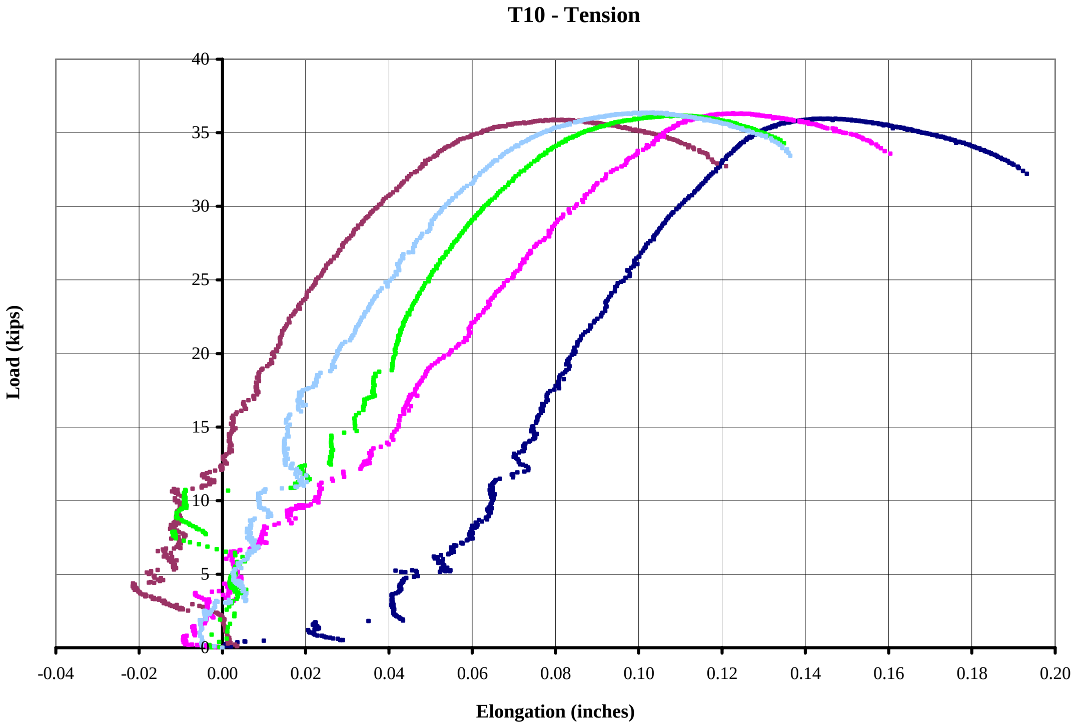

Figure A-101: Lot T10 – 5/8-inch A490 – Tension

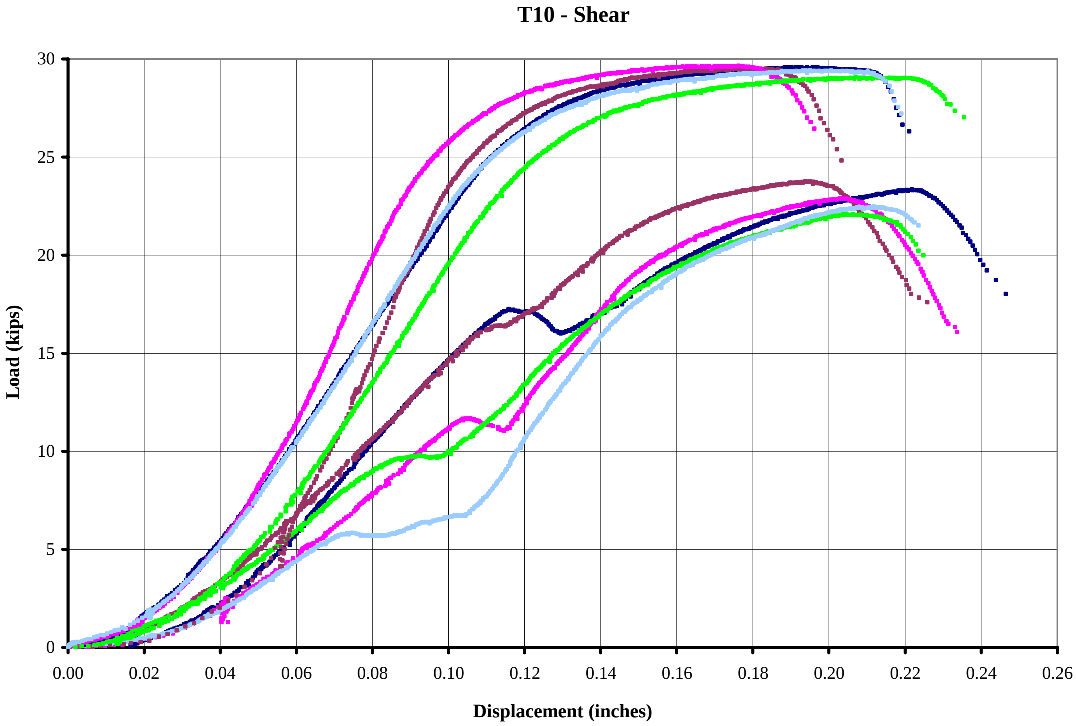

Figure A-102: Lot T10 – 5/8-inch A490 – Shear

C7

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 4.25"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4285 inches

Table A-52: Lot C7 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7454	56,881	8.72%	0.7460	44,010	0.7461	31,167
2	0.7459	55,631	10.64%	0.7464	43,375	0.7462	32,154
3	0.7466	56,312	10.05%	0.7463	43,354	0.7458	31,985
4	0.7458	55,735	11.34%	0.7454	43,281	0.7456	30,640
5	0.7462	54,225	11.17%	0.7461	42,633	0.7456	30,110

Note: The lever arm of the third LVDT was resting on the angle.

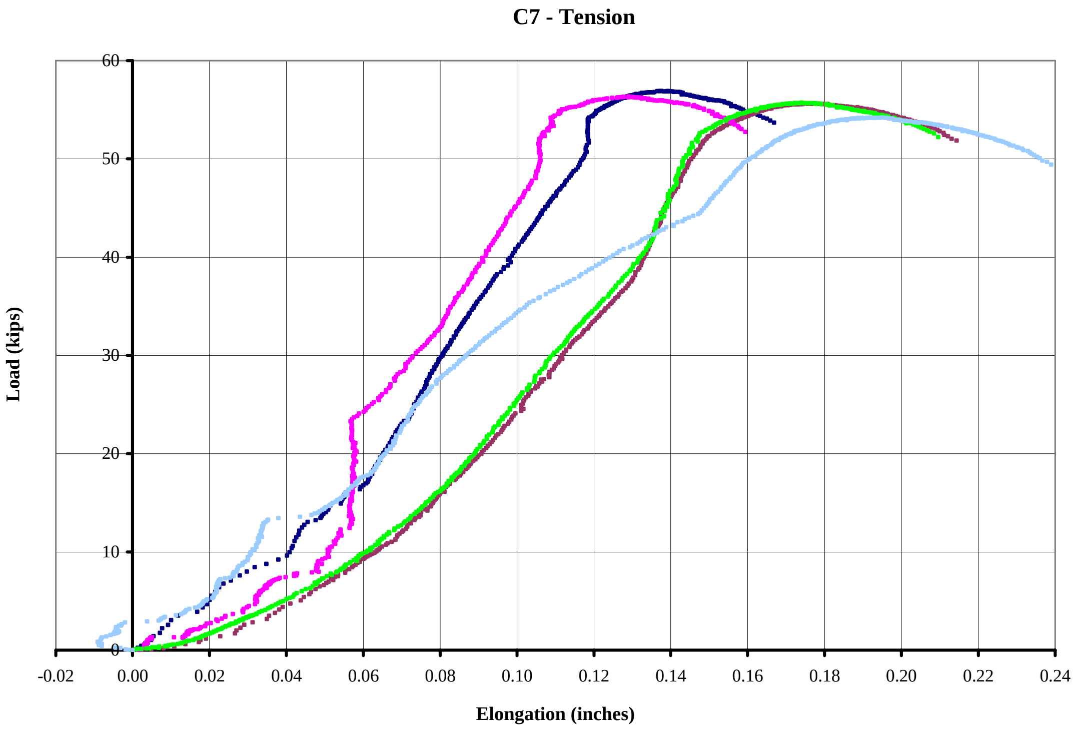

Figure A-103: Lot C7 – 3/4-inch A490 – Tension

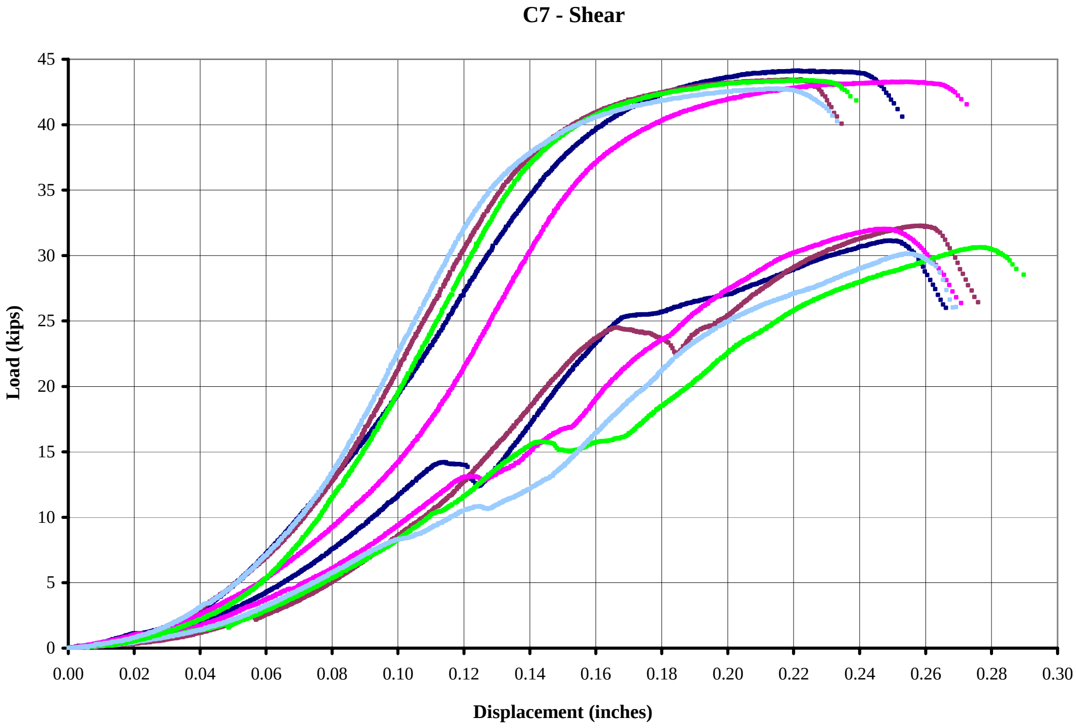

Figure A-104: Lot C7 – 3/4-inch A490 – Shear

C8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 4.5"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4245 inches

Table A-53: Lot C8 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7430	56,395	4.42%	0.7412	44,698	0.7415	33,686
2	0.7429	55,544	15.76%	0.7412	44,237	0.7421	33,621
3	0.7429	56,024	8.67%	0.7410	44,013	0.7415	34,126
4	0.7432	56,182	6.77%	0.7409	43,865	0.7426	32,724
5	0.7431	56,279	9.83%	0.7407	44,384	0.7417	34,941

Note: The lever arm of the third LVDT was resting on the angle.

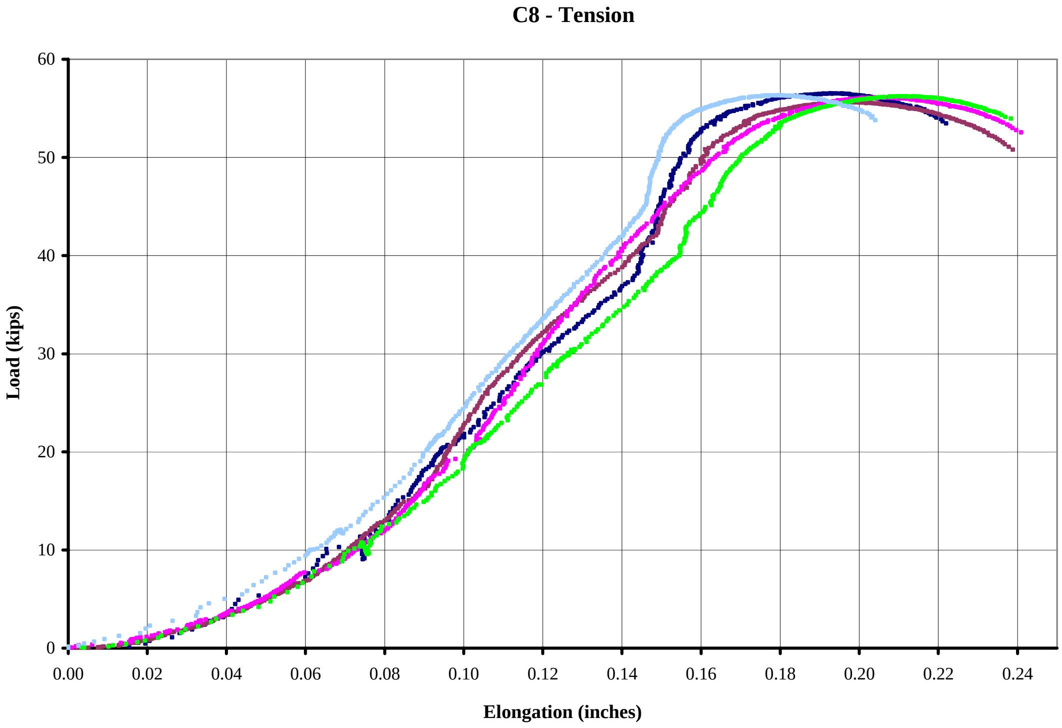

Figure A-105: Lot C8 – 3/4-inch A490 – Tension

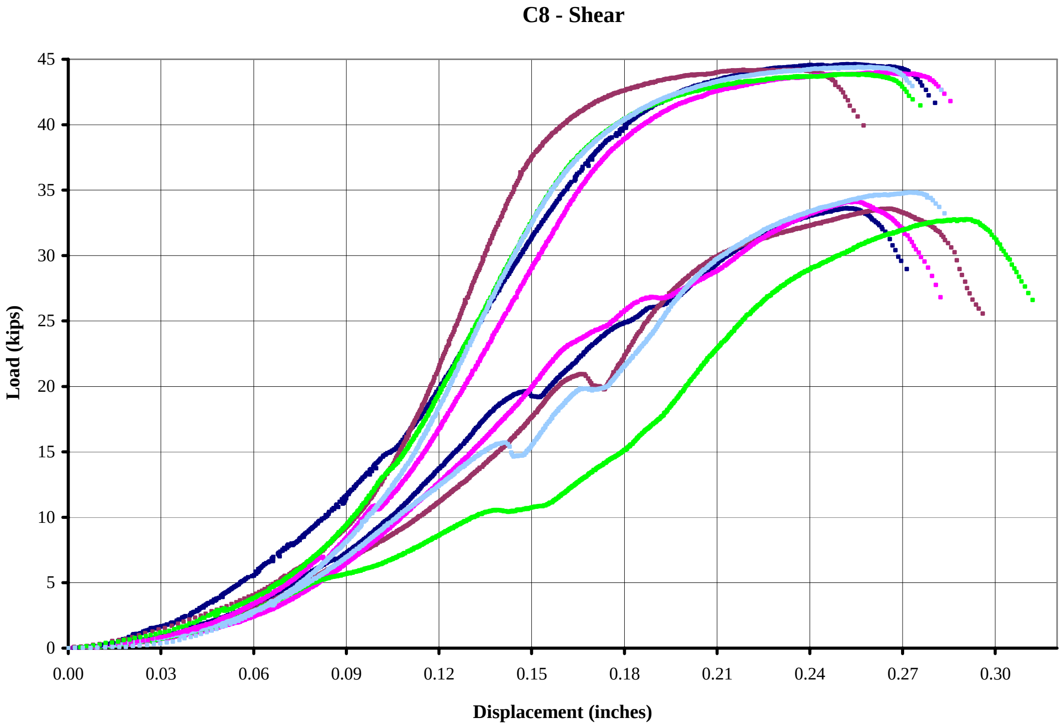

Figure A-106: Lot C8 – 3/4-inch A490 – Shear

C9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 4.75"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.3960 inches

Table A-54: Lot C9 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.7125 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7420	56,265	4.94%	0.7410	43,256	0.7404	33,765
2	0.7413	55,382	6.73%	0.7405	43,195	0.7407	33,621
3	0.7418	55,209	8.95%	0.7415	42,827	0.7407	33,167
4	0.7415	55,086	7.38%	0.7406	42,990	0.7412	33,719
5	0.7420	53,814	8.81%	0.7410	43,083	0.7405	34,011

Note: The lever arm of the third LVDT was resting on the angle.

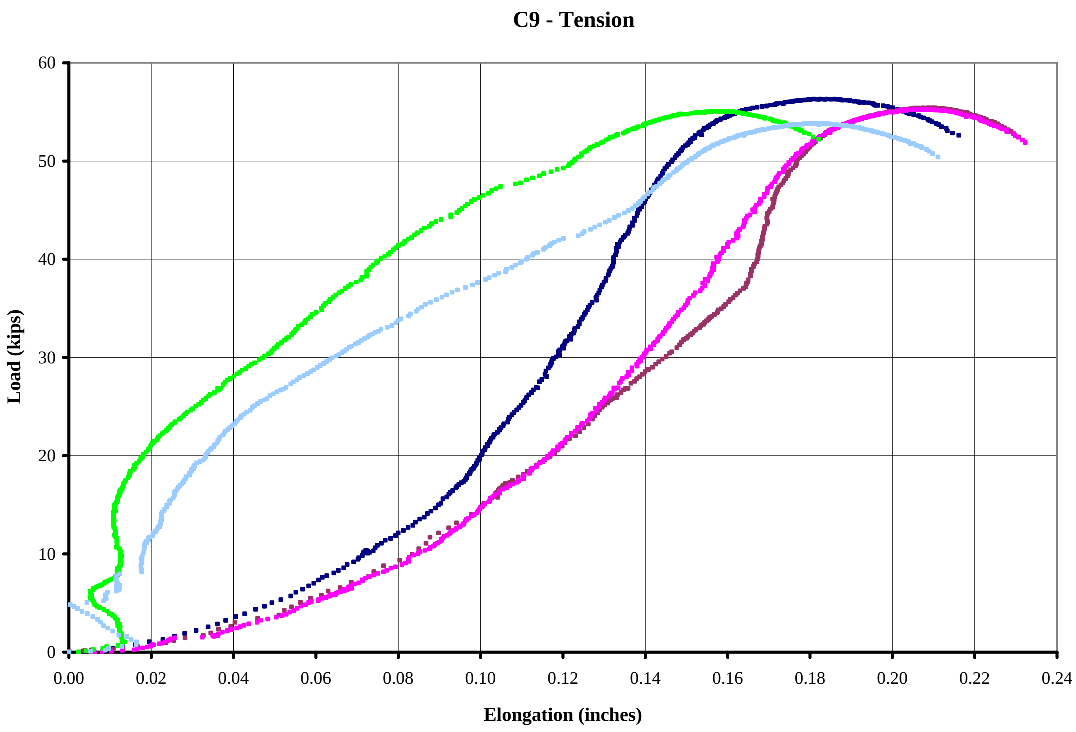

Figure A-107: Lot C9 – 3/4-inch A490 – Tension

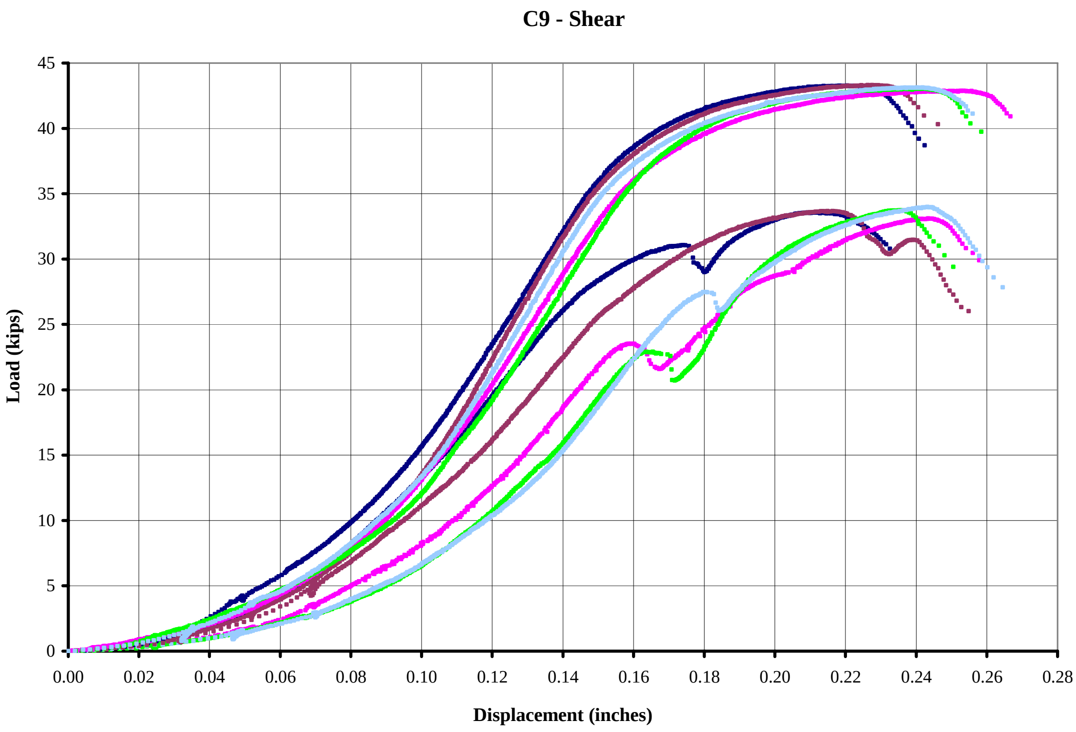

Figure A-108: Lot C9 – 3/4-inch A490 – Shear

C10

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 5"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4445 inches

Table A-55: Lot C10 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7437	52,787	15.47%	0.7429	41,443	0.7431	32,832
2	0.7436	52,033	10.31%	0.7432	40,848	0.7432	32,785
3	0.7434	50,858	10.66%	0.7421	41,324	0.7426	32,407
4	0.7438	52,134	9.48%	0.7432	40,463	0.7426	31,163
5	0.7435	51,961	8.58%	0.7433	41,231	0.7426	32,508

Note: The lever arm of the third LVDT was resting on the angle.

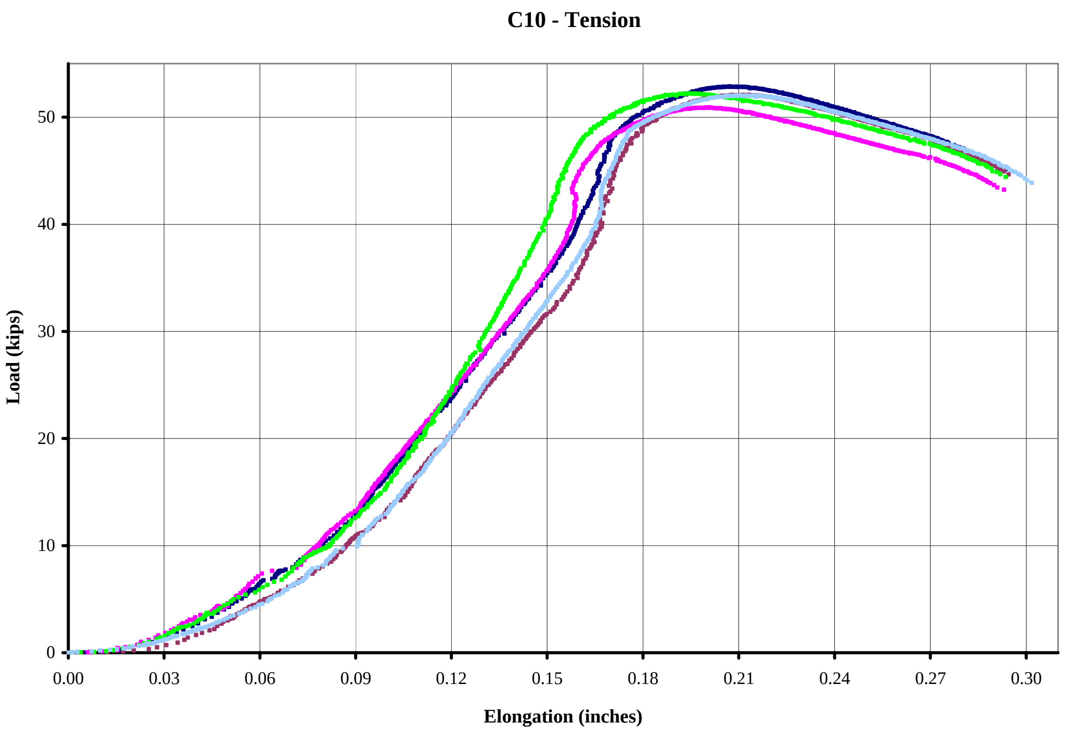

Figure A-109: Lot C10 – 3/4-inch A490 – Tension

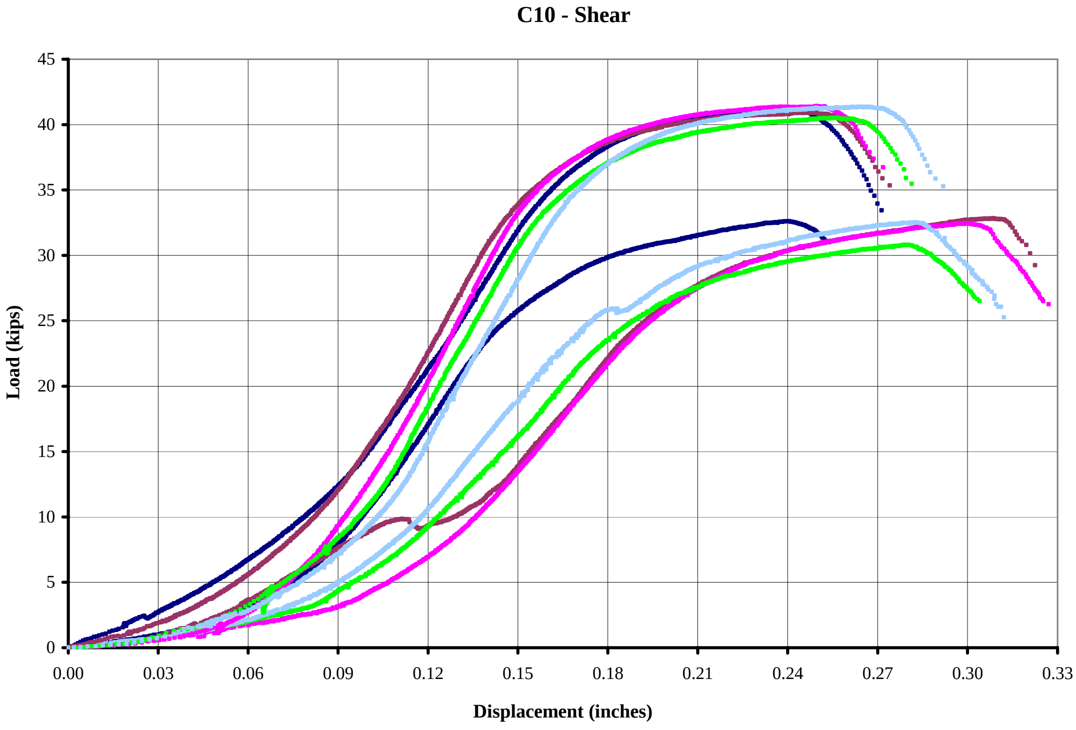

Figure A-110: Lot C10 – 3/4-inch A490 – Shear

L10

Bolt Properties:

Manufacturer:	[redacted]
Lot Number:	[redacted]
Size:	3/4"-10 x 2.75"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4580 inches

Table A-56: Lot L10 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.4125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7442	56,553	1.54%	0.7432	44,723	0.7430	32,032
2	0.7446	55,681	3.36%	0.7427	44,042	0.7436	32,720
3	0.7433	56,618	7.54%	0.7429	43,307	0.7429	32,681
4	0.7436	56,319	5.25%	0.7422	43,382	0.7433	31,913
5	0.7435	55,220	5.97%	0.7426	44,251	0.7428	33,481

Note: The lever arm of the third LVDT was resting on the bolt head.

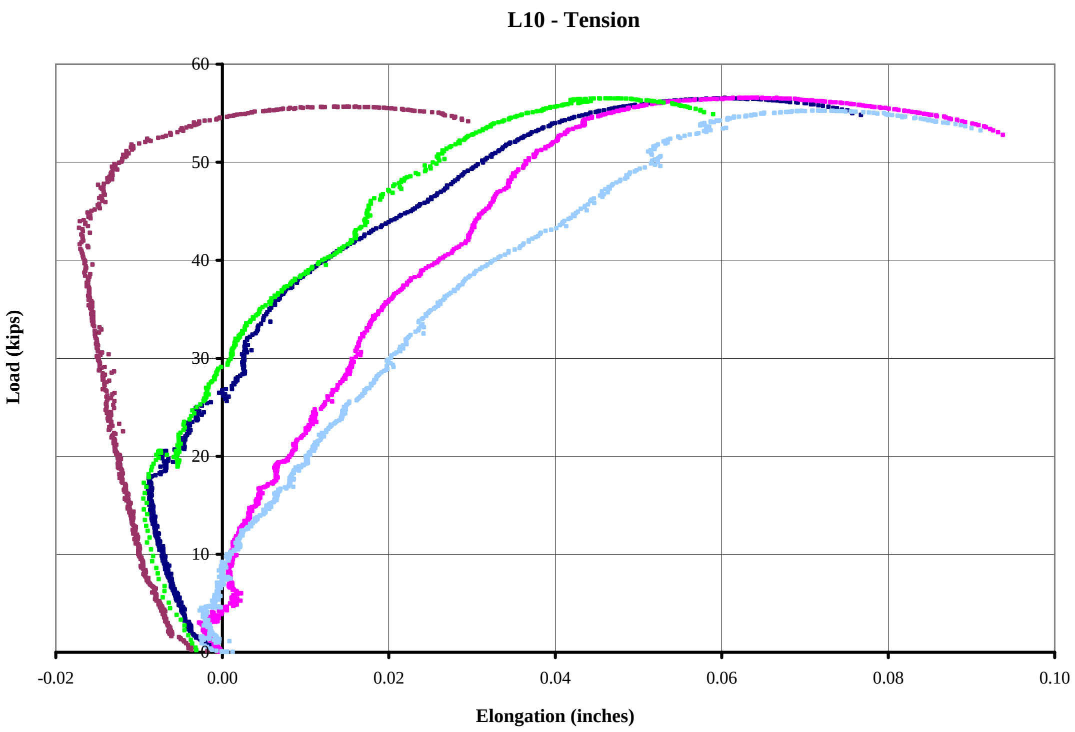

Figure A-111: Lot L10 – 3/4-inch A490 – Tension

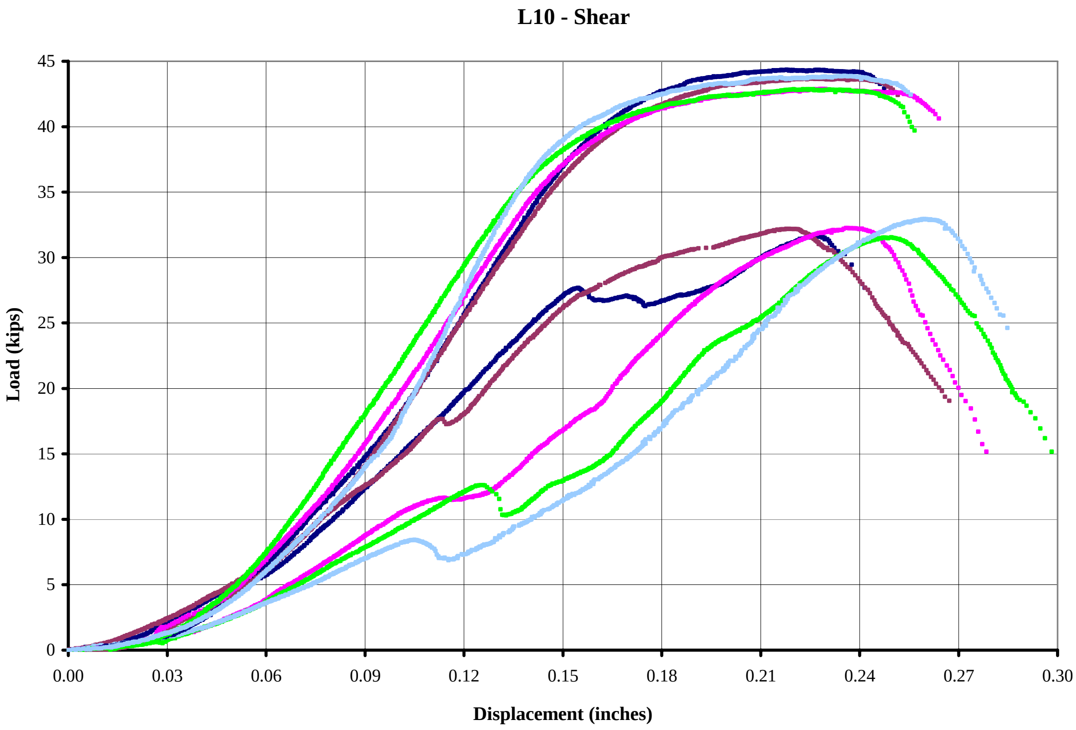

Figure A-112: Lot L10 – 3/4-inch A490 – Shear

N12

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4605 inches

Table A-57: Lot N12 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate:	0.45 in/min		**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7421	56,777	3.12%	0.7425	45,646	0.7427	36,310
2	0.7439	56,759	3.36%	0.7430	45,588	0.7421	33,553
3	0.7440	57,040	4.21%	0.7428	46,147	0.7431	35,431
4	0.7425	57,354	4.25%	0.7428	47,254	0.7430	35,078
5	0.7433	56,806	6.98%	0.7428	46,407	0.7413	35,802
6						0.7411	35,651

Note: The lever arm of the third LVDT was resting on the bolt head.

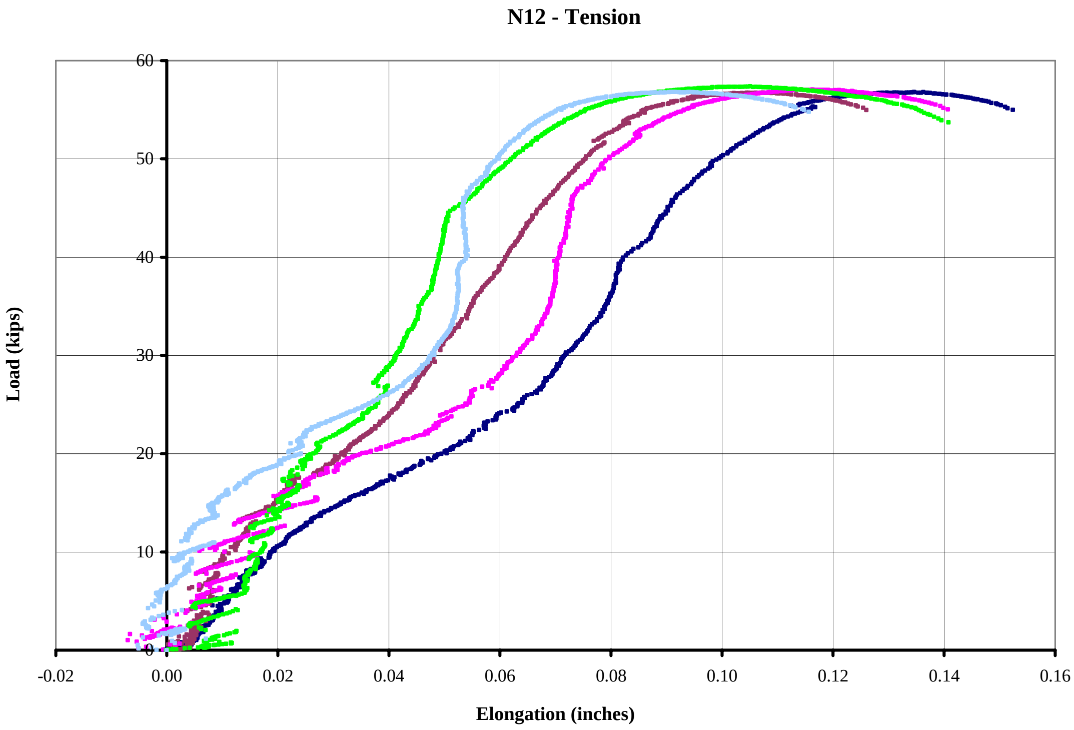

Figure A-113: Lot N12 – 3/4-inch A490 – Tension

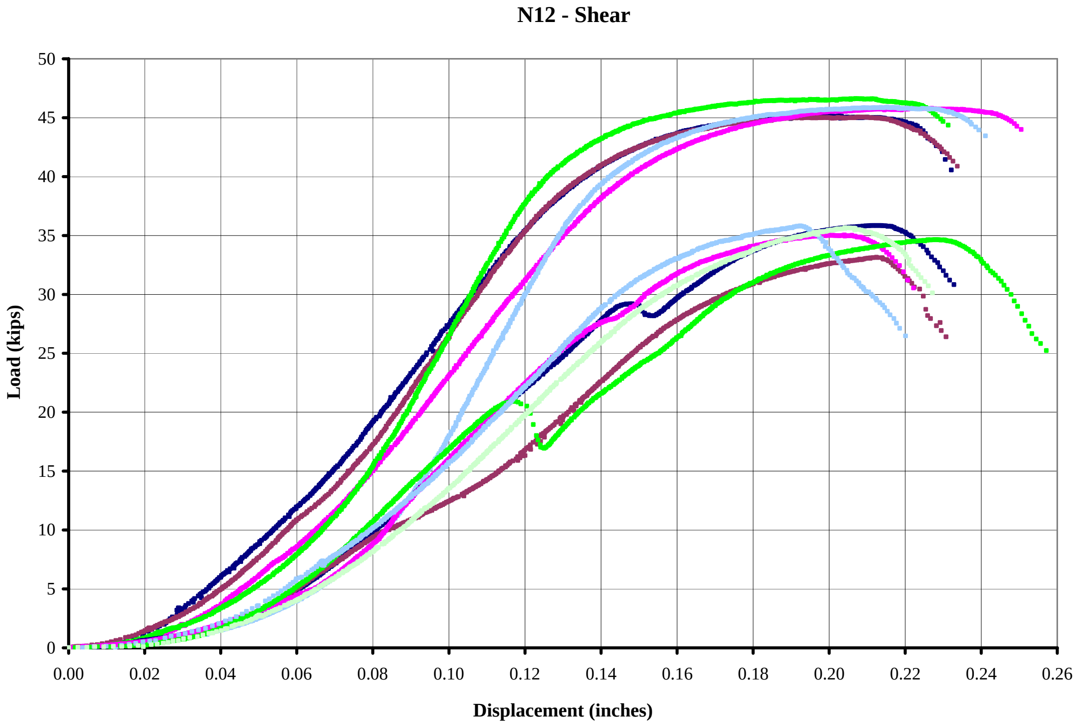

Figure A-114: Lot N12 – 3/4-inch A490 – Shear

N13

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.25"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4000 inches

Table A-58: Lot N13 – 3/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.4875 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7444	51,439	9.54%	0.7434	43,350	0.7433	32,991
2	0.7441	52,578	10.93%	0.7429	43,008	0.7440	34,021
3	0.7435	52,653	8.07%	0.7442	43,184	0.7438	32,511
4	0.7447	53,356	7.50%	0.7433	43,238	0.7436	31,624
5	0.7447	52,163	4.54%	0.7437	41,757	0.7428	31,336

Note: The lever arm of the third LVDT was resting on the bolt head.

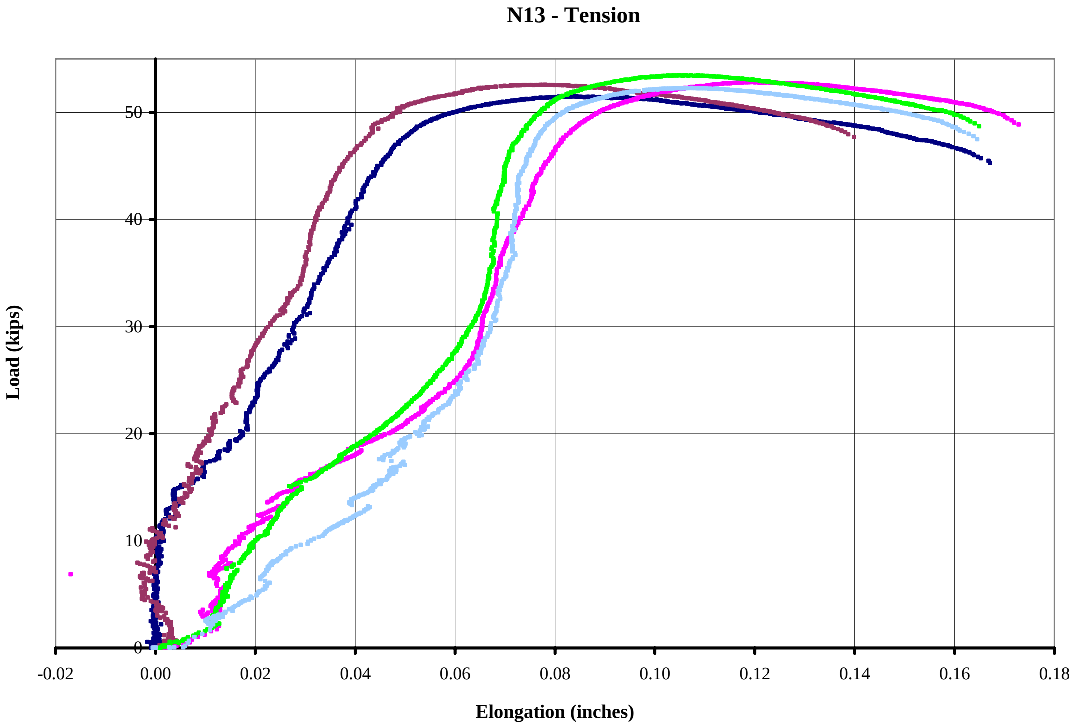

Figure A-115: Lot N13 – 3/4-inch A490 – Tension

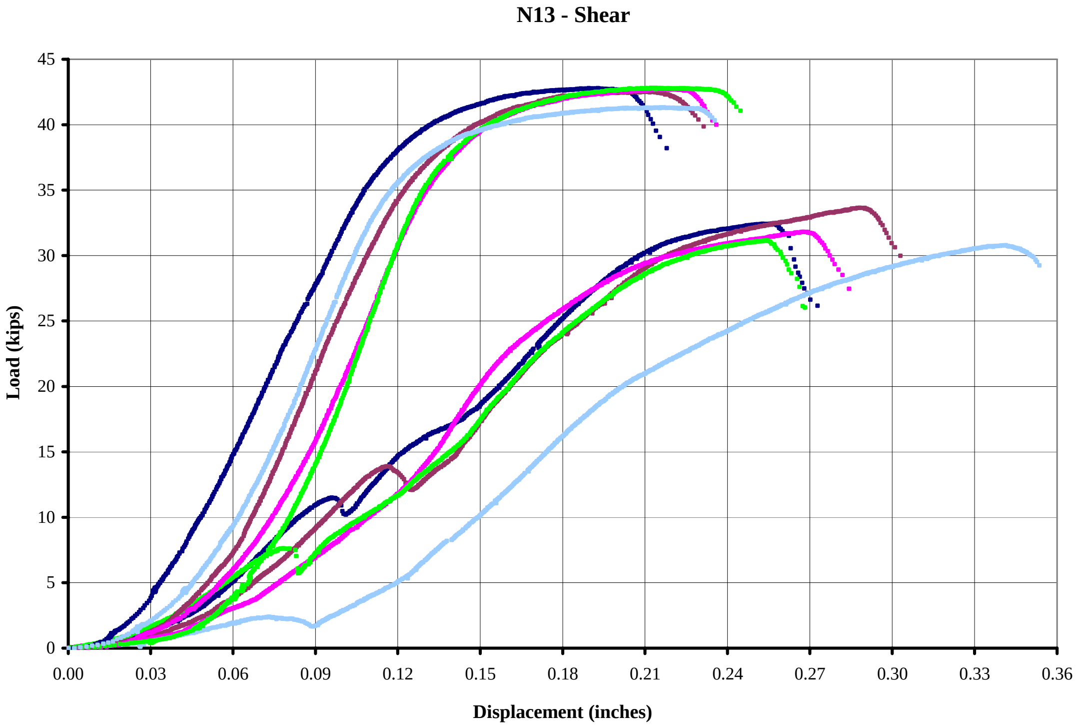

Figure A-116: Lot N13 – 3/4-inch A490 – Shear

T11

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.5"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1 inches

Table A-59: Lot T11 – 3/4-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.525 in/min			Load Rate: 0.5 in/min		Load Rate: 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7365	53,436	11.70%	0.7443	45,008	0.7445	33,517
2	0.7335	53,814	10.57%	0.7439	45,783	0.7445	33,729
3	0.7360	53,886	13.29%	0.7447	46,284	0.7438	33,218
4	0.7345	54,128	7.65%	0.7441	45,286	0.7441	32,619
5	0.7355	54,016	13.68%	0.7447	44,269	0.7441	32,479

Note: The lever arm of the third LVDT was resting on the bolt head.

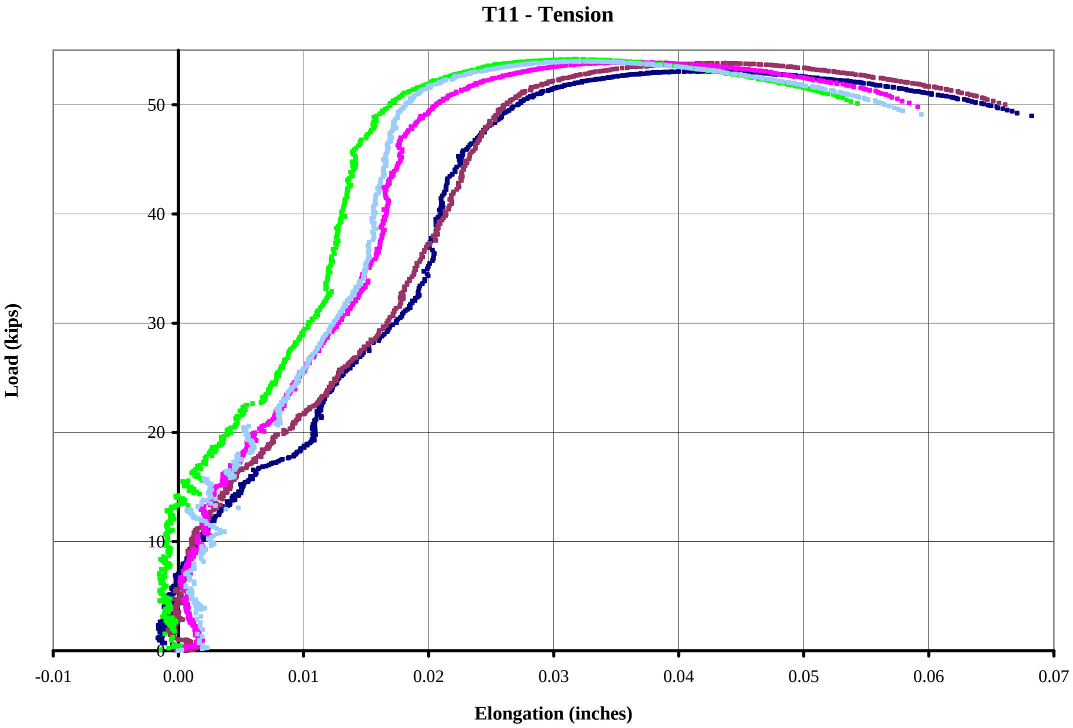

Figure A-117: Lot T11 – 3/4-inch A490 – Tension

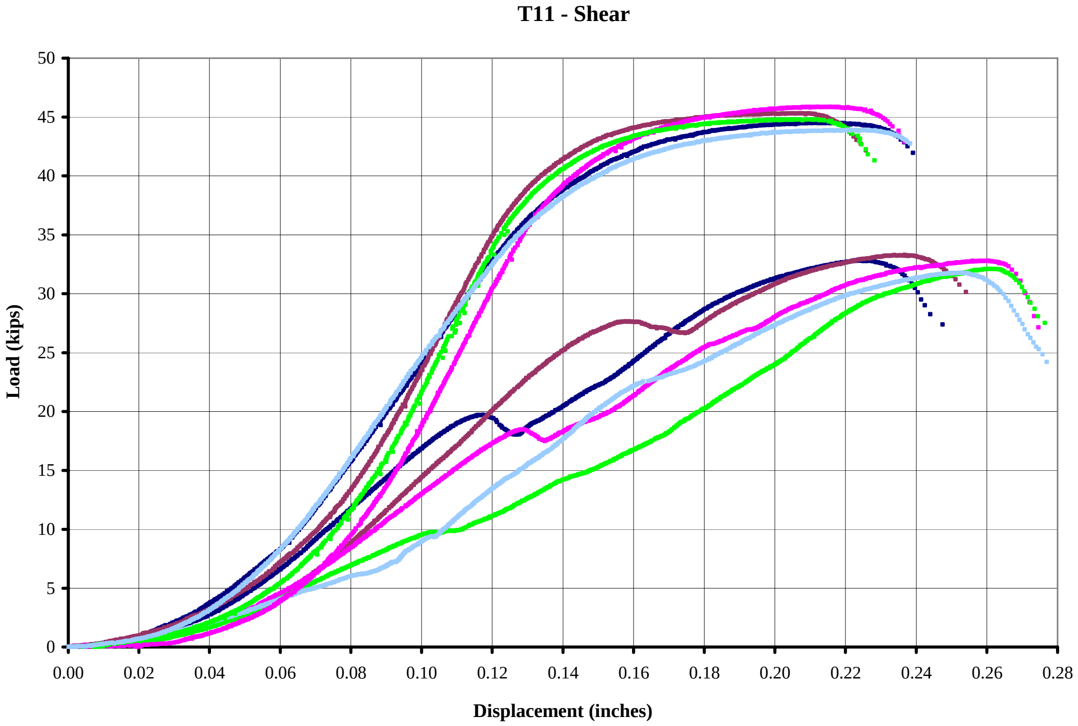

Figure A-118: Lot T11 – 3/4-inch A490 – Shear

T12

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.75"
Grade:	A490
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4170 inches

Table A-60: Lot T12 – 3/4-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.5625 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7355	53,244	15.46%	0.7418	43,981	0.7424	31,614
2	0.7315	53,677	8.57%	0.7423	42,990	0.7426	32,969
3	0.7390	53,237	11.96%	0.7424	43,483	0.7426	34,980
4	0.7345	53,944	10.27%	0.7423	42,488	0.7434	34,313
5	0.7335	53,082	9.70%	0.7428	43,163	0.7422	34,407

Note: The lever arm of the third LVDT was resting on the bolt head.

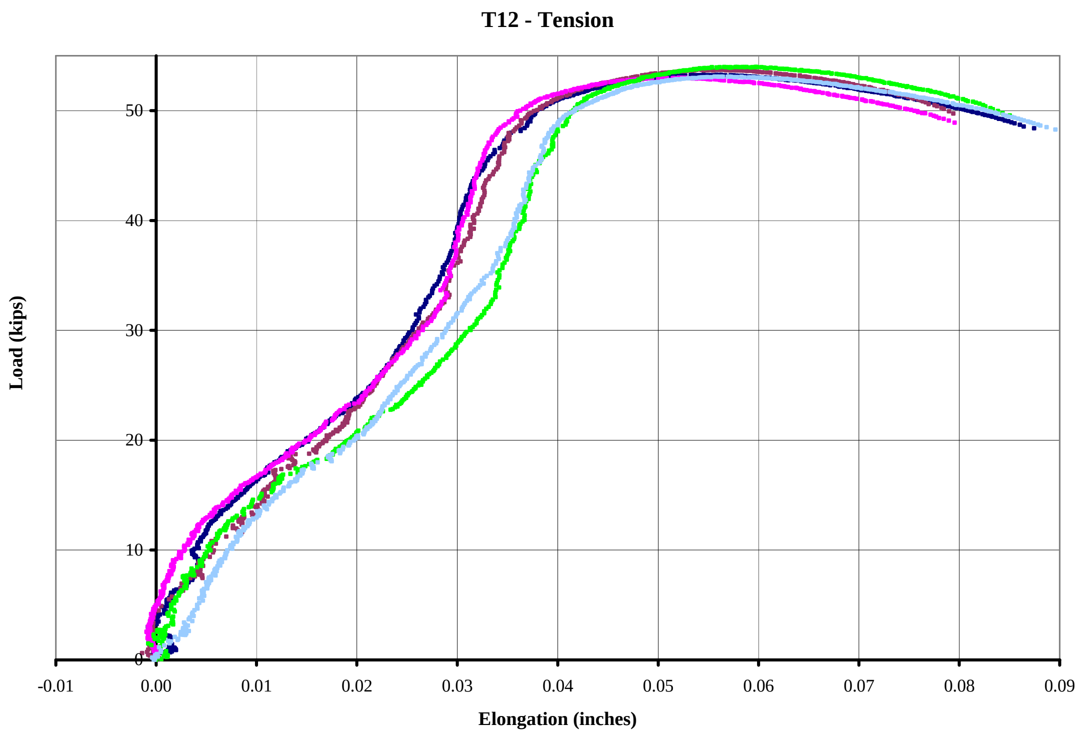

Figure A-119: Lot T12 – 3/4-inch A490 – Tension

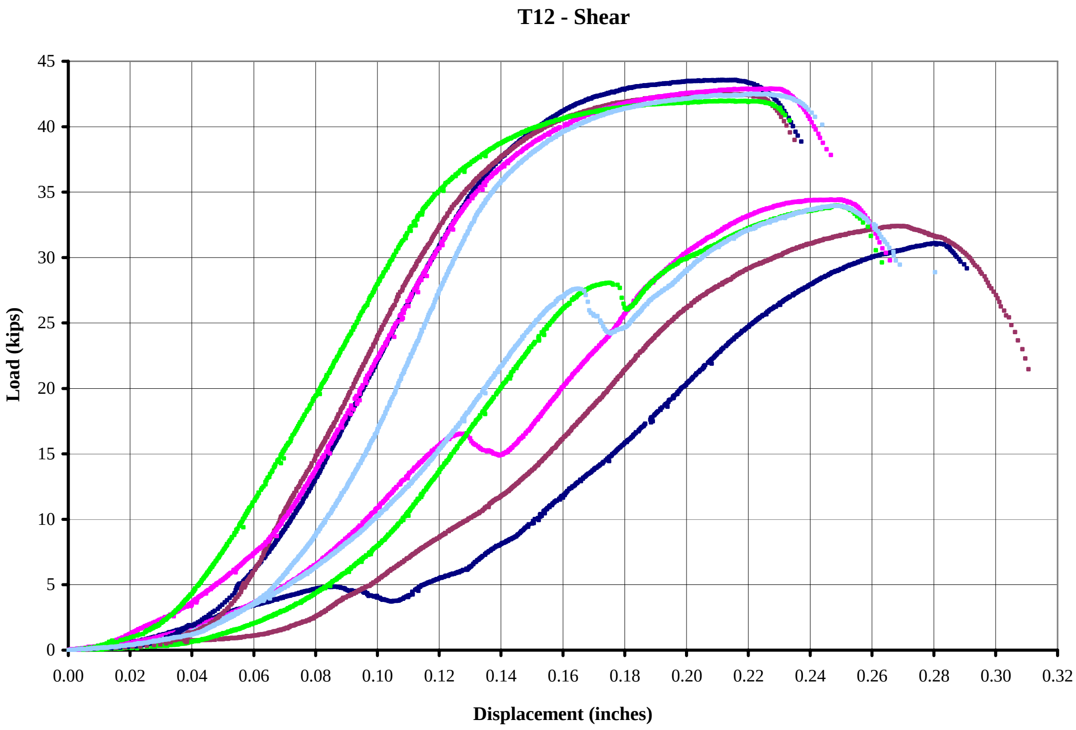

Figure A-120: Lot T12 – 3/4-inch A490 – Shear

C11

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3.75"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.6125 inches

Table A-61: Lot C11 – 7/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate:		0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8676	77,669	5.24%	0.8673	60,396	0.8673	46,169
2	0.8679	77,665	4.43%	0.8670	61,809	0.8675	44,680
3	0.8677	77,593	6.79%	0.8674	58,983	0.8676	44,161
4	0.8664	76,195	6.26%	0.8678	60,677	0.8671	48,011
5	0.8673	77,182	5.92%	0.8675	58,536	0.8672	45,401

Note: The lever arm of the third LVDT was resting on the angle.

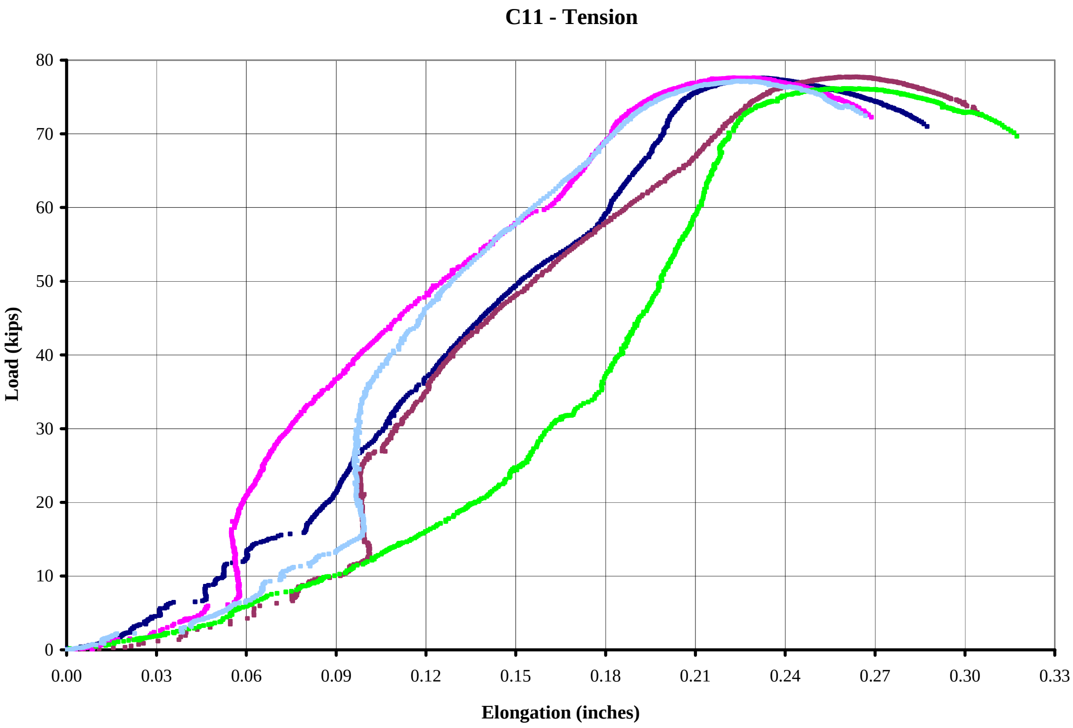

Figure A-121: Lot C11 – 7/8-inch A490 – Tension

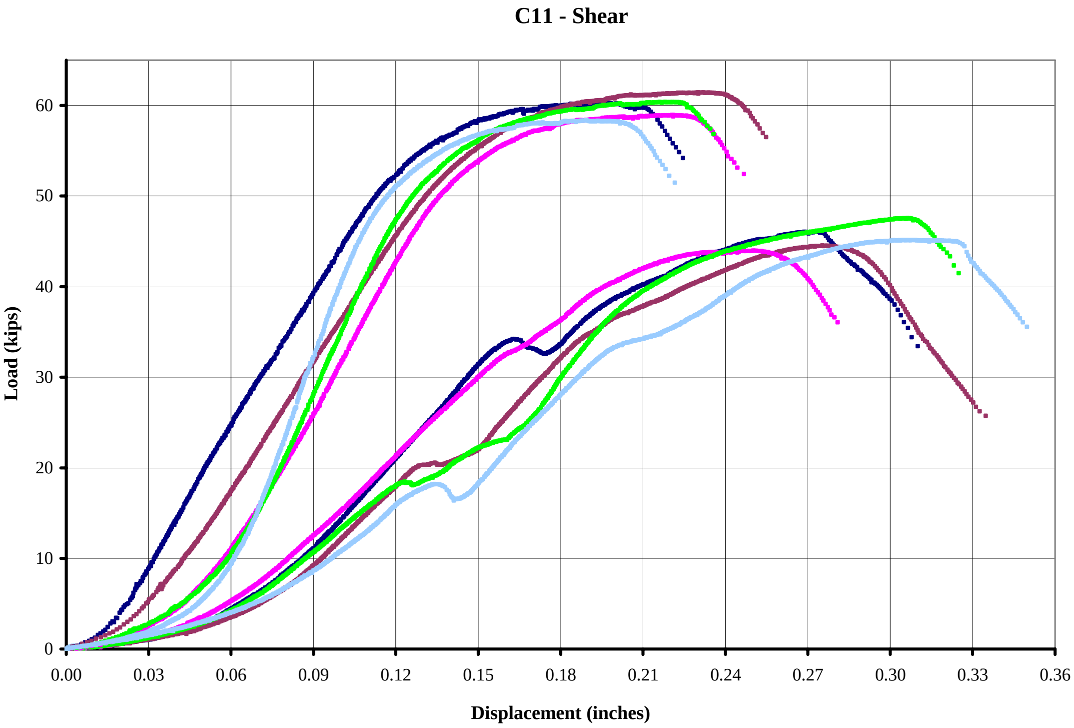

Figure A-122: Lot C11 – 7/8-inch A490 – Shear

C12

Bolt Properties:

Manufacturer:	[redacted]
Lot Number:	[redacted]
Size:	7/8"-9 x 4.5"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.4945 inches

Table A-62: Lot C12 – 7/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8685	77,399	8.20%	0.8672	59,596	0.8687	44,179
2	0.8691	77,135	7.19%	0.8686	59,700	0.8686	45,451
3	0.8690	77,016	9.43%	0.8692	59,113	0.8690	44,049
4	0.8691	77,071	8.13%	0.8685	59,524	0.8691	44,392
5	0.8680	77,204	7.13%	0.8690	59,920	0.8694	44,291

Note: The lever arm of the third LVDT was resting on the angle.

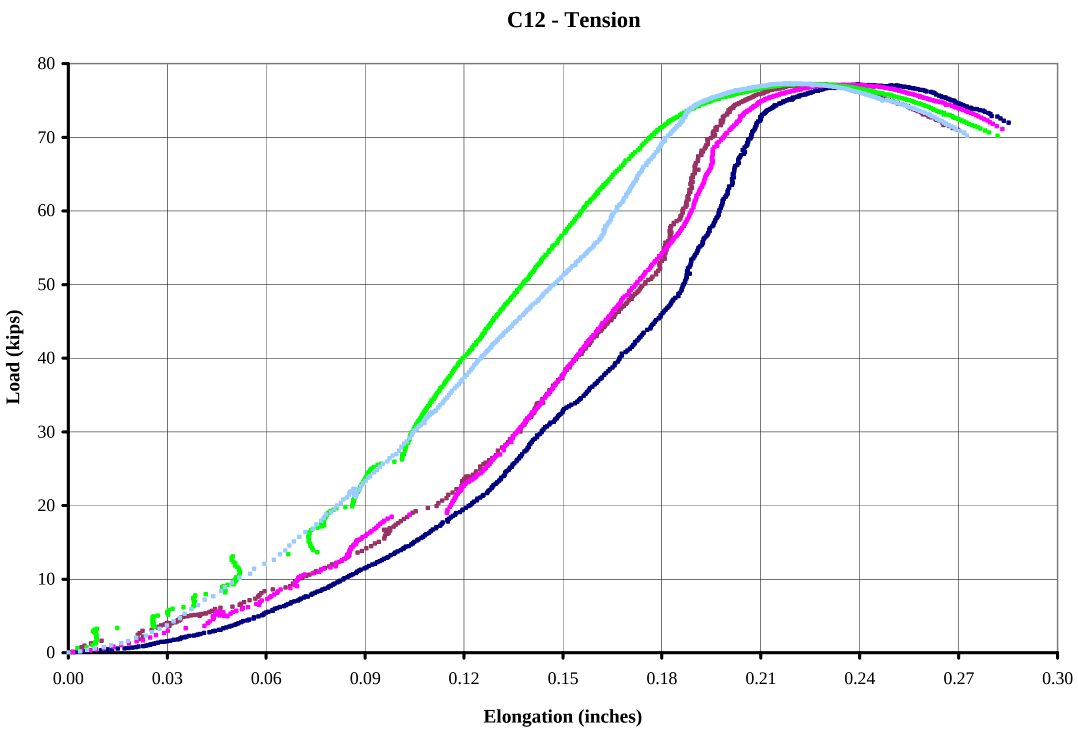

Figure A-123: Lot C12 – 7/8-inch A490 – Tension

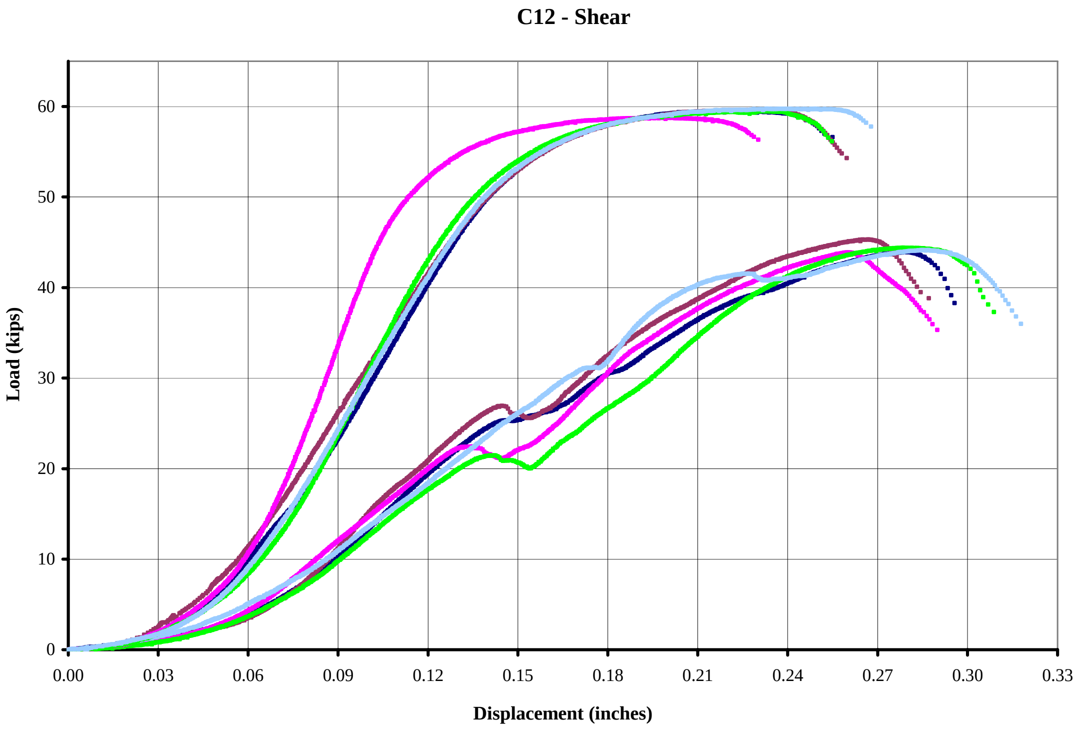

Figure A-124: Lot C12 – 7/8-inch A490 – Shear

C13

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.75"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5665 inches

Table A-63: Lot C13 – 7/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.7125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8677	73,217	10.34%	0.8680	57,491	0.8686	44,165
2	0.8672	73,985	9.96%	0.8677	58,179	0.8692	41,984
3	0.8684	73,416	11.84%	0.8693	58,028	0.8678	42,070
4	0.8676	73,524	8.81%	0.8683	57,653	0.8678	42,002
5	0.8678	73,819	9.99%	0.8679	57,401	0.8683	44,103

Note: The lever arm of the third LVDT was resting on the angle.

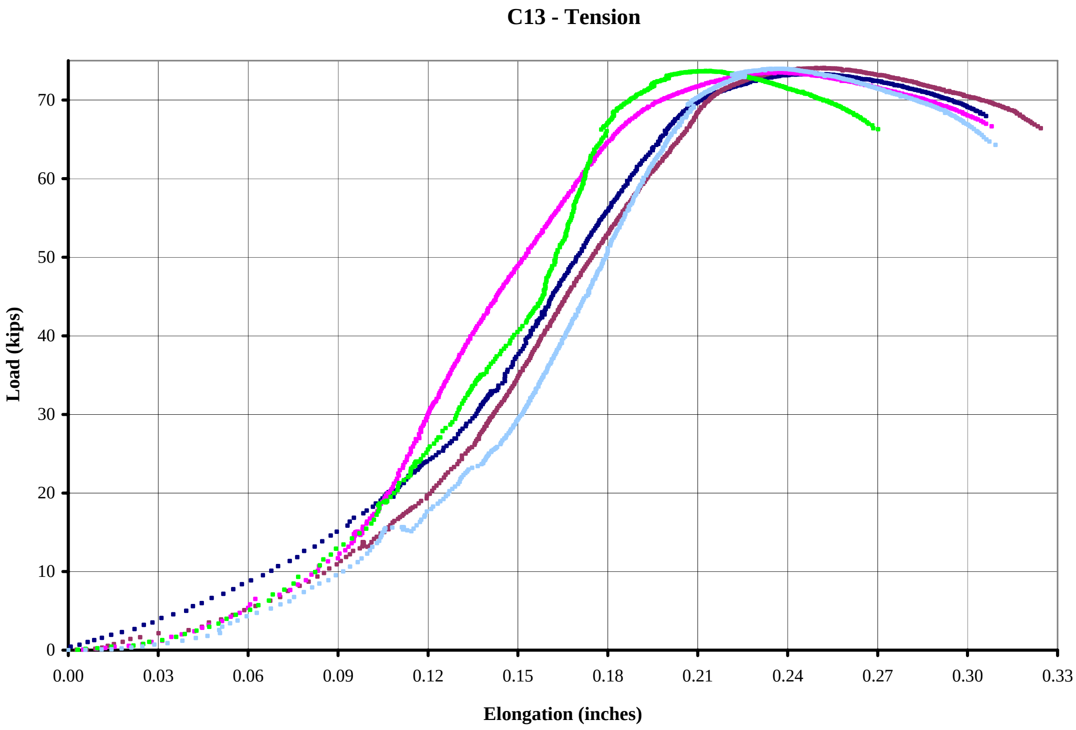

Figure A-125: Lot C13 – 7/8-inch A490 – Tension

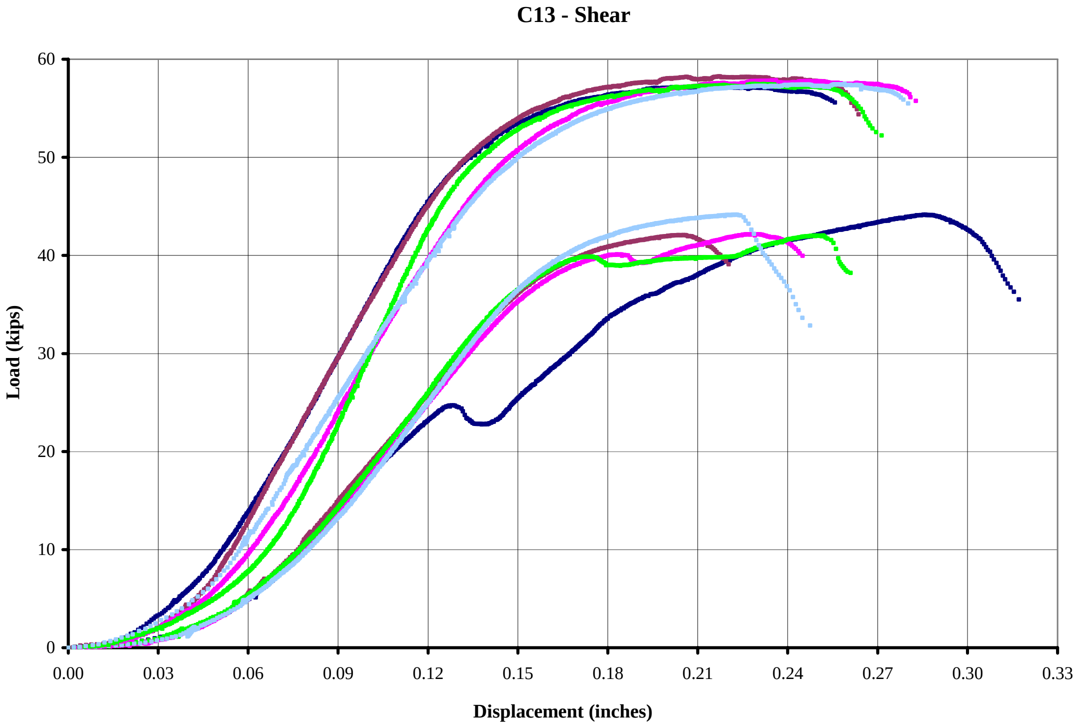

Figure A-126: Lot C13 – 7/8-inch A490 – Shear

C15

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 5"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.6290 inches

Table A-64: Lot C15 – 7/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.75 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8687	72,907	8.84%	0.8705	56,081	0.8698	42,193
2	0.8676	73,408	9.05%	0.8699	56,135	0.8697	42,283
3	0.8680	73,131	10.50%	0.8691	56,150	0.8691	41,267
4	0.8695	73,073	10.22%	0.8695	54,845	0.8702	43,491
5	0.8692	73,124	9.79%	0.8690	55,079	0.8689	42,312

Note: The lever arm of the third LVDT was resting on the angle.

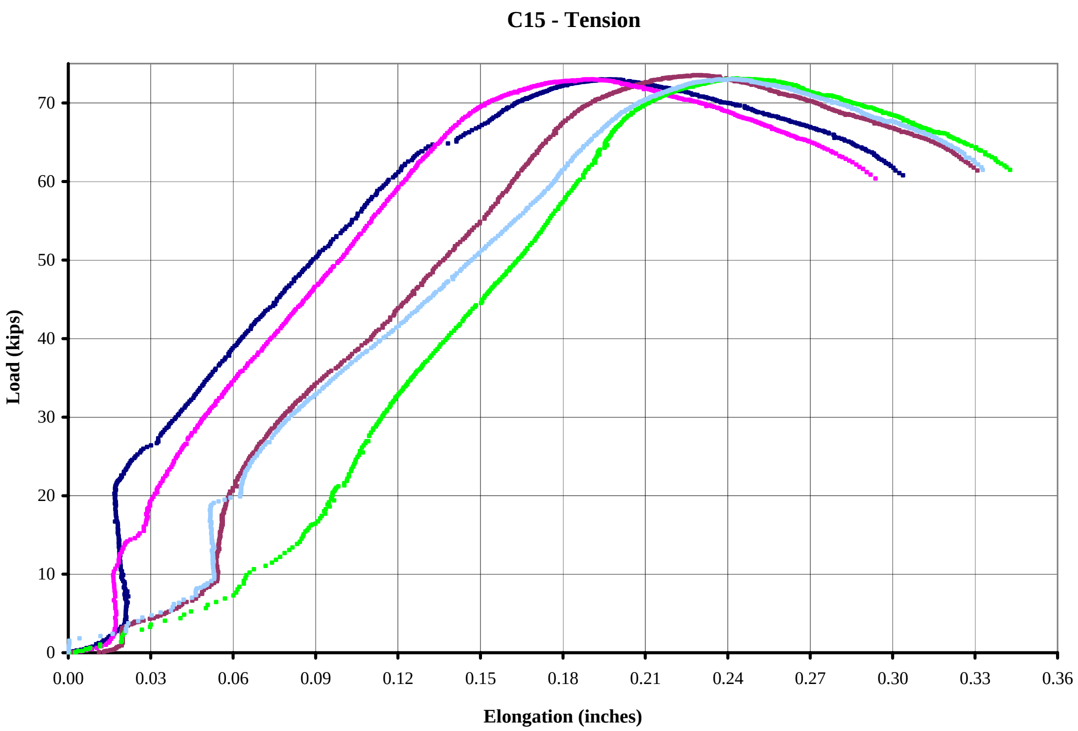

Figure A-127: Lot C15 – 7/8-inch A490 – Tension

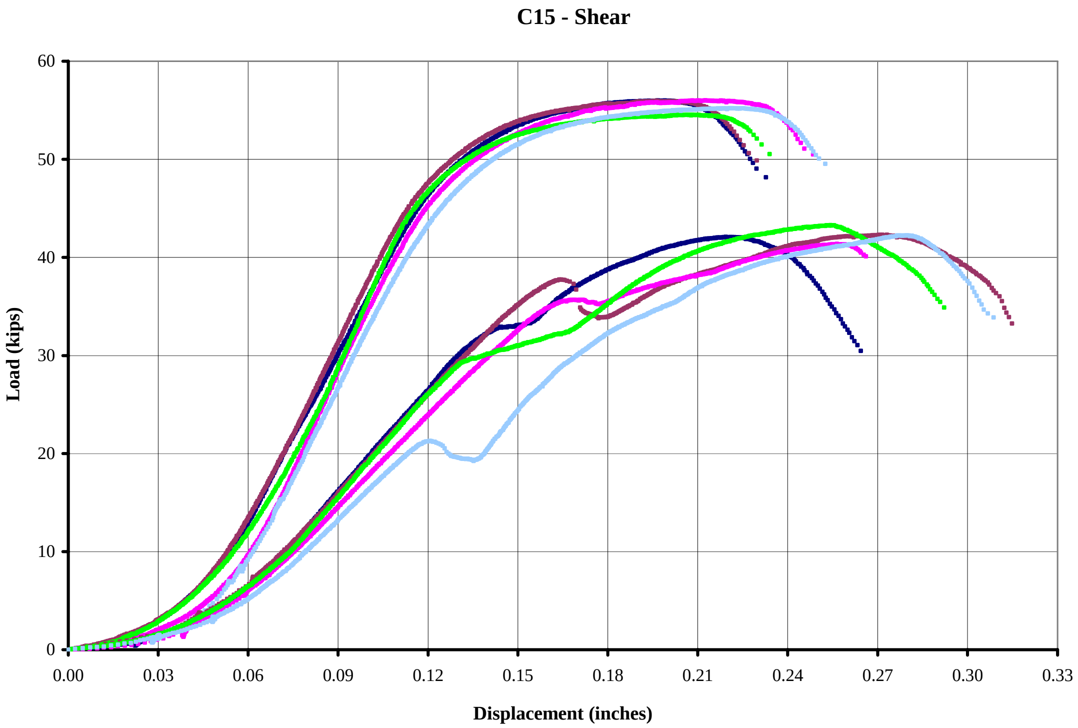

Figure A-128: Lot C15 – 7/8-inch A490 – Shear

L11

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5205 inches

Table A-65: Lot L11 – 7/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.45 in/min			Load Rate: 0.5 in/min		Load Rate: 0.5 in/min	
	Average Diameter (inches)	Failure Load (pounds)	Elongation	Average Diameter (inches)	Failure Load (pounds)	Average Diameter (inches)	Failure Load (pounds)
1	0.8759	74,591	7.17%	0.8706	58,496	0.8713	46,212
2	0.8747	73,877	6.25%	0.8709	59,001	0.8714	46,371
3	0.8730	75,185	5.03%	0.8712	58,824	0.8712	44,175
4	0.8722	75,196	8.32%	0.8710	58,875	0.8713	46,302
5	0.8729	75,070	7.23%	0.8713	58,558	0.8712	43,956

Note: The lever arm of the third LVDT was resting on the bolt head.

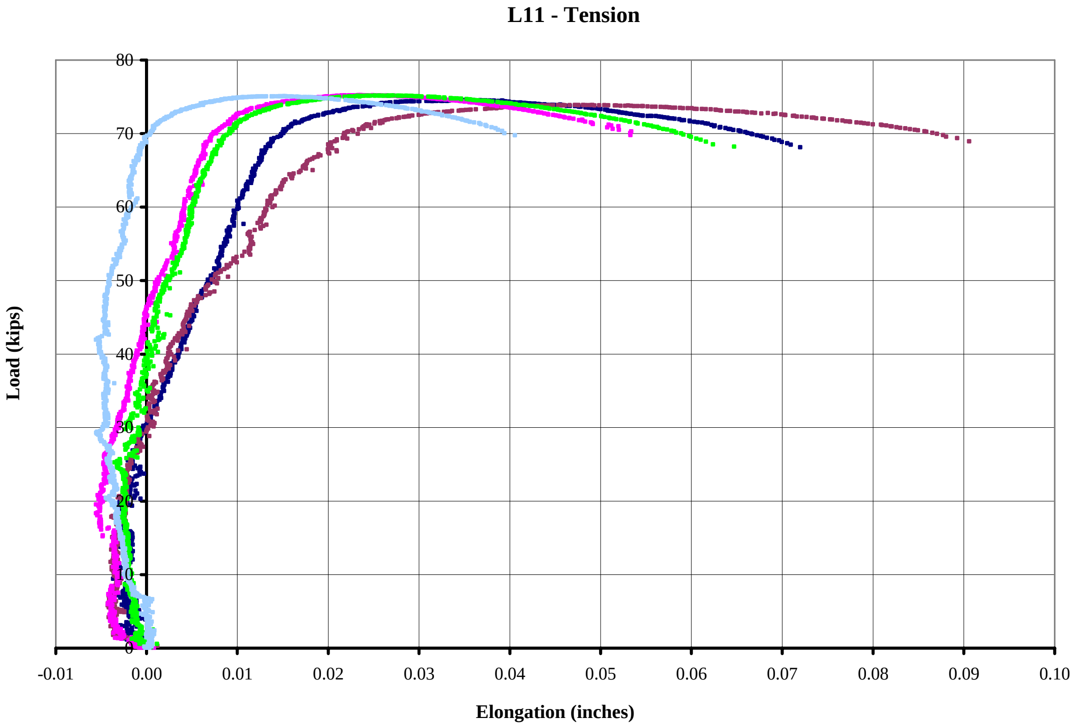

Figure A-129: Lot L11 – 7/8-inch A490 – Tension

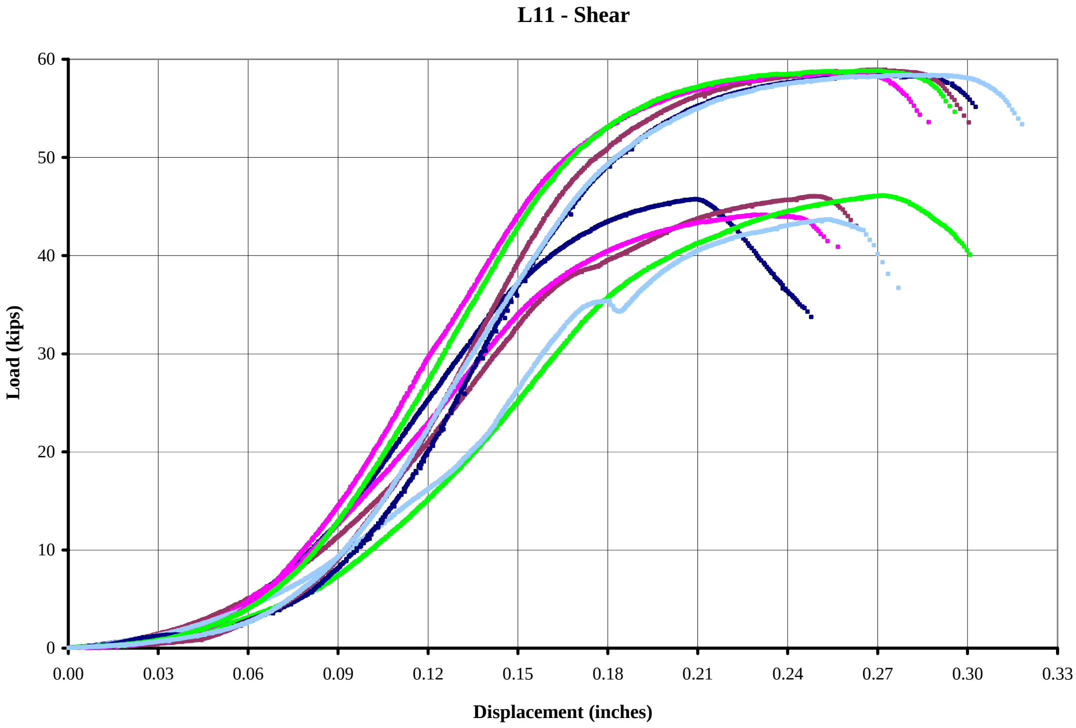

Figure A-130: Lot L11 – 7/8-inch A490 – Shear

L12

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 5"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5890 inches

Table A-66: Lot L12 – 7/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.75 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8694	79,201	10.92%	0.8692	62,674	0.8691	47,275
2	0.8698	78,581	9.06%	0.8686	63,326	0.8689	48,425
3	0.8692	78,361	7.90%	0.8689	61,827	0.8698	45,235
4	0.8705	78,599	9.41%	0.8694	62,537	0.8689	45,268
5	0.8701	77,060	12.52%	0.8684	62,274	0.8689	46,987

Note: The lever arm of the third LVDT was resting on the bolt head.

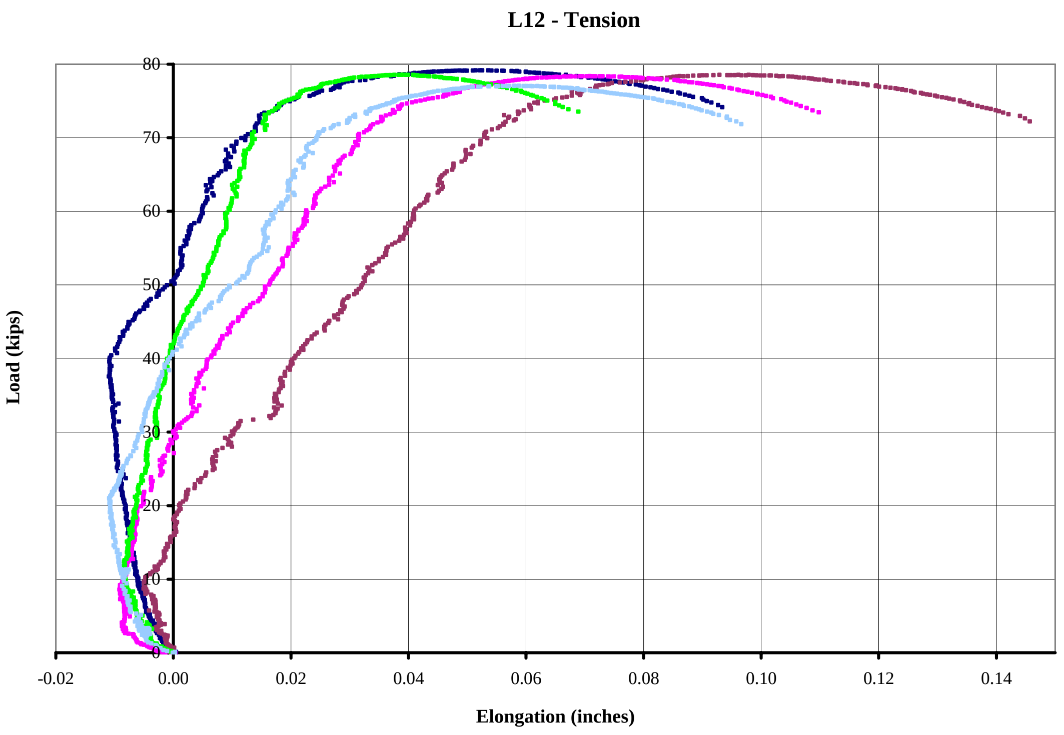

Figure A-131: Lot L12 – 7/8-inch A490 – Tension

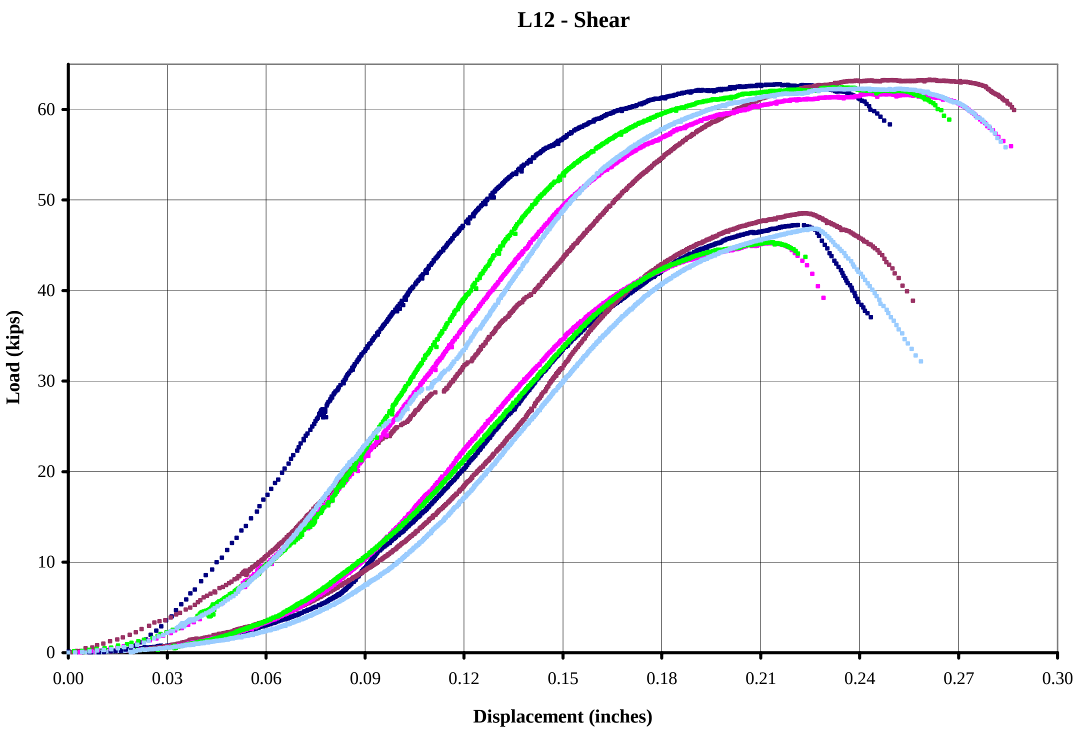

Figure A-132: Lot L12 – 7/8-inch A490 – Shear

N14

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3.75"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5525 inches

Table A-67: Lot N14 – 7/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8719	76,944	9.60%	0.8704	61,207	0.8699	45,498
2	0.8750	75,315	7.50%	0.8703	61,142	0.8703	46,457
3	0.8743	75,629	5.57%	0.8704	60,428	0.8693	46,688
4	0.8721	76,670	8.05%	0.8699	60,807	0.8698	46,522
5	0.8733	76,494	4.83%	0.8703	61,888	0.8698	45,963
6	0.8757	77,060	8.99%				

Note: The lever arm of the third LVDT was resting on the bolt head.

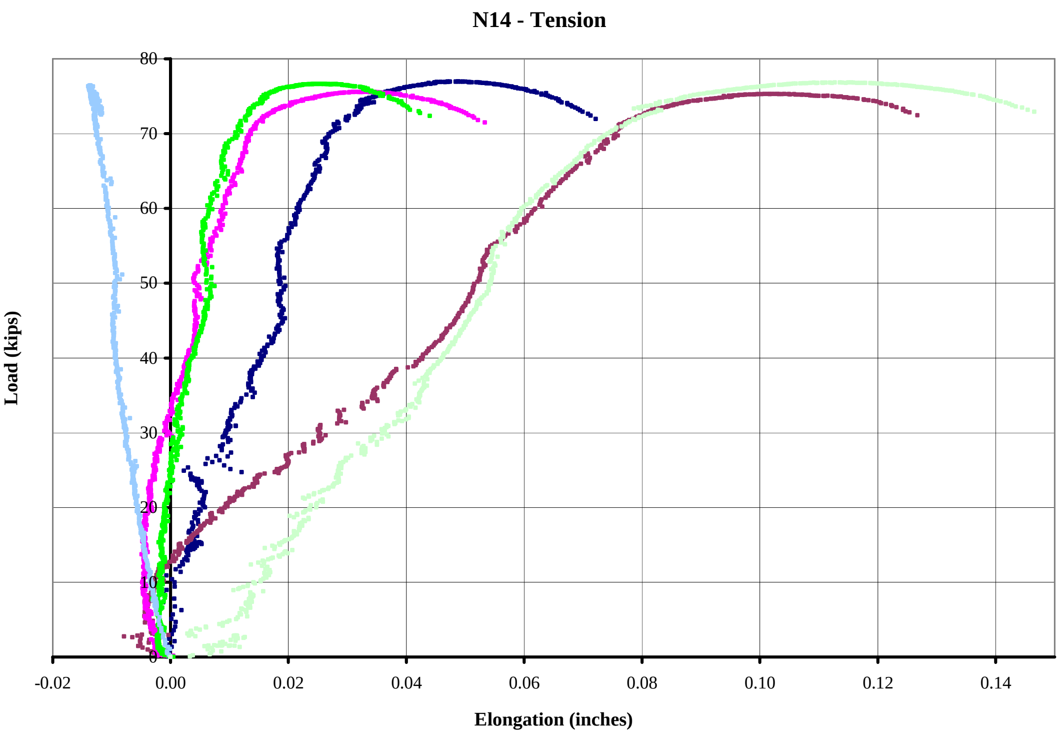

Figure A-133: Lot N14 – 7/8-inch A490 – Tension

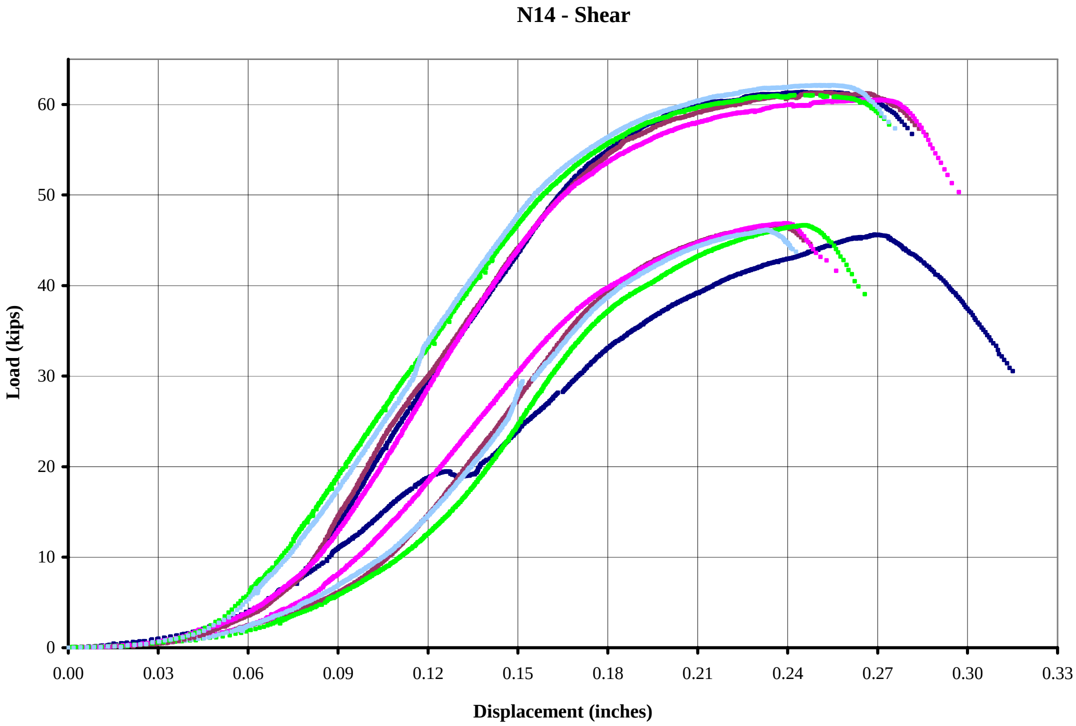

Figure A-134: Lot N14 – 7/8-inch A490 – Shear

N15

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5185 inches

Table A-68: Lot N15 – 7/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8735	73,628	9.94%	0.8696	56,921	0.8697	45,307
2	0.8711	71,620	10.54%	0.8692	56,867	0.8707	43,692
3	0.8726	74,601	6.88%	0.8699	57,963	0.8705	45,343
4	0.8750	73,610	8.66%	0.8698	62,714	0.8706	44,193
5	0.8752	72,413	6.35%	0.8693	58,042	0.8711	45,105

Note: The lever arm of the third LVDT was resting on the bolt head.

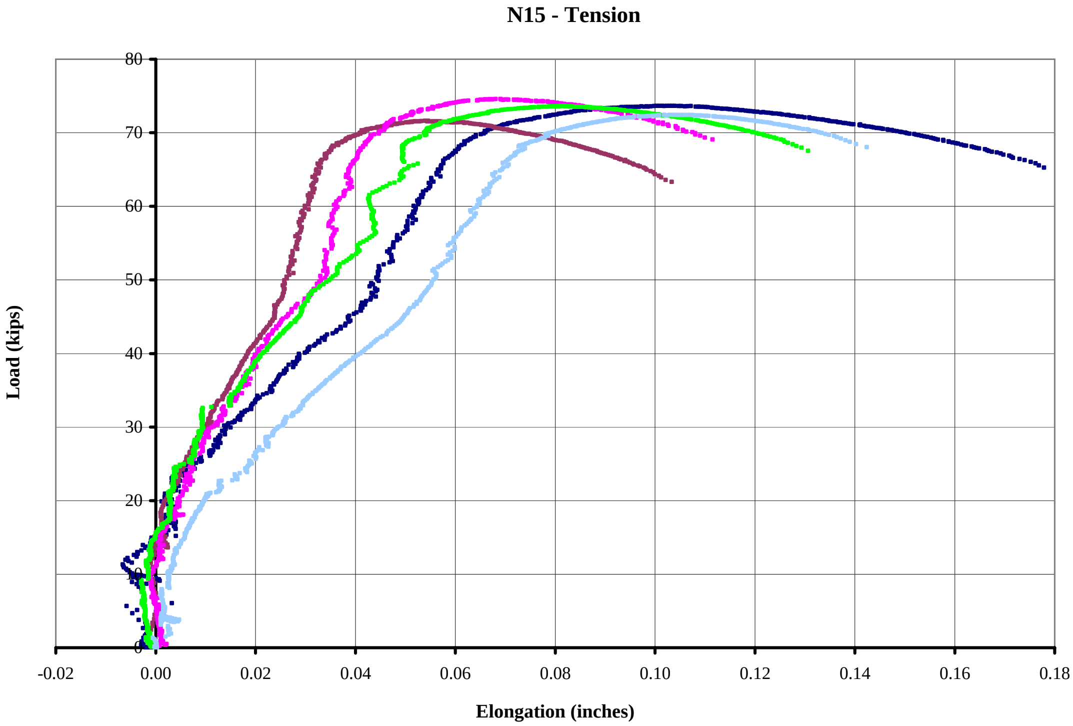

Figure A-135: Lot N15 – 7/8-inch A490 – Tension

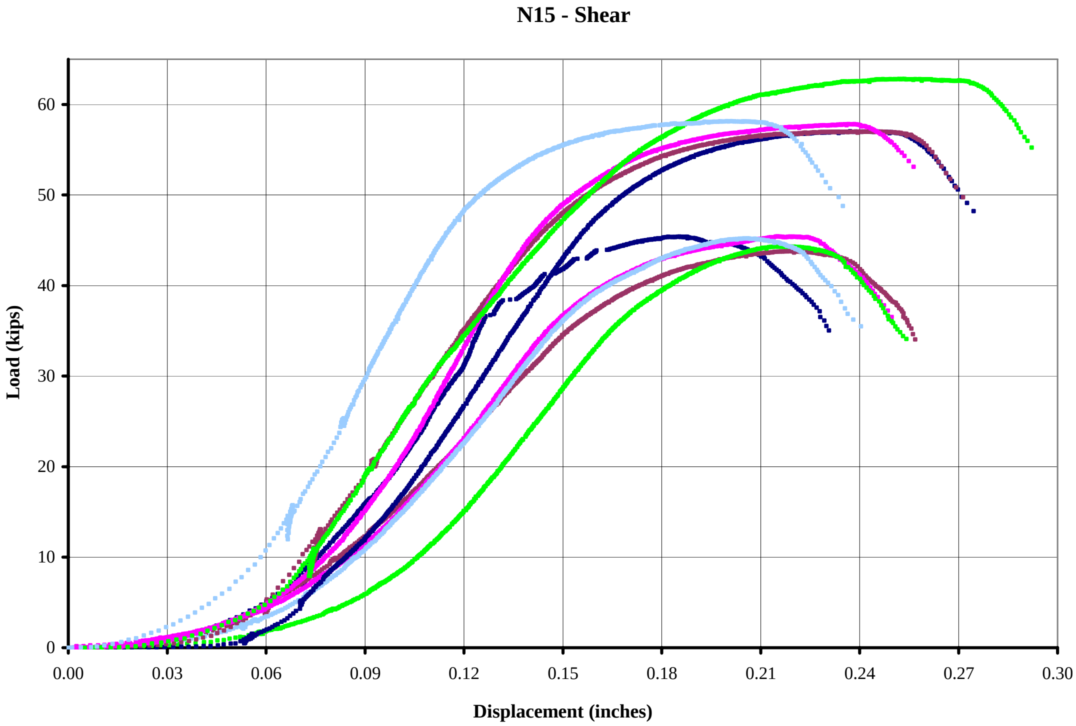

Figure A-136: Lot N15 – 7/8-inch A490 – Shear

T13

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5685 inches

Table A-69: Lot T13 – 7/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.60 in/min	Load Rate:	0.5 in/min	Load Rate:	0.5 in/min
	Average Diameter (inches)	Failure Load (pounds)	Elongation	Average Diameter (inches)	Failure Load (pounds)	Average Diameter (inches)	Failure Load (pounds)
1	0.8740	77,914	9.75%	0.8742	61,571	0.8743	46,219
2	0.8762	76,620	9.40%	0.8740	61,207	0.8739	47,823
3	0.8758	78,927	5.67%	0.8732	61,539	0.8737	46,587
4	0.8756	77,777	8.70%	0.8739	60,353	0.8741	47,881
5	0.8745	77,907	9.75%	0.8741	61,088	0.8737	47,697

Note: The lever arm of the third LVDT was resting on the bolt head.

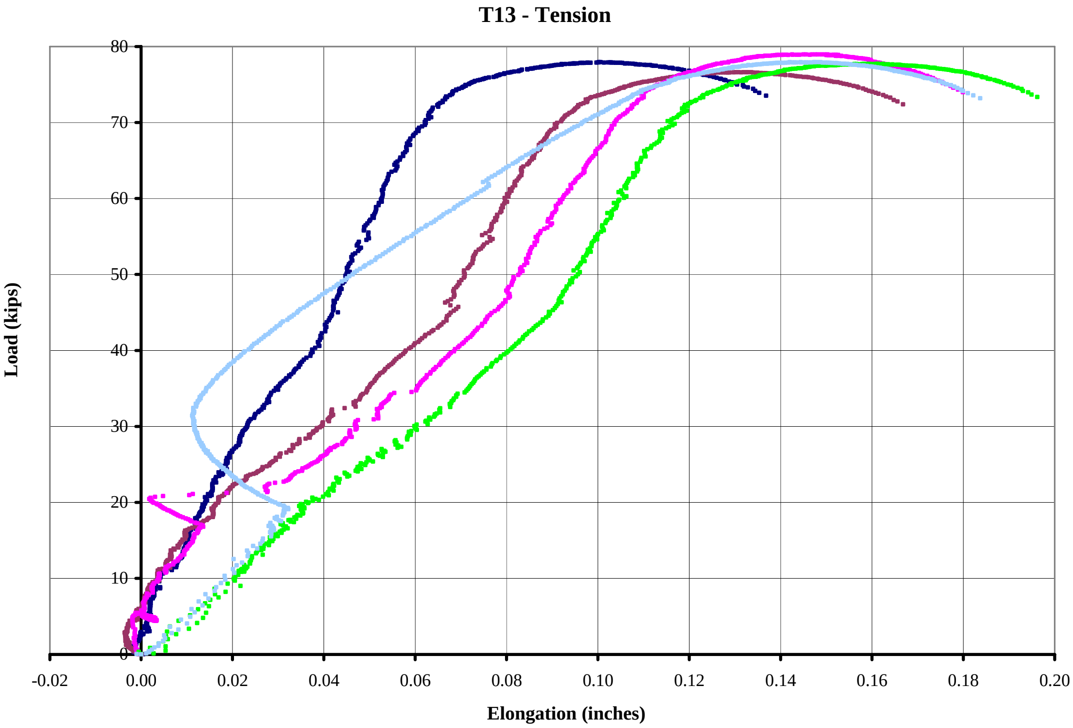

Figure A-137: Lot T13 – 7/8-inch A490 – Tension

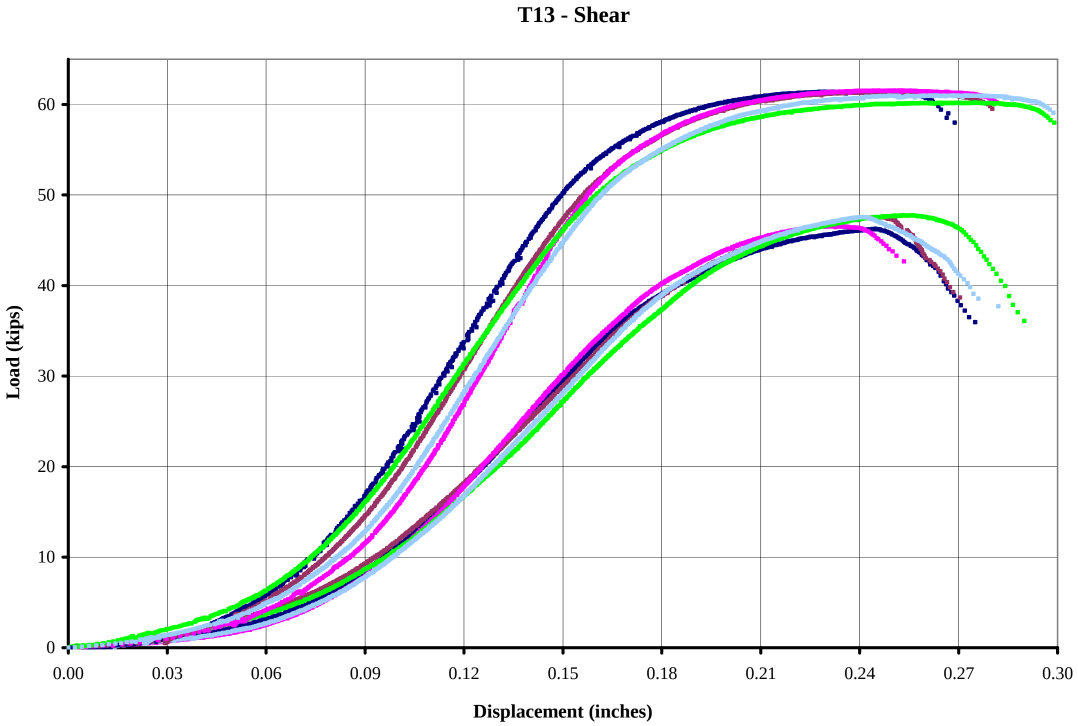

Figure A-138: Lot T13 – 7/8-inch A490 – Shear

T14

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.25"
Grade:	A490
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5865 inches

Table A-70: Lot T14 – 7/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8745	75,611	8.45%	0.8701	59,902	0.8700	47,578
2	0.8737	74,252	6.84%	0.8701	59,617	0.8699	44,943
3	0.8728	76,364	6.97%	0.8704	60,169	0.8696	43,181
4	0.8717	75,420	7.85%	0.8703	58,485	0.8696	44,312
5	0.8736	75,730	7.28%	0.8703	59,996	0.8687	44,377

Note: The lever arm of the third LVDT was resting on the bolt head.

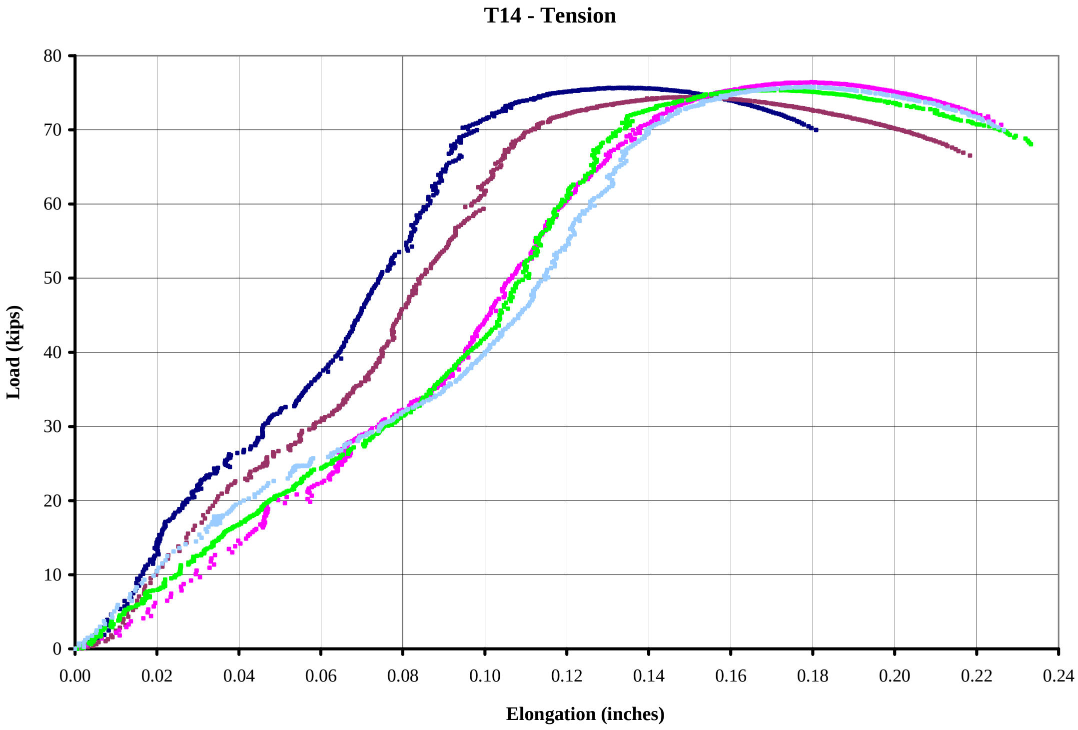

Figure A-139: Lot T14 – 7/8-inch A490 – Tension

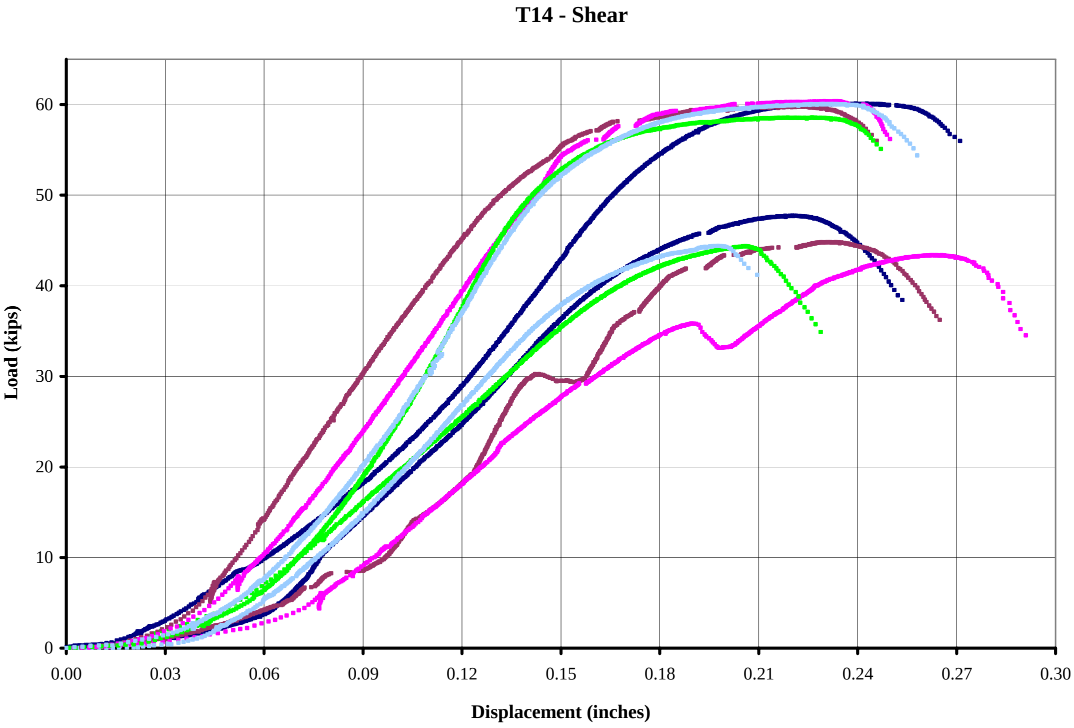

Figure A-140: Lot T14 – 7/8-inch A490 – Shear

C16

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8325 inches

Table A-71: Lot C16 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9961	102,360	3.40%	0.9965	78,992	0.9979	58,561
2	0.9965	103,164	3.53%	0.9973	79,561	0.9974	58,824
3	0.9972	103,294	2.91%	0.9976	80,091	0.9964	68,704
4	0.9959	103,157	4.61%	0.9972	79,792	0.9978	61,636
5	0.9967	102,976	3.02%	0.9978	79,291	0.9973	60,021

Note: The lever arm of the third LVDT was resting on the angle.

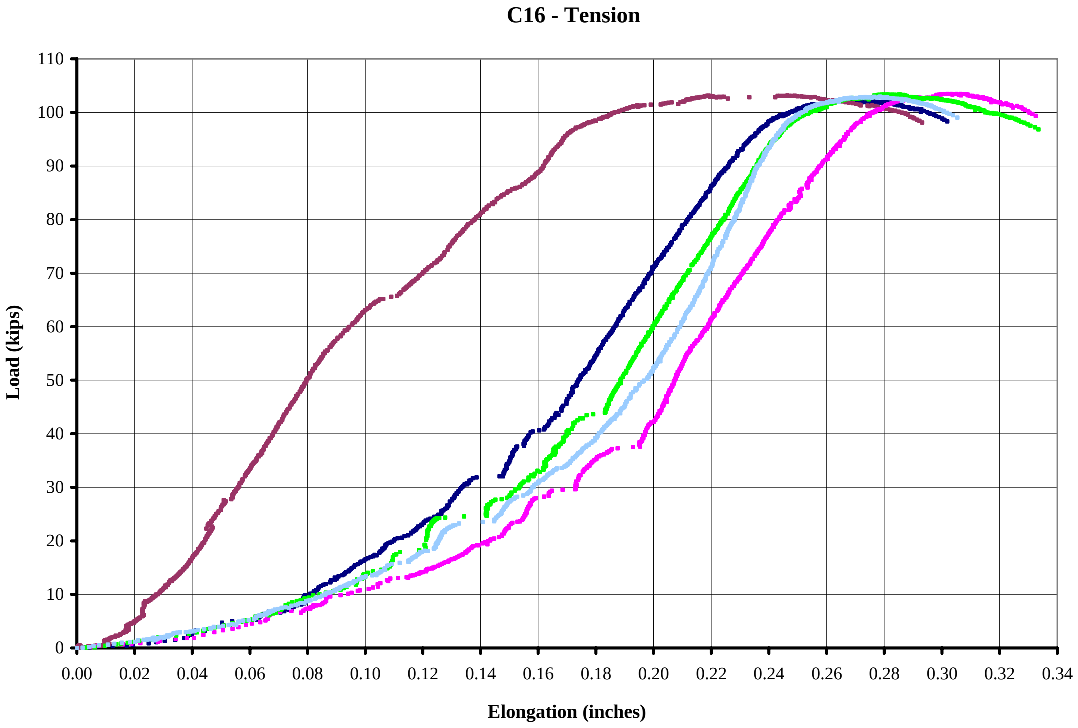

Figure A-141: Lot C16 – 1-inch A490 – Tension

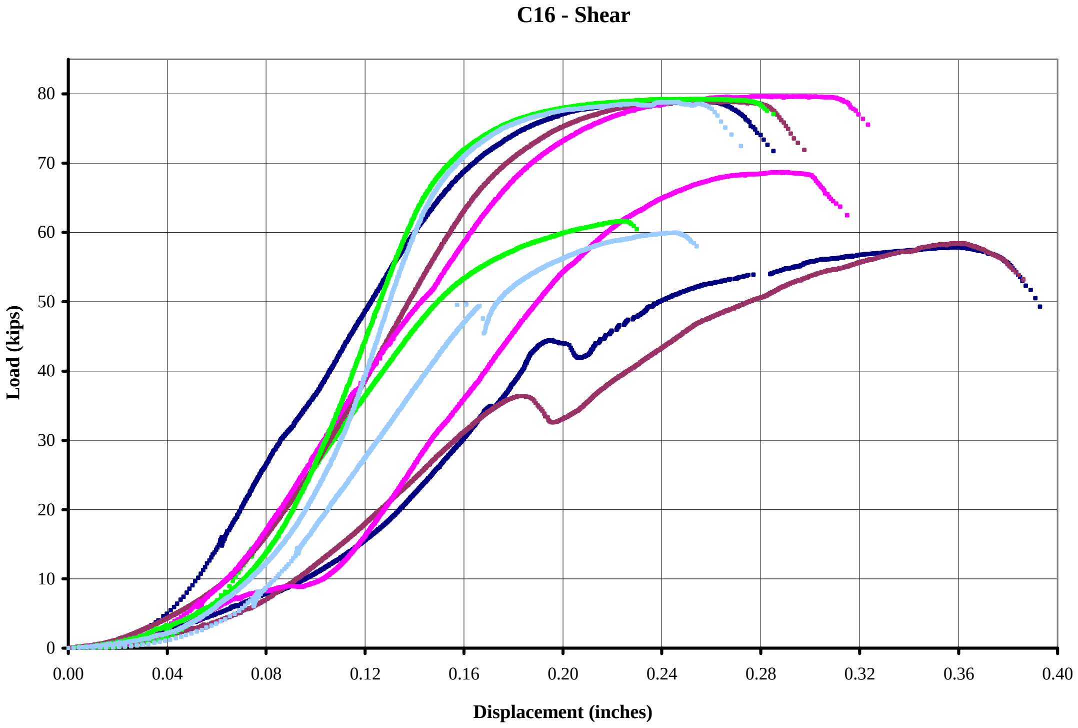

Figure A-142: Lot C16 – 1-inch A490 – Shear

C17

Bolt Properties:

Manufacturer:
Lot Number:
Size: 1"-8 x 4.5"
Grade: A490
Nominal Thread Length: 1 3/4 inches
Measured Thread Length: 1.8290 inches

Table A-72: Lot C17 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.675 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9960	99,476	3.73%	0.9964	76,559	0.9969	56,431
2	0.9963	99,404	3.30%	0.9964	77,359	0.9954	58,622
3	0.9961	98,701	3.45%	0.9967	76,728	0.9963	58,824
4	0.9960	99,008	2.85%	0.9970	77,161	0.9966	58,435
5	0.9960	99,343	3.78%	0.9967	77,409	0.9971	60,043

Note: The lever arm of the third LVDT was resting on the angle.
Data for X4 was not recorded for the Load versus Displacement graph due to technical problems.

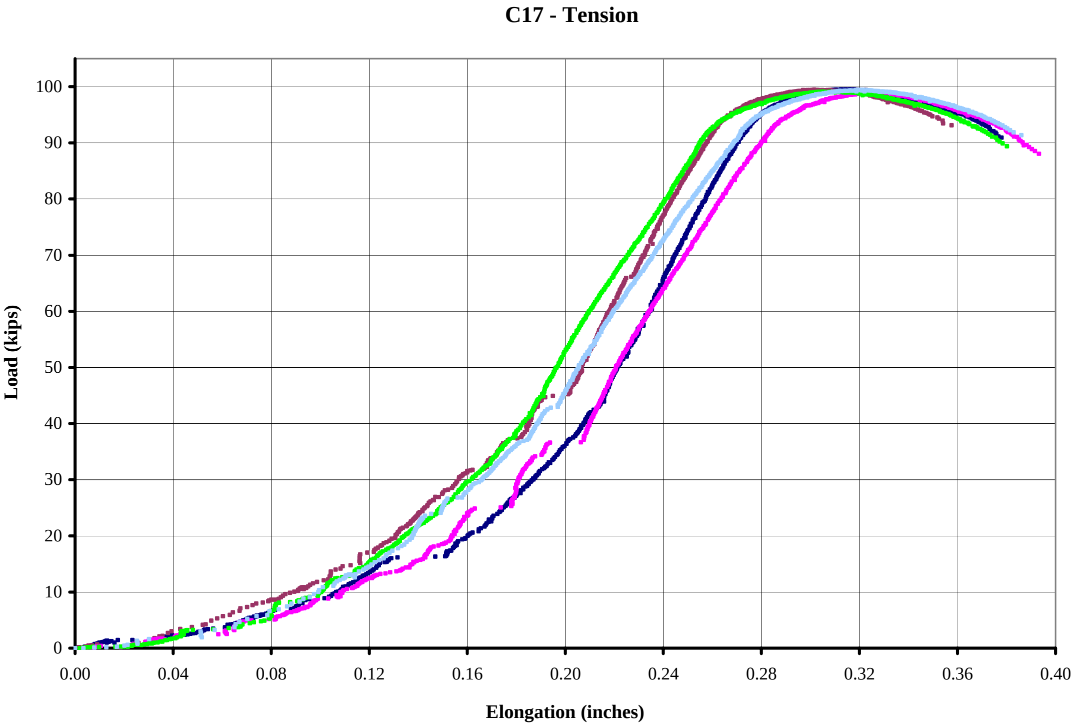

Figure A-143: Lot C17 – 1-inch A490 – Tension

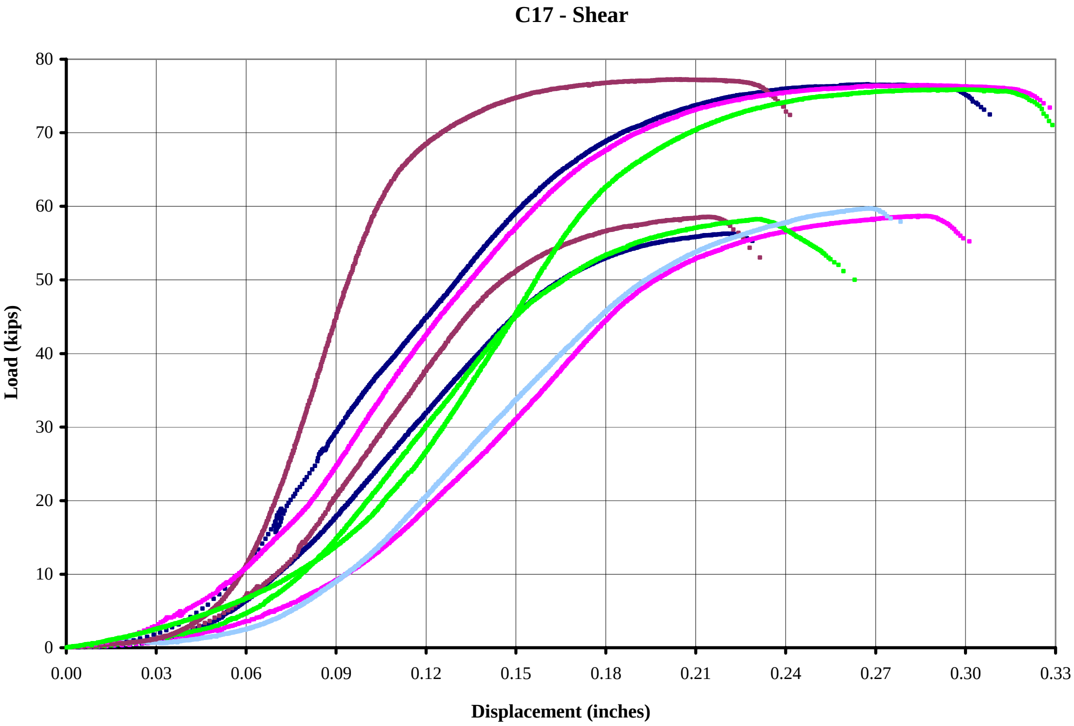

Figure A-144: Lot C17 – 1-inch A490 – Shear

L13

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.7905 inches

Table A-73: Lot L13 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.45 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9946	95,843	5.36%	0.9930	69,277	0.9930	53,908
2	0.9959	95,994	5.56%	0.9903	69,386	0.9929	51,961
3	0.9952	96,733	6.28%	0.9929	71,765	0.9932	49,507
4	0.9947	98,950	12.65%	0.9921	72,089	0.9926	51,929
5	0.9948	96,531	5.45%	0.9924	71,419	0.9905	51,212
6				0.9918	71,833		

Note: The lever arm of the third LVDT was resting on the bolt head.

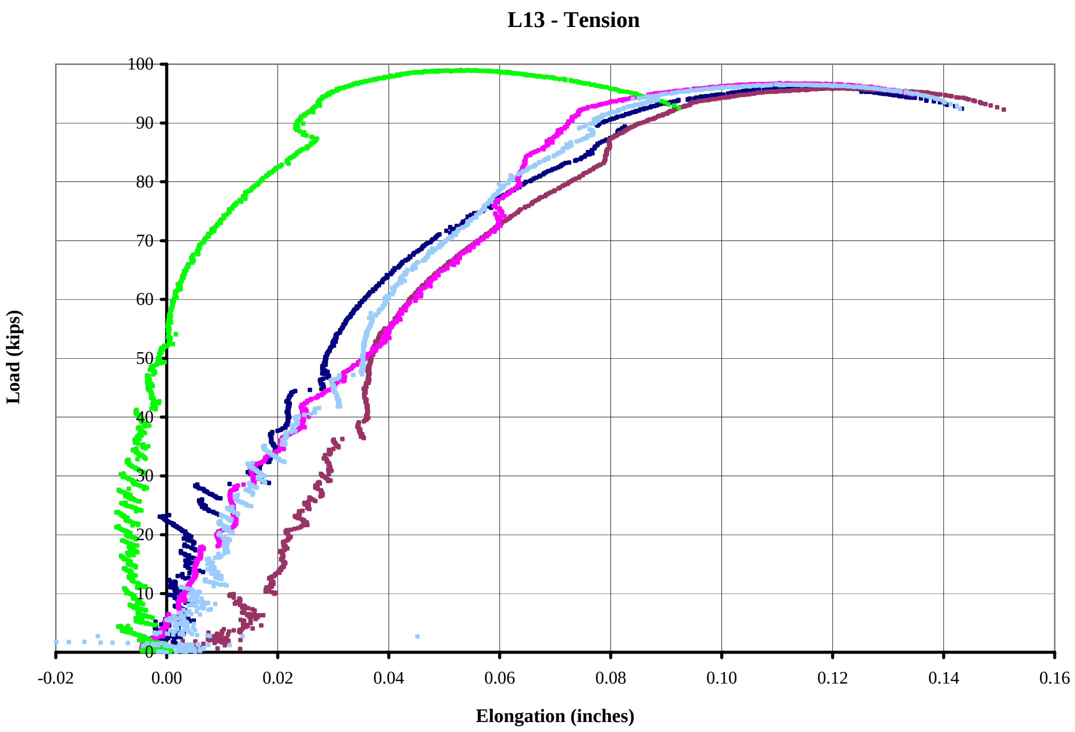

Figure A-145: Lot L13 – 1-inch A490 – Tension

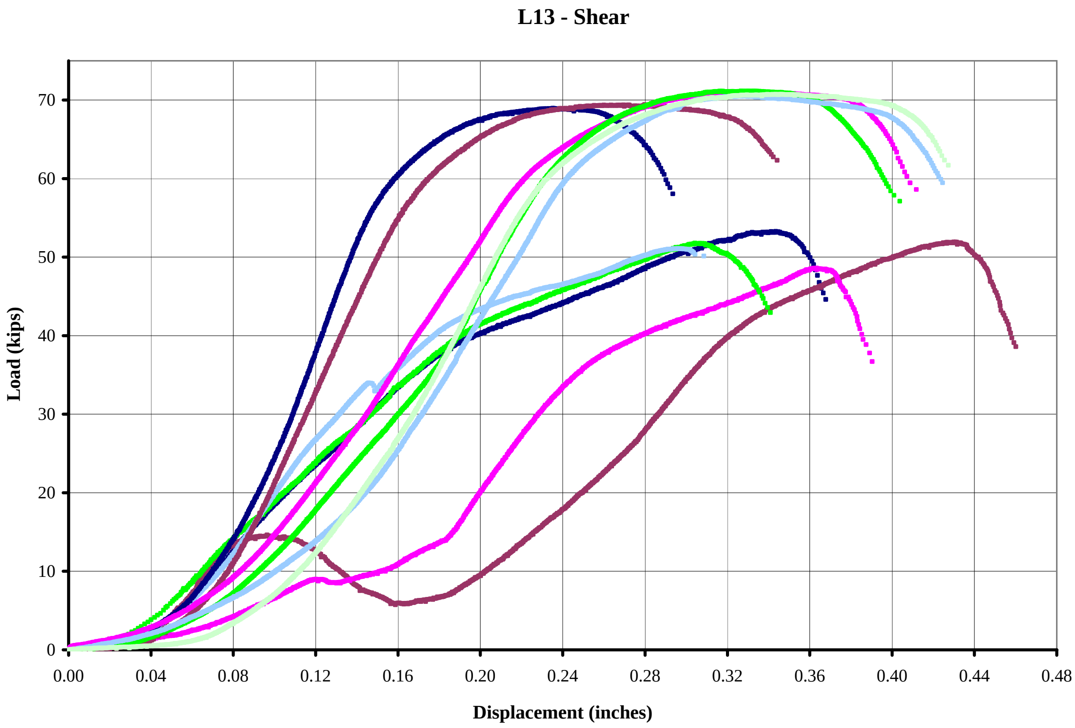

Figure A-146: Lot L13 – 1-inch A490 – Shear

L14

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 5"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8220 inches

Table A-74: Lot L14 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9956	99,192	7.14%	0.9932	76,119	0.9928	57,851
2	0.9970	99,365	8.01%	0.9932	76,962	0.9951	56,352
3	0.9962	98,939	8.59%	0.9924	75,762	0.9929	57,909
4	0.9974	99,469	6.20%	0.9939	75,661	0.9924	57,595
5	0.9971	98,626	8.75%	0.9927	75,369	0.9933	59,718
6				0.9934	76,346		

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for X3 was not recorded for the Load versus Displacement
graph due to technical problems.

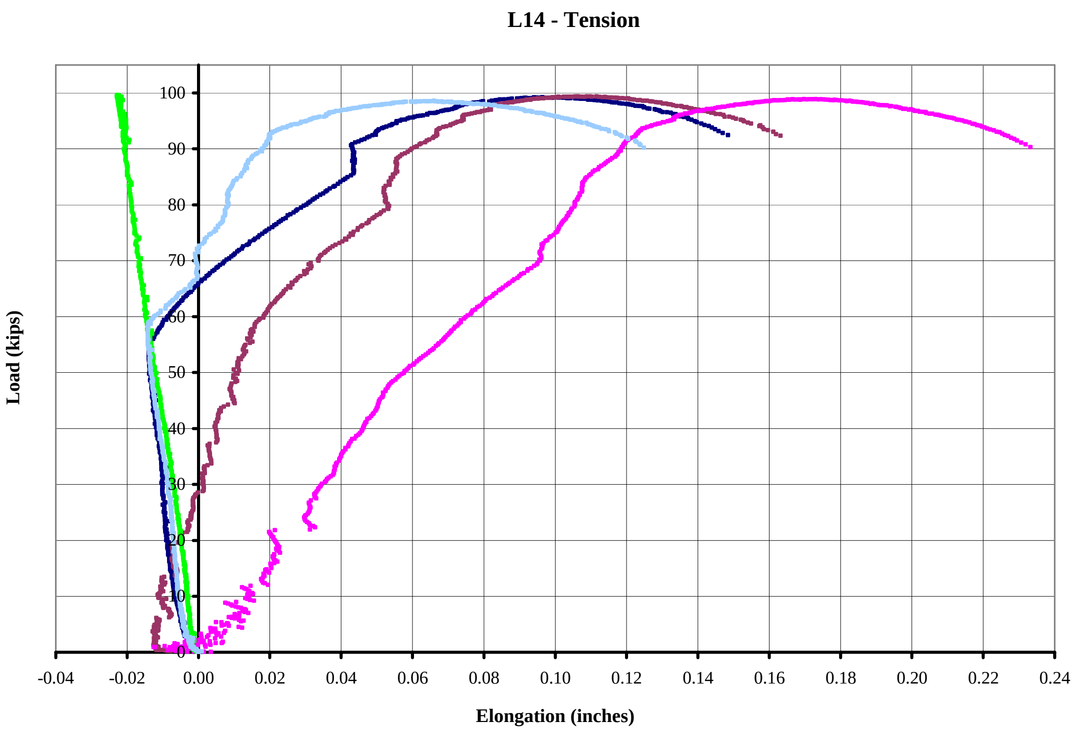

Figure A-147: Lot L14 – 1-inch A490 – Tension

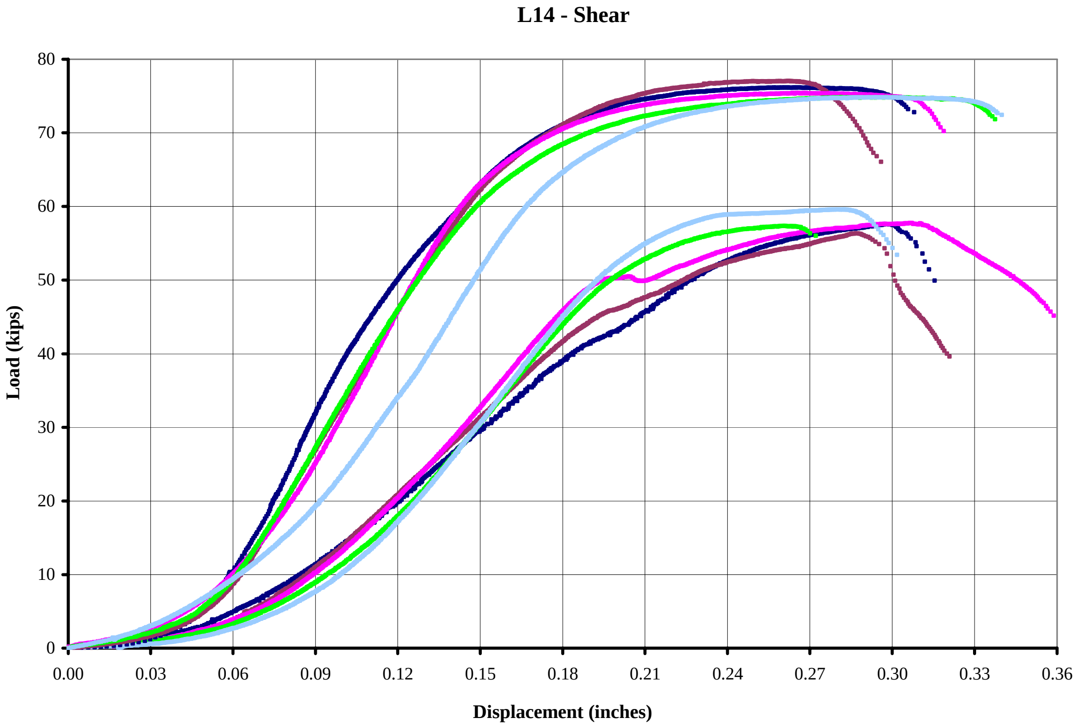

Figure A-148: Lot L14 – 1-inch A490 – Shear

N16

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.7870 inches

Table A-75: Lot N16 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.45 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9951	100,396	3.67%	0.9917	73,765	0.9918	60,947
2	0.9954	104,018	5.82%	0.9916	74,320	0.9917	60,969
3	0.9942	100,291	5.71%	0.9911	74,144	0.9919	56,622
4	0.9933	98,954	7.81%	0.9920	76,937	0.9917	59,985
5	0.9954	100,943	5.90%	0.9924	73,416	0.9916	59,884
6						0.9913	57,811

Note: The lever arm of the third LVDT was resting on the bolt head.

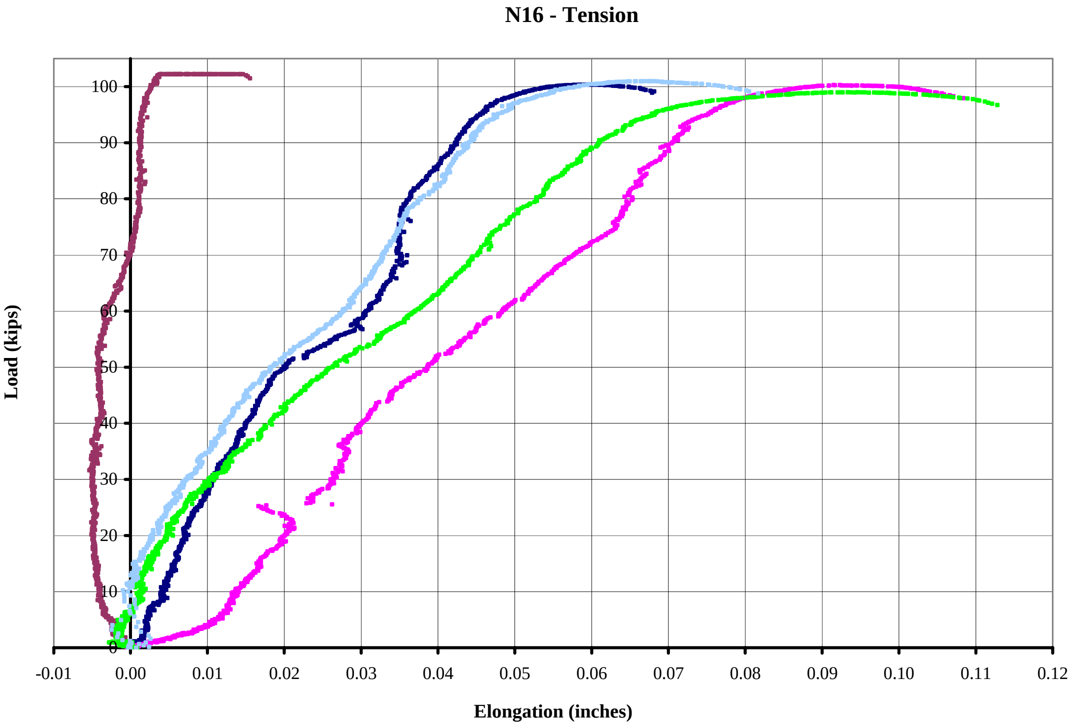

Figure A-149: Lot N16 – 1-inch A490 – Tension

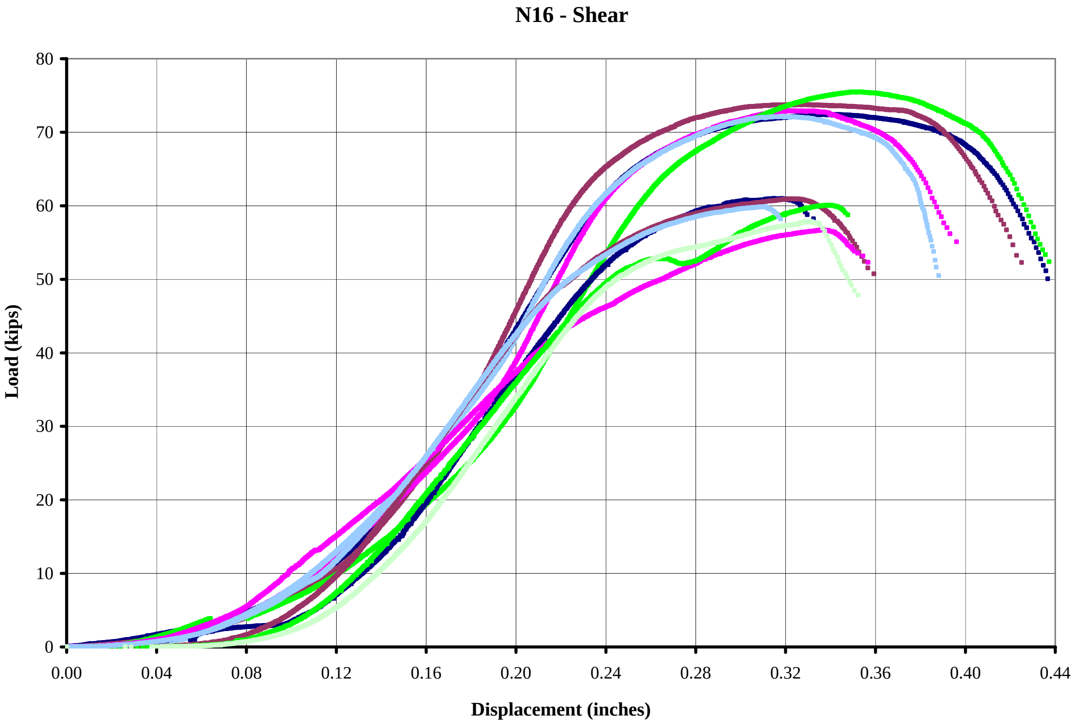

Figure A-150: Lot N16 – 1-inch A490 – Shear

N17

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.25"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8805 inches

Table A-76: Lot N17 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.4875 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9971	99,004	3.16%	0.9913	75,456	0.9738	60,645
2	0.9982	97,202	1.33%	0.9917	75,394	0.9915	58,294
3	0.9973	97,126	3.06%	0.9909	75,438	0.9909	61,005
4	0.9971	95,847	3.75%	0.9911	74,792	0.9920	58,212
5	0.9961	97,743	2.95%	0.9912	75,391	0.9912	59,960

Note: The lever arm of the third LVDT was resting on the bolt head.

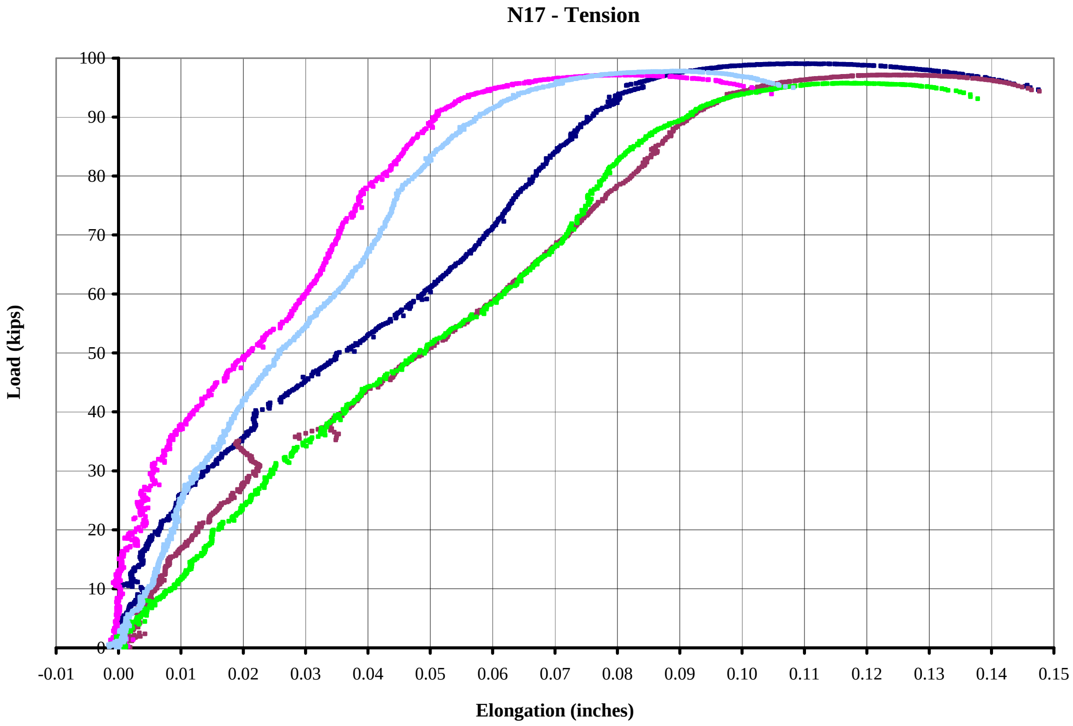

Figure A-151: Lot N17 – 1-inch A490 – Tension

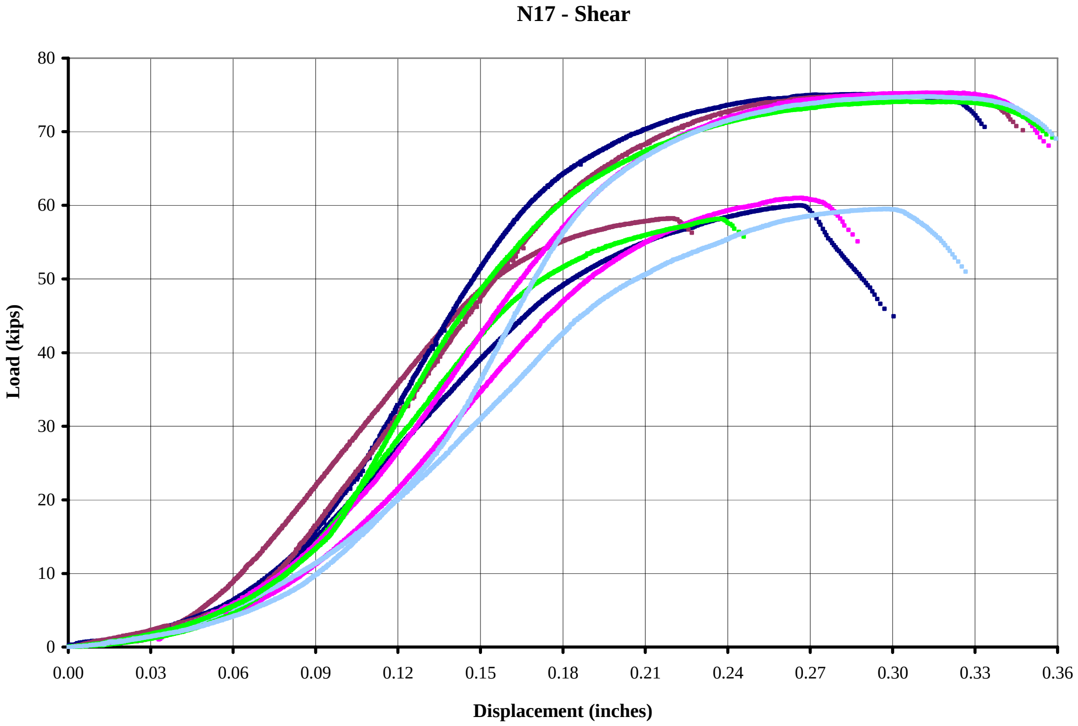

Figure A-152: Lot N17 – 1-inch A490 – Shear

N18

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4.75"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8530 inches

Table A-77: Lot N18 – 1-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.475 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9992	104,054	8.26%	0.9932	78,386	0.9929	62,234
2	0.9950	103,384	8.39%	0.9933	80,192	0.9924	61,196
3	0.9956	102,652	5.96%	0.9930	80,264	0.9934	63,272
4	0.9947	103,413	4.02%	0.9930	80,790	0.9933	62,642
5	0.9966	103,326	7.74%	0.9932	79,760	0.9927	62,533

Note: The lever arm of the third LVDT was resting on the bolt head.

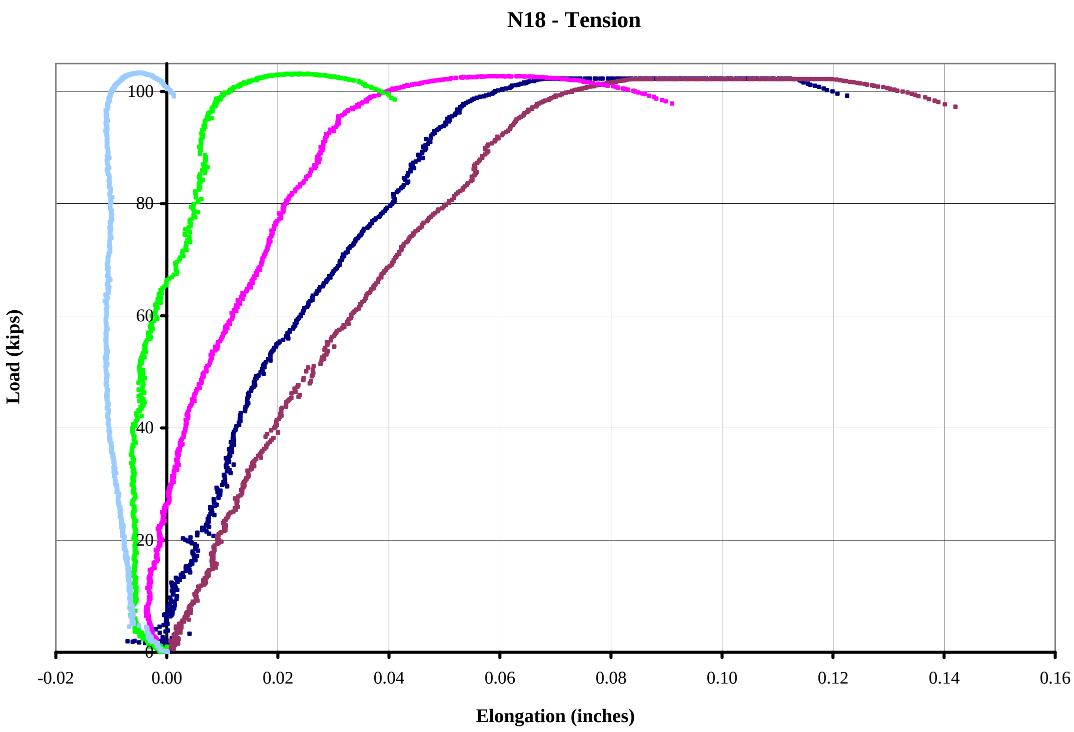

Figure A-153: Lot N18 – 1-inch A490 – Tension

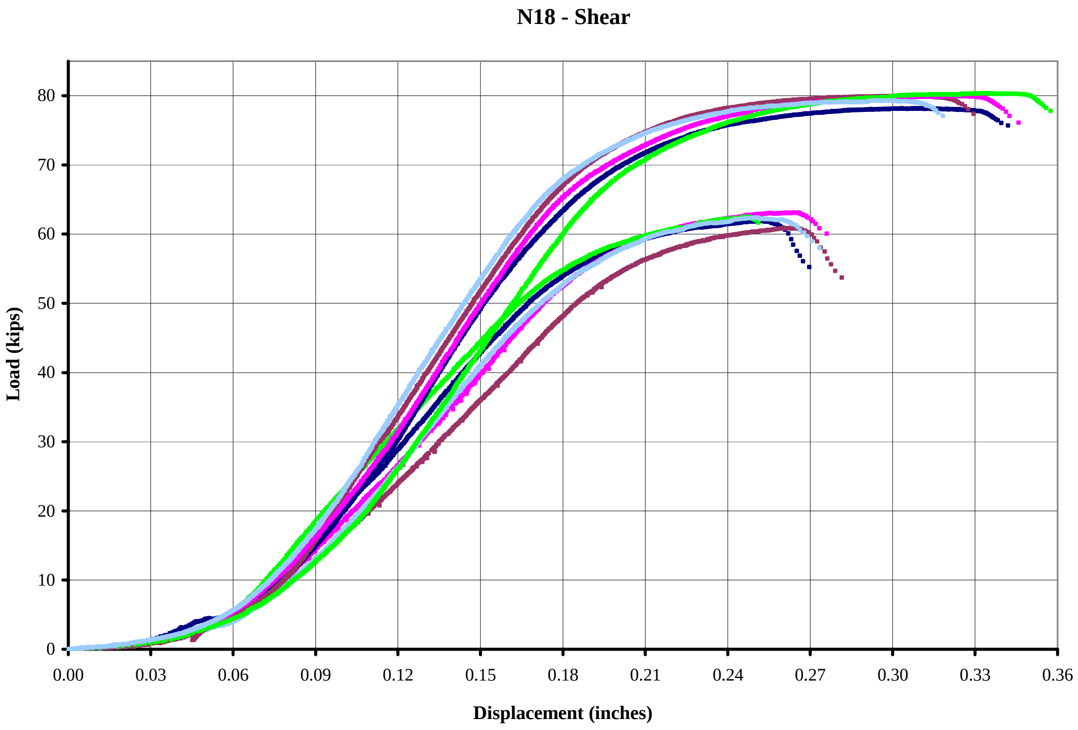

Figure A-154: Lot N18 – 1-inch A490 – Shear

T15

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8205 inches

Table A-78: Lot T15 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9976	98,878	6.21%	0.9922	78,790	0.9924	59,257
2	0.9975	98,525	5.99%	0.9927	79,623	0.9941	56,961
3	0.9982	99,426	3.95%	0.9950	76,526	0.9927	59,524
4	0.9971	98,943	5.16%	0.9936	80,531	0.9931	60,176
5	1.0001	98,939	5.19%	0.9923	79,435	0.9929	56,665

Note: The lever arm of the third LVDT was resting on the bolt head.
Data for T1 was not recorded for the Load versus Elongation graph
due to technical problems.

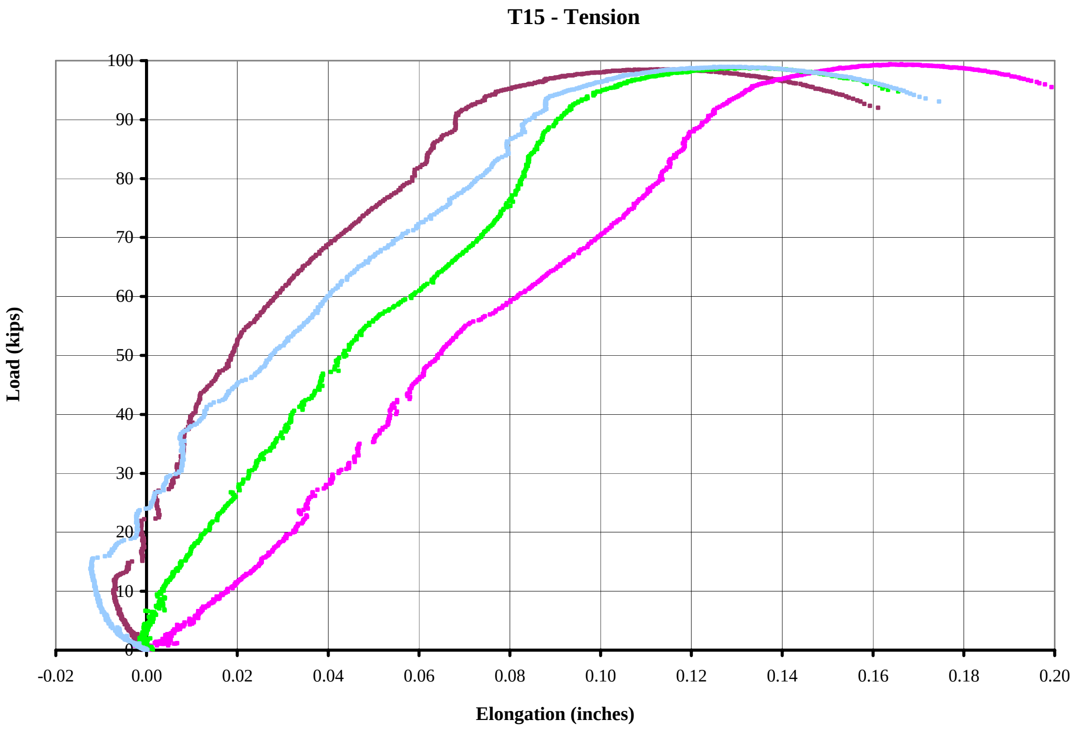

Figure A-155: Lot T15 – 1-inch A490 – Tension

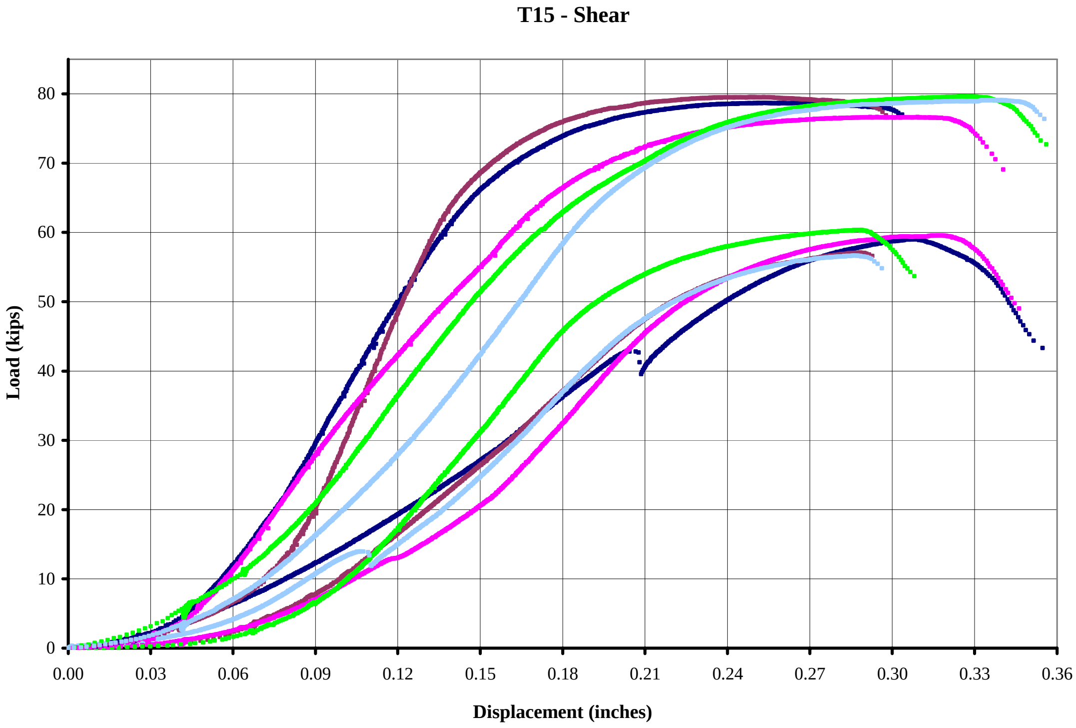

Figure A-156: Lot T15 – 1-inch A490 – Shear

T16

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 4.25"
Grade:	A490
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.8660 inches

Table A-79: Lot T16 – 1-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9963	101,088	4.10%	0.9960	74,792	0.9961	55,728
2	0.9970	100,662	7.69%	0.9958	78,044	0.9960	50,739
3	0.9960	100,893	7.07%	0.9959	77,766	0.9951	57,862
4	0.9957	101,697	7.74%	0.9960	78,527	0.9968	58,442
5	0.9981	100,349	5.06%	0.9922	79,035	0.9963	57,065
6				0.9931	78,678	0.9990	60,551

Note: The lever arm of the third LVDT was resting on the bolt head.

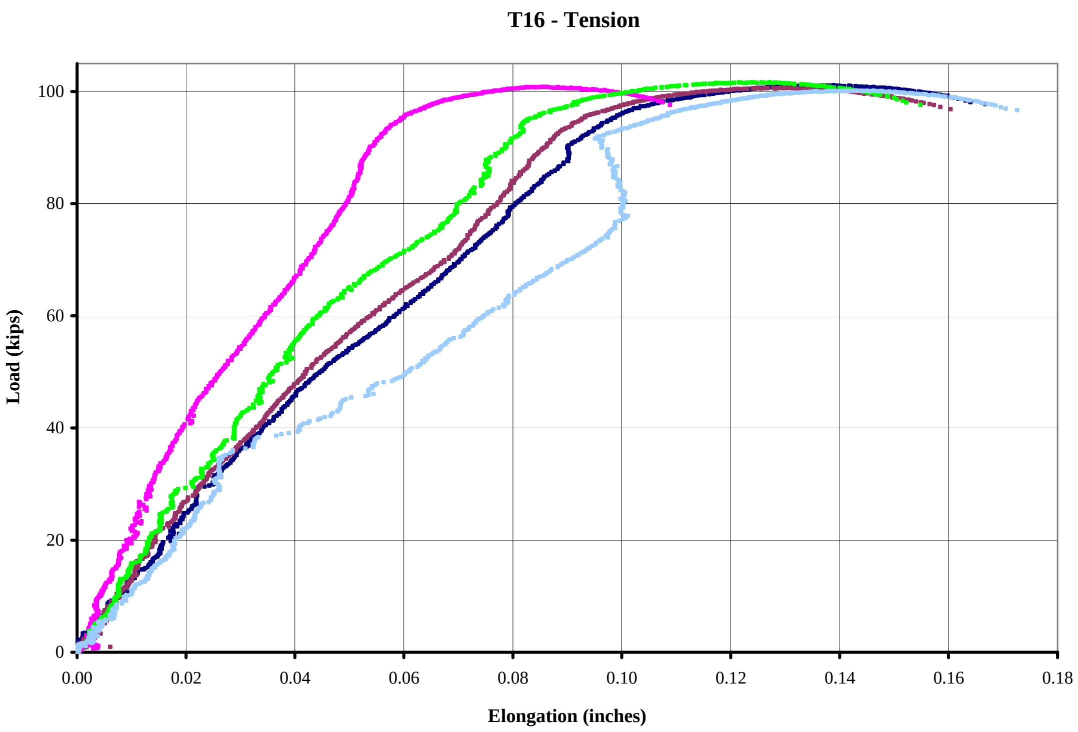

Figure A-157: Lot T16 – 1-inch A490 – Tension

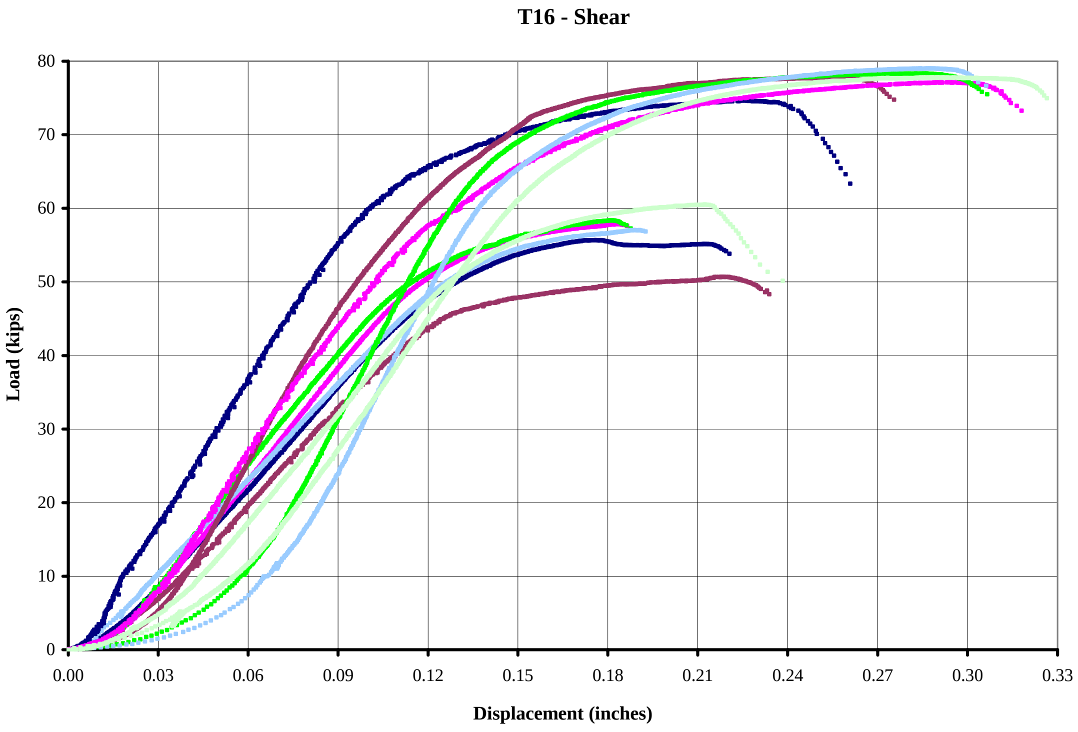

Figure A-158: Lot T16 – 1-inch A490 – Shear

C18

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1435 inches

Table A-80: Lot C18 – 1-1/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1196	122,069	2.46%	1.1197	99,339	1.1212	69,818
2	1.1206	123,513	2.16%	1.1219	99,040	1.1205	68,297
3	1.1194	123,397	2.82%	1.1218	97,184	1.1217	70,092
4	1.1191	123,238	2.75%	1.1207	98,536	1.1215	68,683
5	1.1209	123,917	2.33%	1.1203	98,229	1.1218	66,917

Note: The lever arm of the third LVDT was resting on the angle.

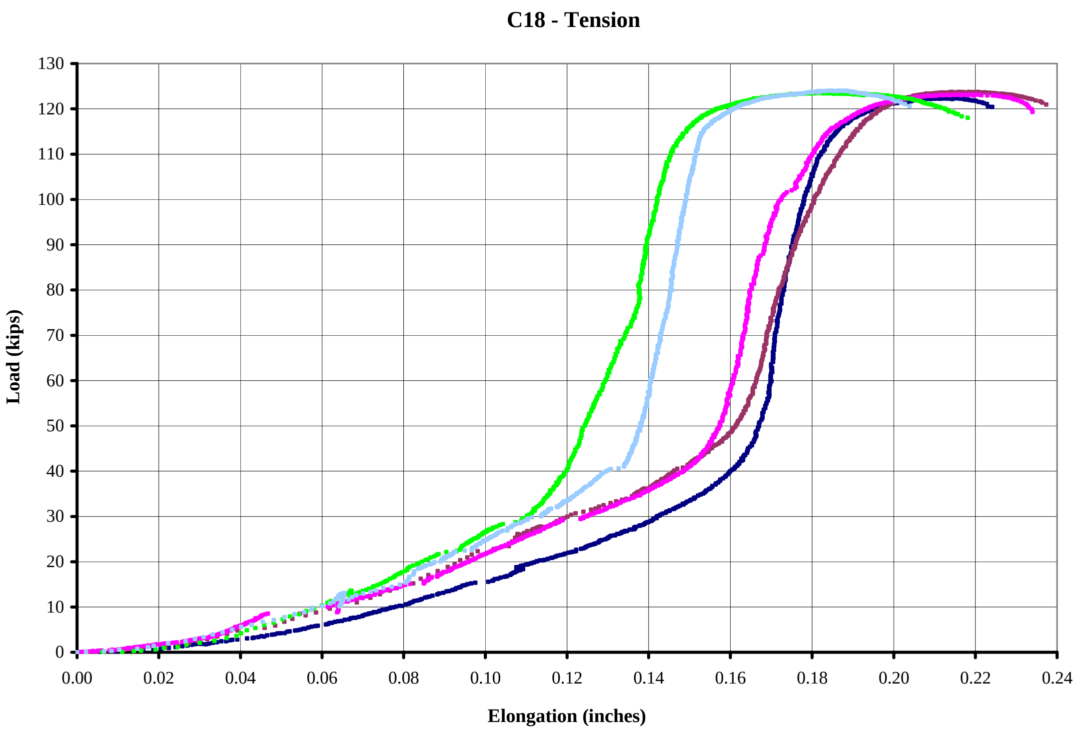

Figure A-159: Lot C18 – 1-1/8-inch A490 – Tension

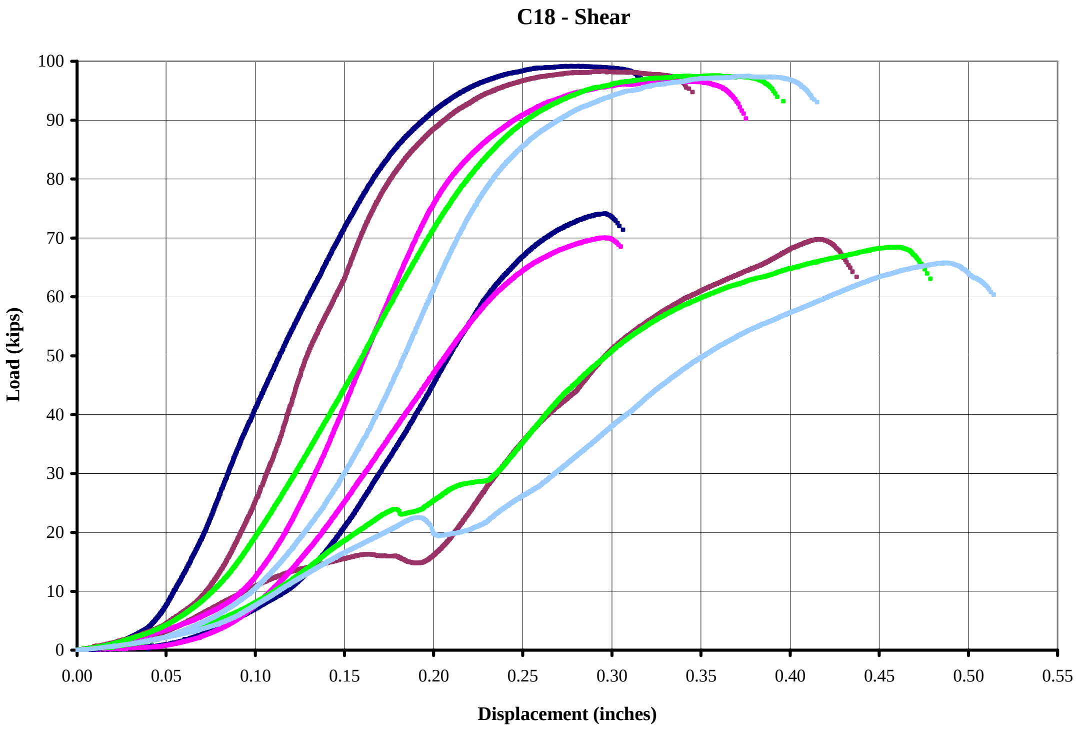

Figure A-160: Lot C18 – 1-1/8-inch A490 – Shear

C19

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.5"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1535 inches

Table A-81: Lot C19 – 1-1/8-inch A490 – Data

<table>
<tr><th rowspan="4">Test</th><th colspan="3" rowspan="2">Tension</th><th colspan="4">Shear</th></tr>
<tr><th colspan="2">Threads Excluded</th><th colspan="2">Threads Not Excluded</th></tr>
<tr><th colspan="3">Load Rate: 0.675 in/min</th><th colspan="2">Load Rate: 0.5 in/min</th><th colspan="2">Load Rate: 0.5 in/min</th></tr>
<tr><th>Average Diameter (inches)</th><th>Failure Load (pounds)</th><th>Elongation</th><th>Average Diameter (inches)</th><th>Failure Load (pounds)</th><th>Average Diameter (inches)</th><th>Failure Load (pounds)</th></tr>
<tr><td>1</td><td>1.1194</td><td>125,634</td><td>2.92%</td><td>1.1192</td><td>96,539</td><td>1.1195</td><td>73,051</td></tr>
<tr><td>2</td><td>1.1200</td><td>125,403</td><td>2.03%</td><td>1.1181</td><td>95,601</td><td>1.1189</td><td>69,036</td></tr>
<tr><td>3</td><td>1.1189</td><td>125,706</td><td>2.40%</td><td>1.1179</td><td>96,564</td><td>1.1193</td><td>68,694</td></tr>
<tr><td>4</td><td>1.1176</td><td>126,745</td><td>3.34%</td><td>1.1178</td><td>96,813</td><td>1.1187</td><td>70,070</td></tr>
<tr><td>5</td><td>1.1178</td><td>126,846</td><td>3.70%</td><td>1.1200</td><td>95,137</td><td>1.1191</td><td>68,117</td></tr>
</table>

Note: The lever arm of the third LVDT was resting on the angle.

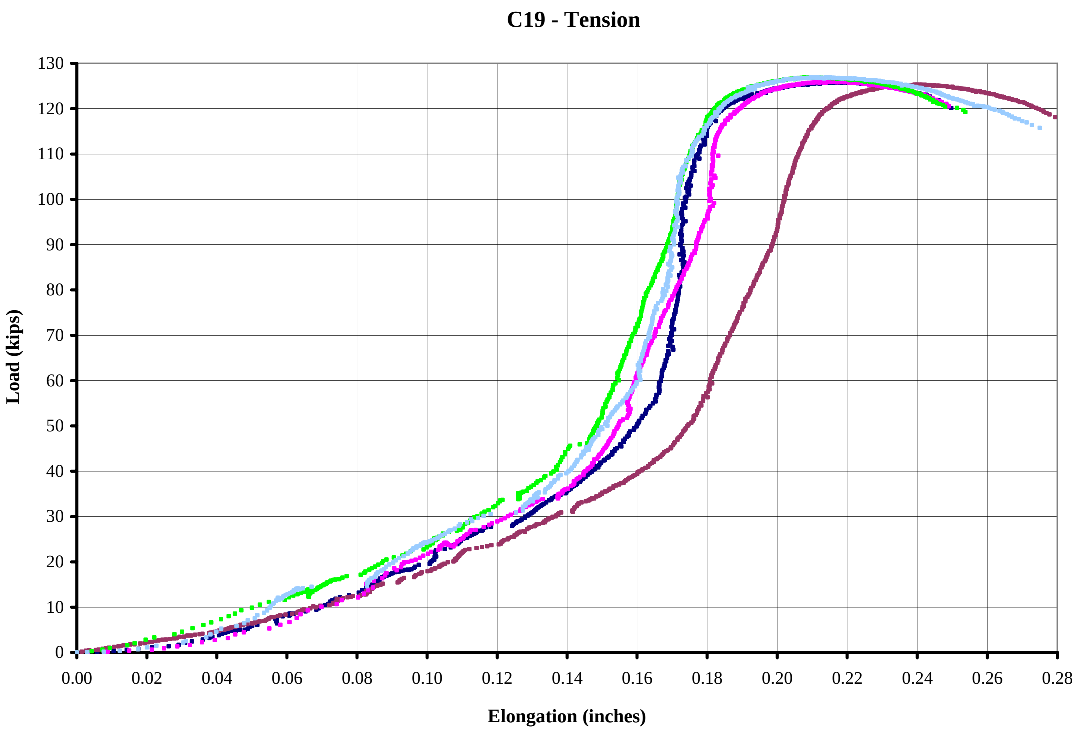

Figure A-161: Lot C19 – 1-1/8-inch A490 – Tension

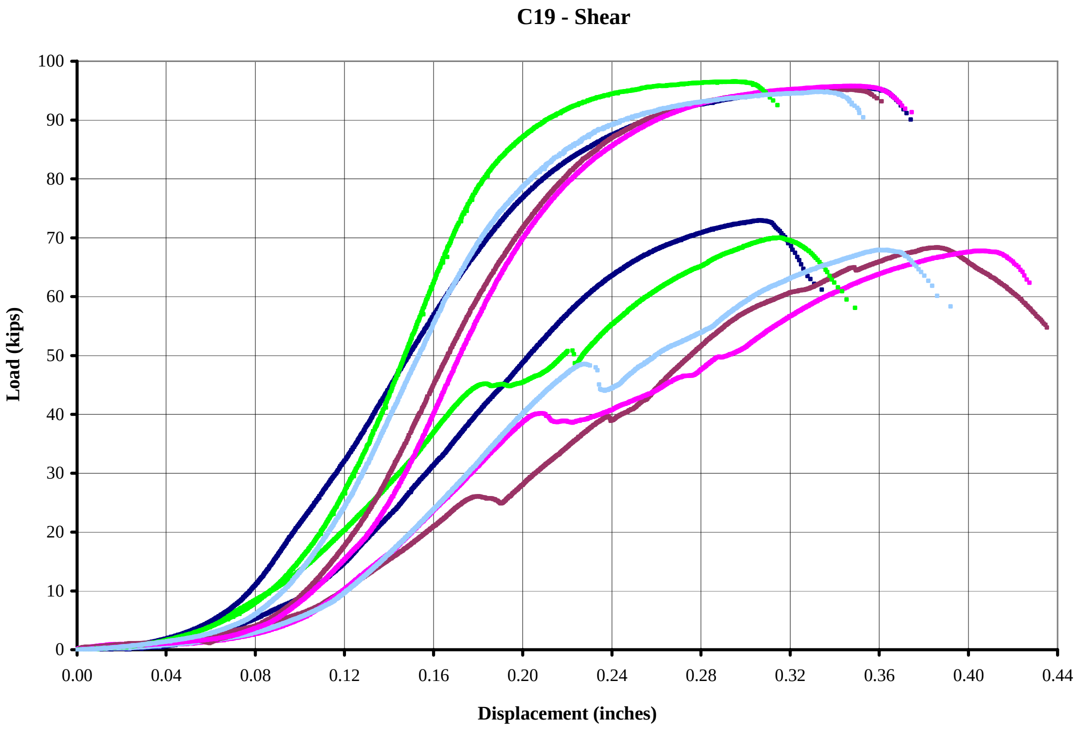

Figure A-162: Lot C19 – 1-1/8-inch A490 – Shear

C20

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 5"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.0990 inches

Table A-82: Lot C20 – 1-1/8-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1181	124,869	2.85%	1.1175	97,689	1.1175	70,734
2	1.1187	125,937	2.12%	1.1162	97,858	1.1147	72,276
3	1.1192	126,053	3.65%	1.1178	97,591	1.1151	76,378
4	1.1163	125,244	3.18%	1.1173	96,906	1.1155	75,751
5	1.1185	124,480	2.70%	1.1178	97,296	1.1161	74,021

Note: The lever arm of the third LVDT was resting on the angle.

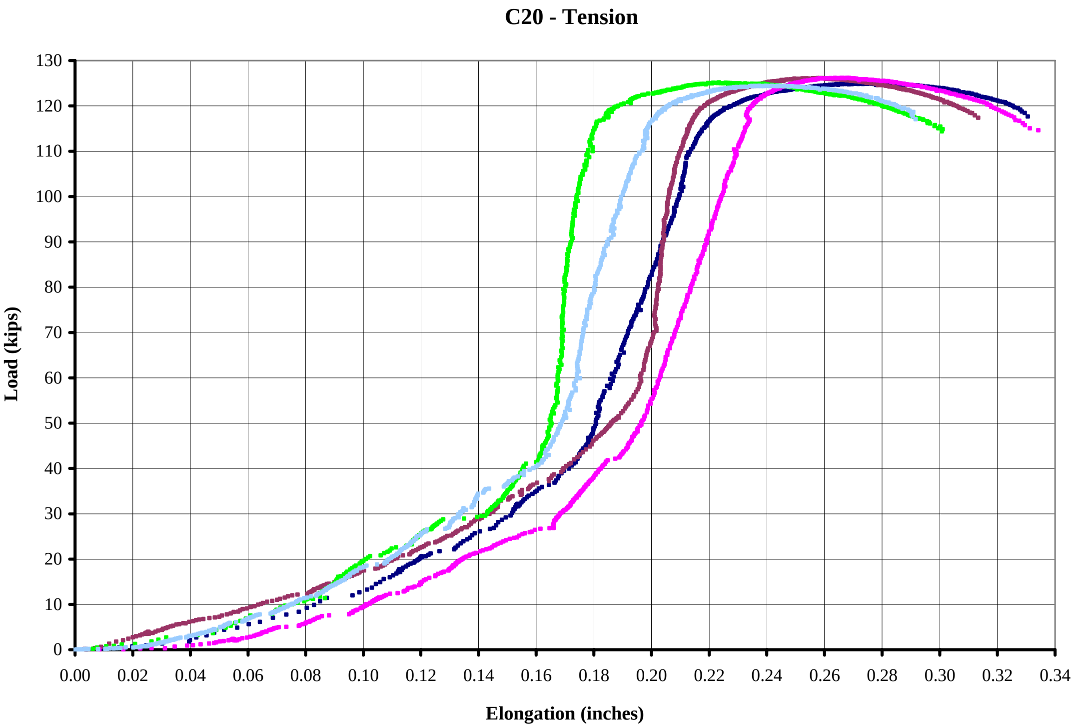

Figure A-163: Lot C20 – 1-1/8-inch A490 – Tension

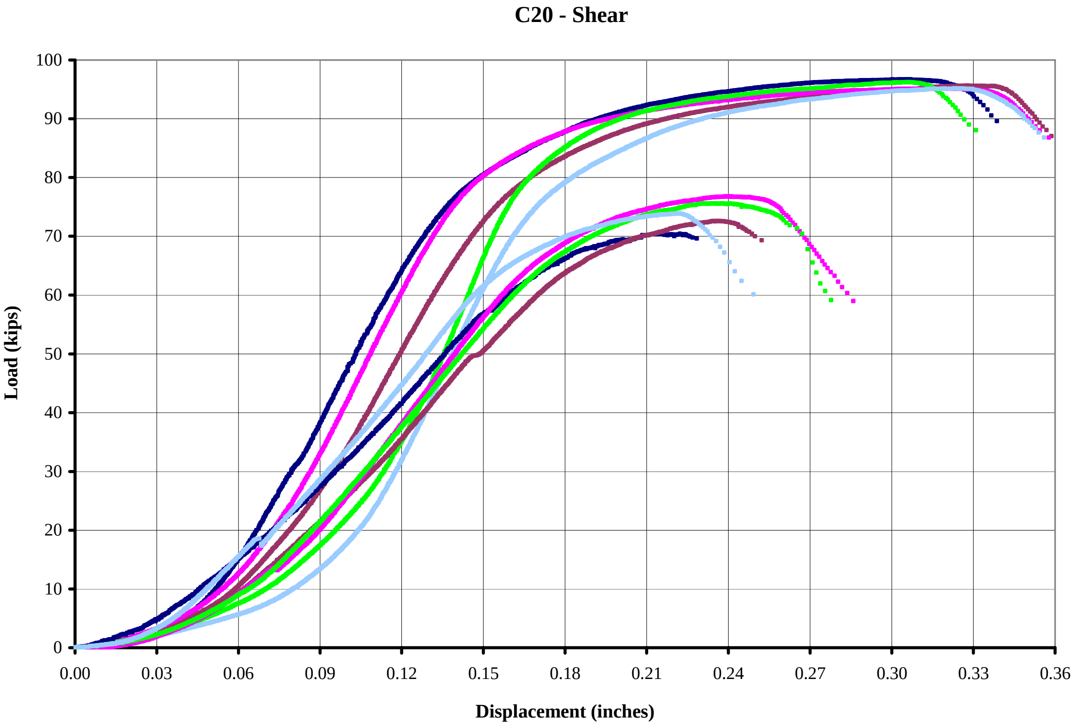

Figure A-164: Lot C20 – 1-1/8-inch A490 – Shear

L15

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.25"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1585 inches

Table A-83: Lot L15 – 1-1/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.6375 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1175	123,787	4.11%	1.1192	95,775	1.1187	72,323
2	1.1191	124,205	2.96%	1.1171	94,592	1.1180	72,053
3	1.1193	122,964	4.89%	1.1173	97,890	1.1183	71,671
4	1.1194	123,830	2.38%	1.1194	97,094	1.1191	70,618
5	1.1194	125,576	2.89%	1.1167	94,444	1.1170	68,805

Note: The lever arm of the third LVDT was resting on the angle.

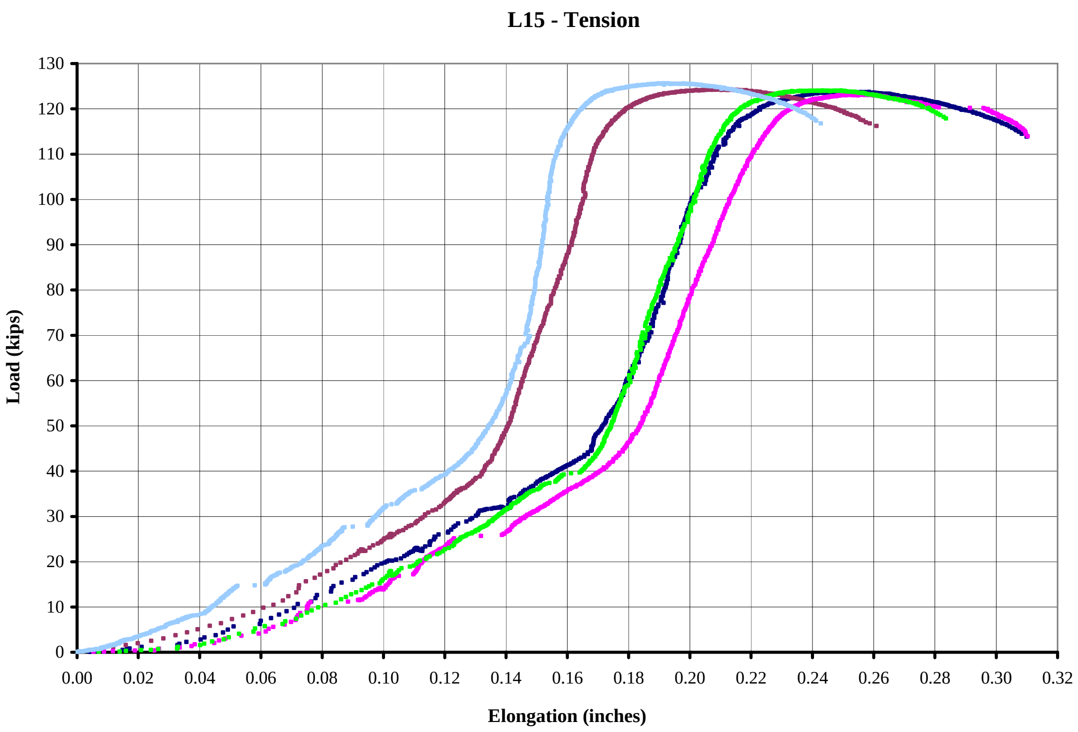

Figure A-165: Lot L15 – 1-1/8-inch A490 – Tension

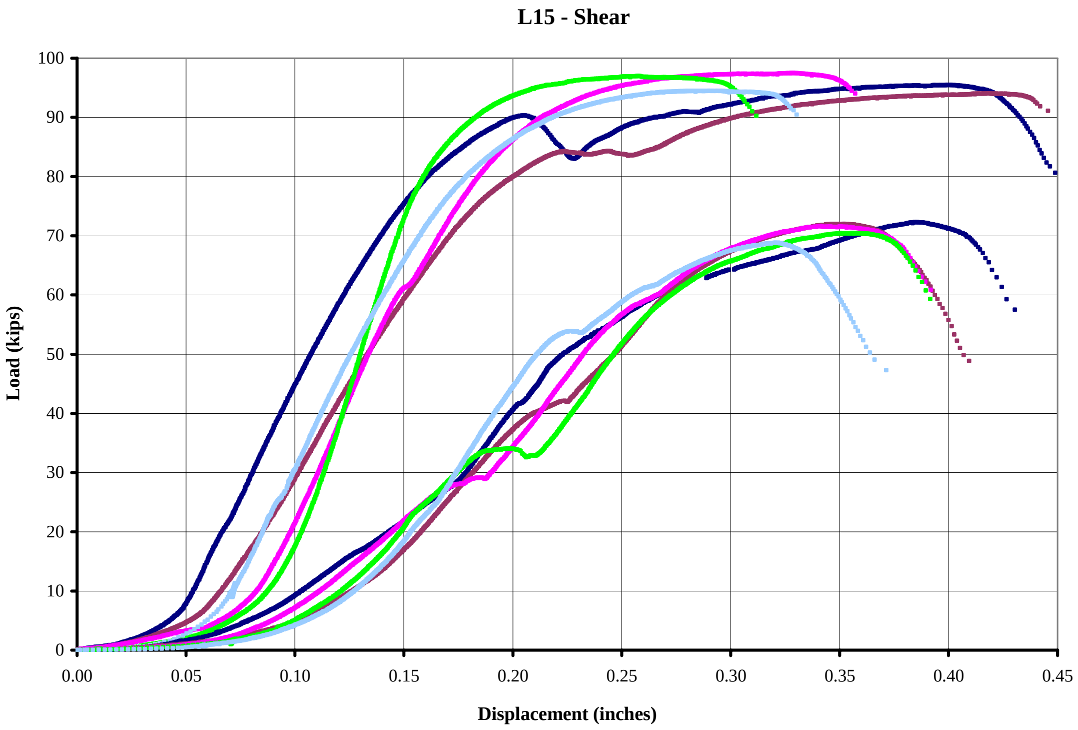

Figure A-166: Lot L15 – 1-1/8-inch A490 – Shear

N19

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 3.75"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1145 inches

Table A-84: Lot N19 – 1-1/8-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.5625 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1191	121,016	5.25%	1.1184	88,410	1.1183	72,028
2	1.1186	120,150	3.43%	1.1182	90,577	1.1191	70,950
3	1.1180	121,160	3.71%	1.1168	92,163	1.1182	69,710
4	1.1189	119,688	3.92%	1.1184	90,213	1.1188	70,842
5	1.1175	121,766	3.82%	1.1179	89,405	1.1197	70,179

Note: The lever arm of the third LVDT was resting on the angle.

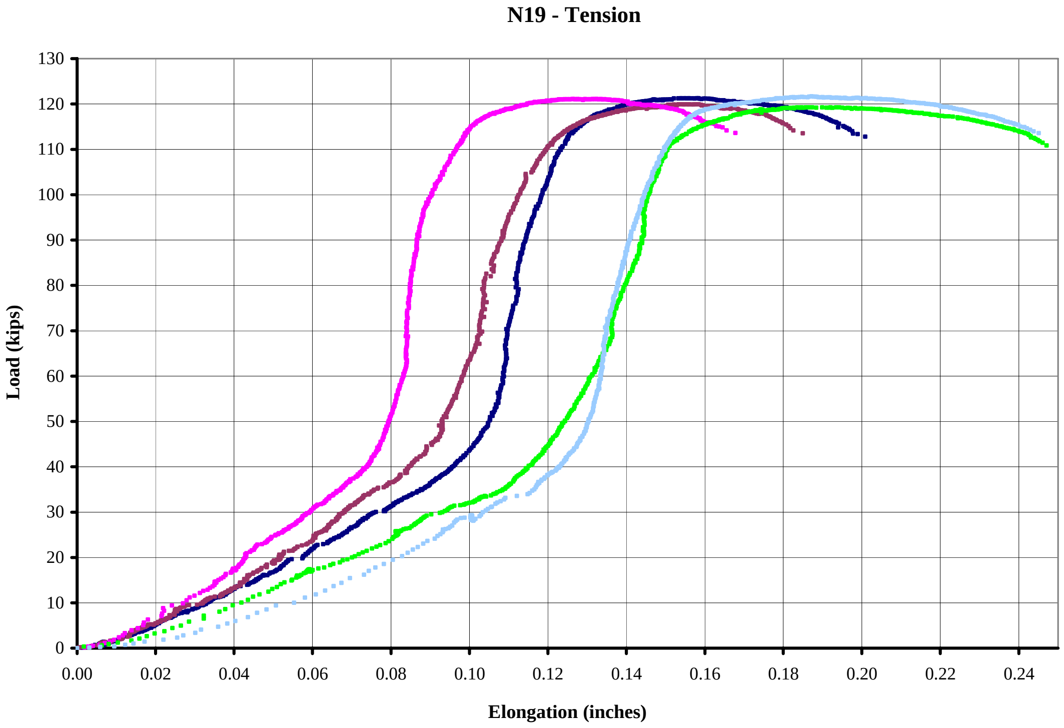

Figure A-167: Lot N19 – 1-1/8-inch A490 – Tension

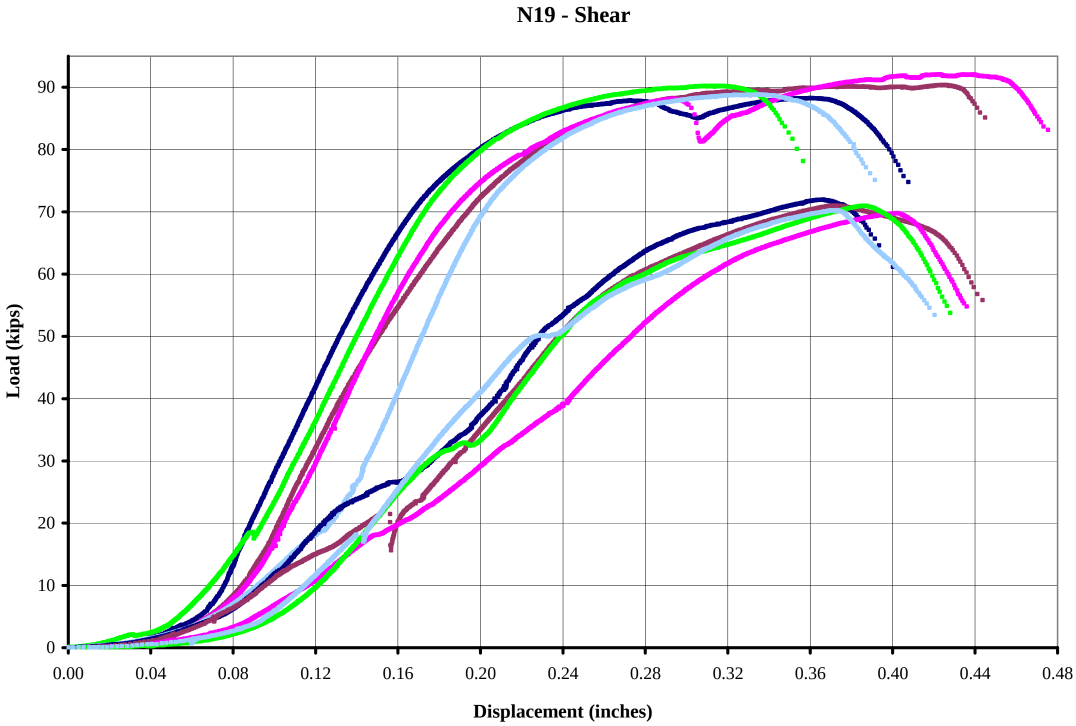

Figure A-168: Lot N19 – 1-1/8-inch A490 – Shear

C21

Bolt Properties:

Manufacturer:
Lot Number:
Size: 1-1/4"-7 x 4"
Grade: A490
Nominal Thread Length: 2 inches
Measured Thread Length: 2.1400 inches

Table A-85: Lot C21 – 1-1/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2455	157,053	4.25%	1.2427	122,055	1.2454	91,161
2	1.2461	160,444	7.27%	1.2448	118,707	1.2447	96,405
3	1.2448	157,601	3.48%	1.2437	117,668	1.2430	88,706
4	1.2439	156,605	3.43%	1.2440	120,612	1.2425	89,679
5	1.2457	158,496	2.95%	1.2438	118,620	1.2447	94,953

Note: The lever arm of the third LVDT was resting on the angle.

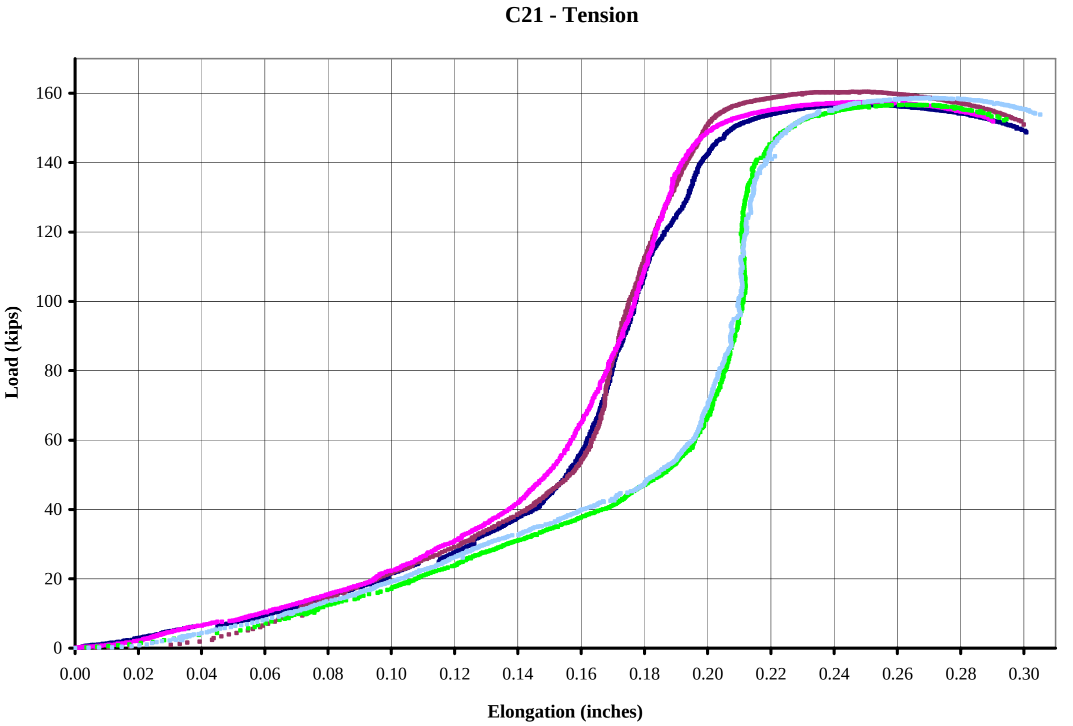

Figure A-169: Lot C21 – 1-1/4-inch A490 – Tension

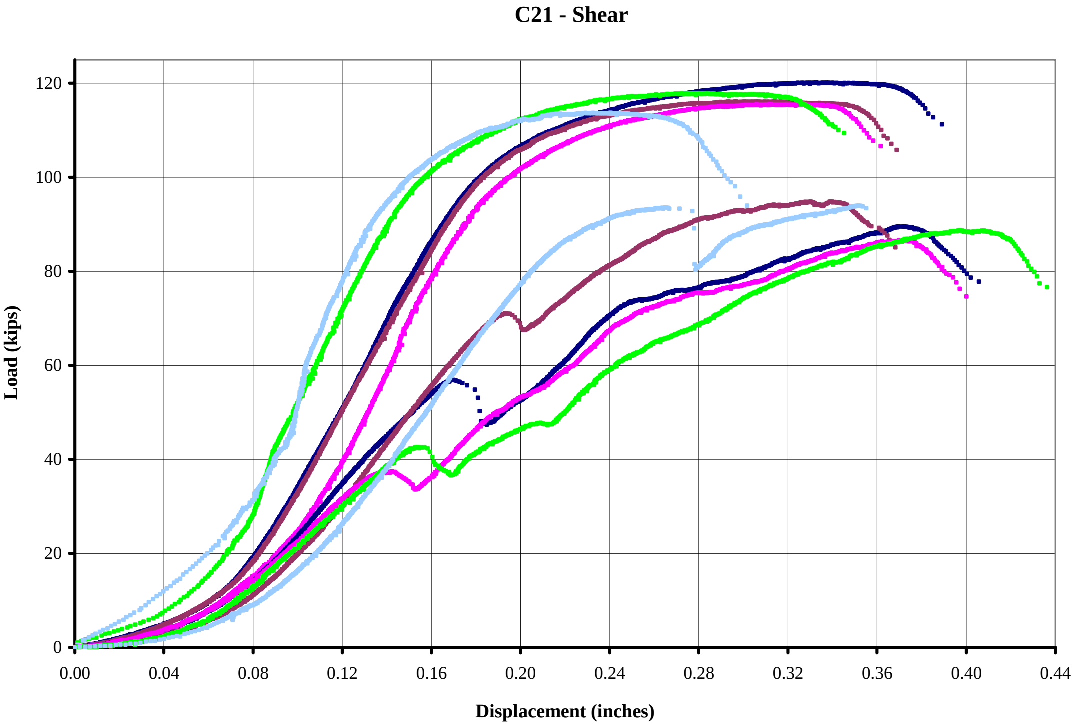

Figure A-170: Lot C21 – 1-1/4-inch A490 – Shear

C22

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.5"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1725 inches

Table A-86: Lot C22 – 1-1/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.675 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2445	158,092	6.18%	1.2449	123,816	1.2455	94,336
2	1.2458	156,187	4.71%	1.2443	122,228	1.2445	87,300
3	1.2458	156,547	4.26%	1.2451	121,651	1.2452	90,116
4	1.2440	156,533	5.39%	1.2464	122,271	1.2446	91,190
5	1.2468	158,178	3.38%	1.2429	122,632	1.2446	87,549
6	1.2447	157,125	3.30%				

Note: The lever arm of the third LVDT was resting on the angle.

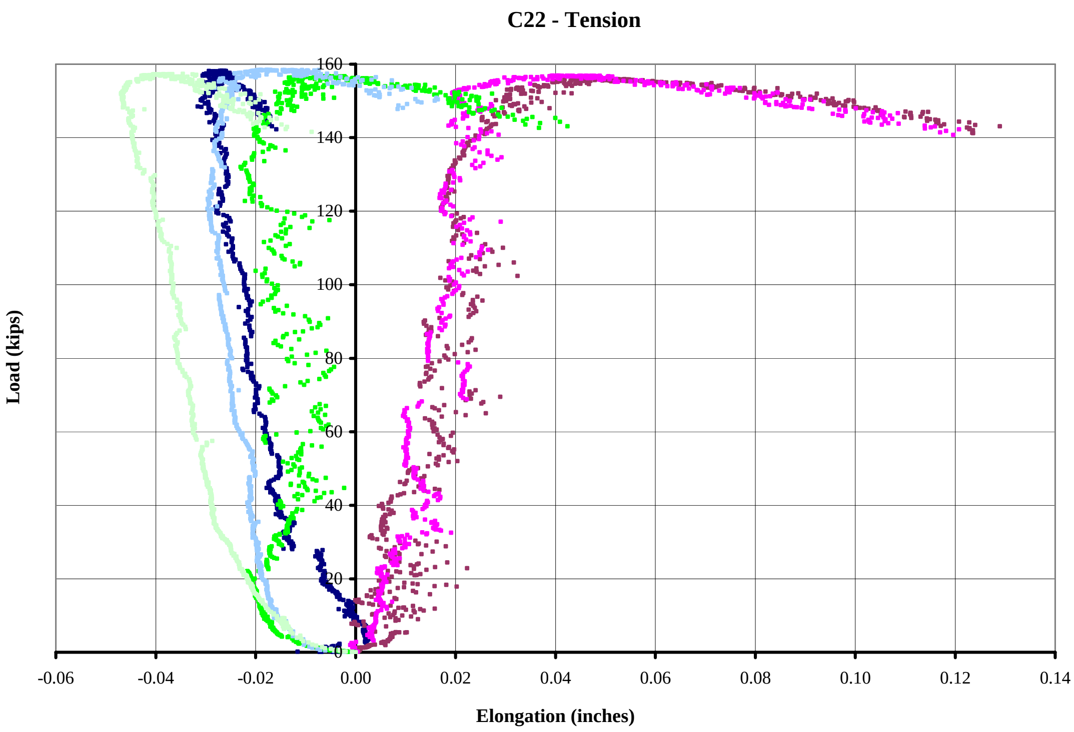

Figure A-171: Lot C22 – 1-1/4-inch A490 – Tension

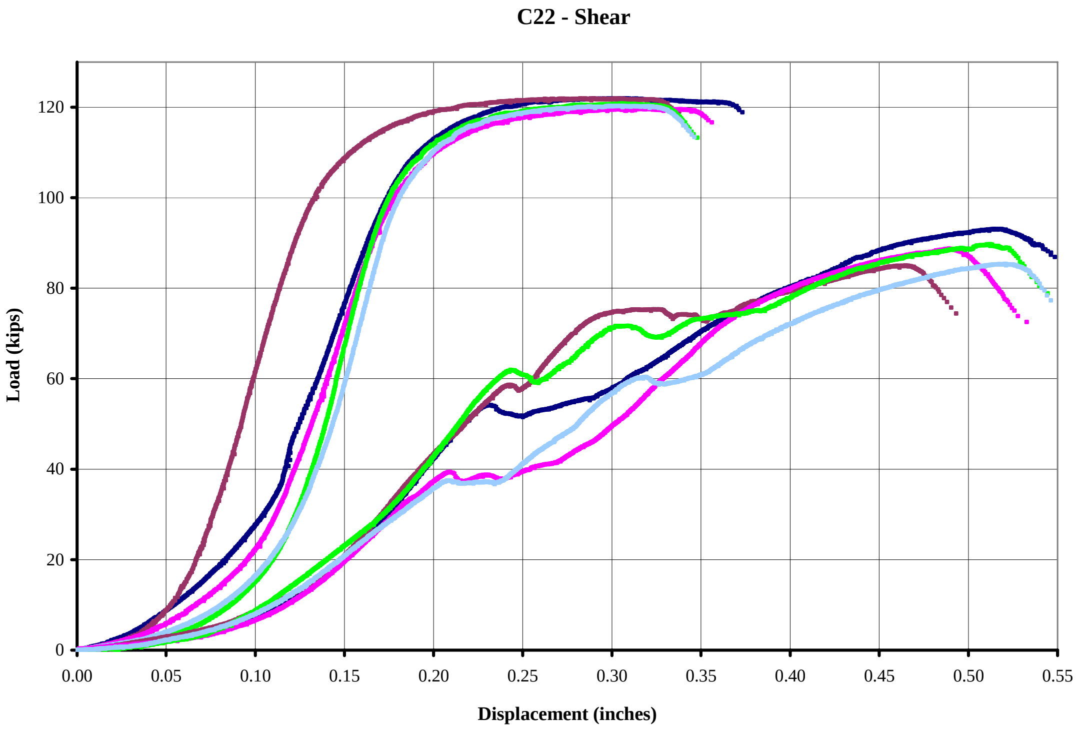

Figure A-172: Lot C22 – 1-1/4-inch A490 – Shear

C23

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.75"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1360 inches

Table A-87: Lot C23 – 1-1/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.7125 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2440	160,747	2.77%	1.2453	119,399	1.2443	93,767
2	1.2437	158,828	3.43%	1.2434	127,481	1.2442	90,000
3	1.2431	159,203	2.54%	1.2442	120,973	1.2436	91,655
4	1.2434	161,541	3.49%	1.2435	122,416	1.2434	97,133
5	1.2441	160,372	3.12%	1.2442	119,674	1.2444	90,043

Note: The lever arm of the third LVDT was resting on the angle.

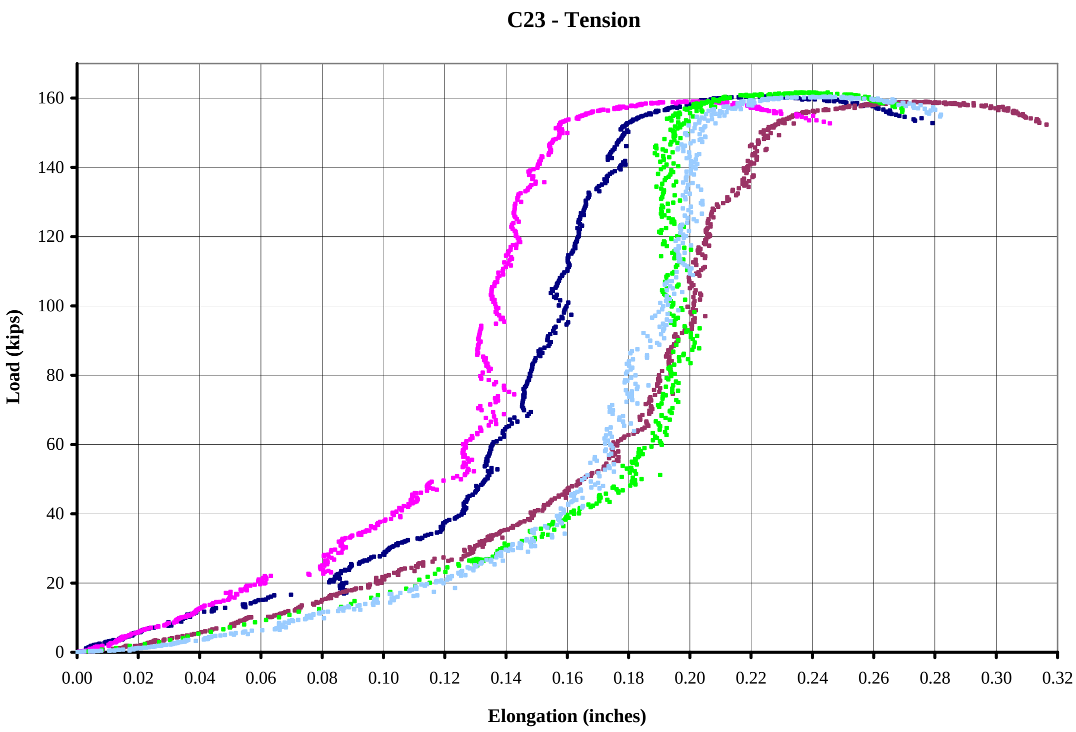

Figure A-173: Lot C23 – 1-1/4-inch A490 – Tension

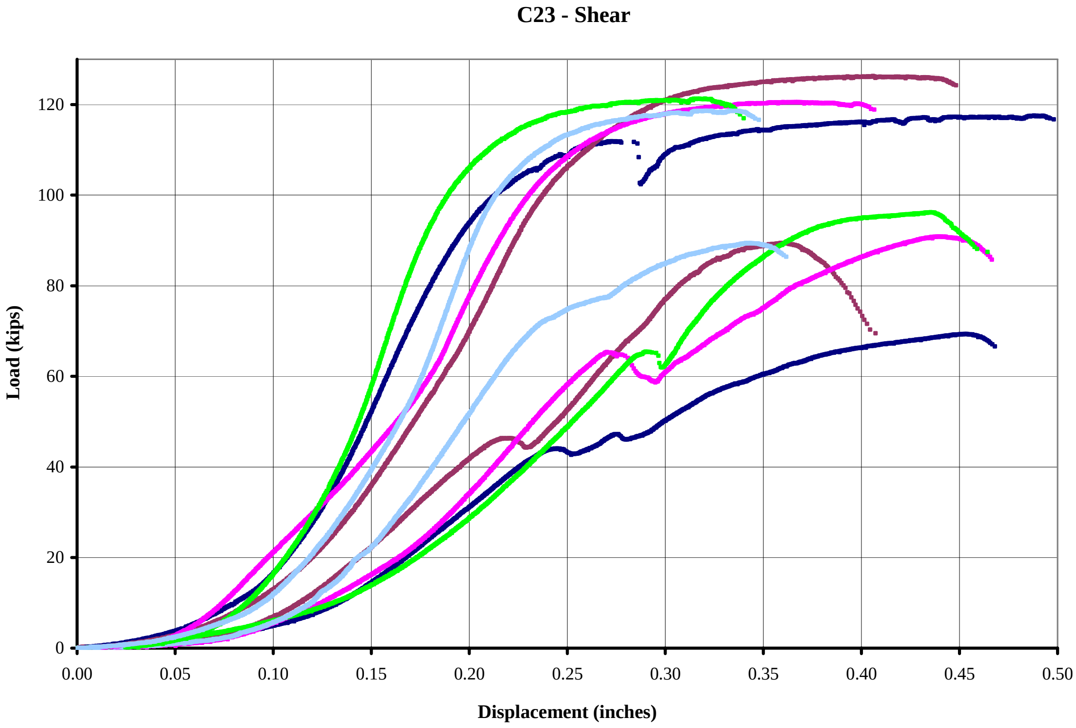

Figure A-174: Lot C23 – 1-1/4-inch A490 – Shear

C24

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 5"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.1000 inches

Table A-88: Lot C24 – 1-1/4-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.75 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2440	159,939	2.45%	1.2435	120,612	1.2432	91,442
2	1.2423	158,958	2.86%	1.2433	120,713	1.2422	93,796
3	1.2432	159,376	3.24%	1.2432	118,894	1.2436	87,354
4	1.2433	158,452	3.56%	1.2436	121,593	1.2419	90,627
5	1.2430	159,795	2.39%	1.2439	121,550	1.2439	86,233

Note: The lever arm of the third LVDT was resting on the angle.

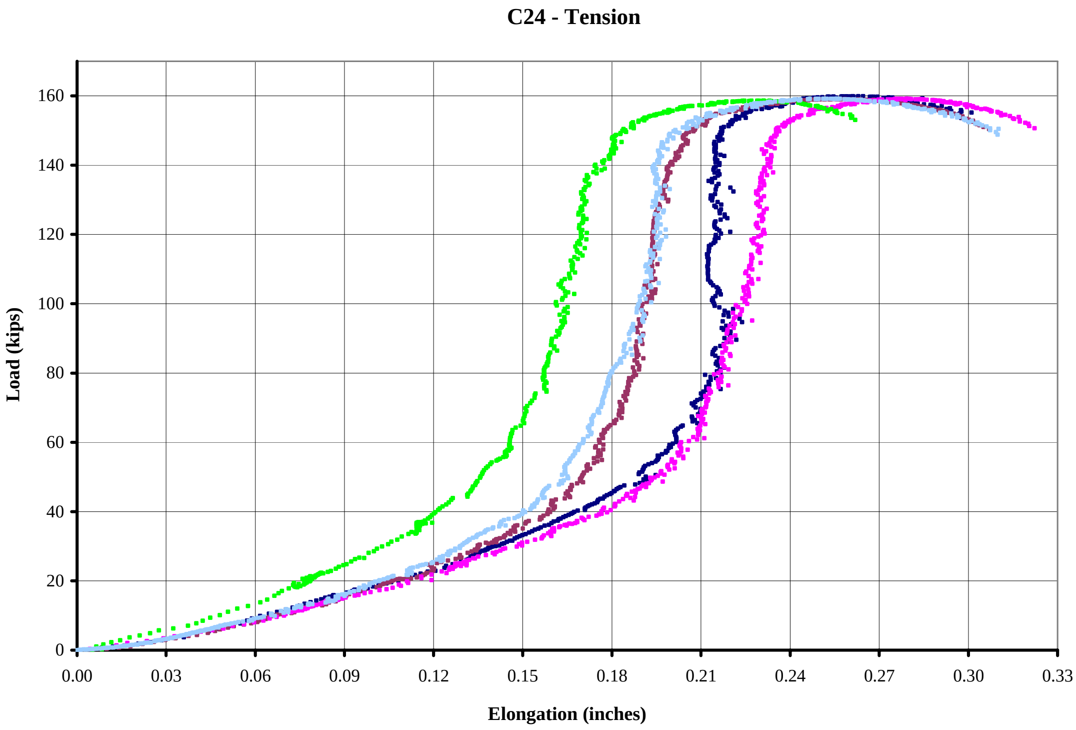

Figure A-175: Lot C24 – 1-1/4-inch A490 – Tension

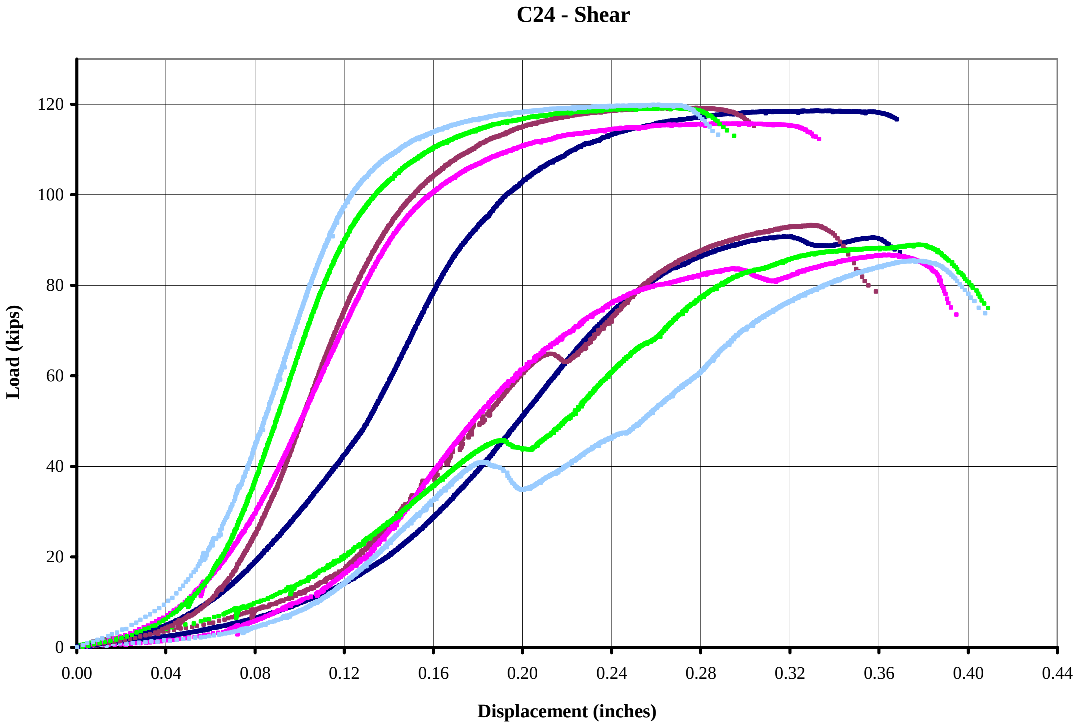

Figure A-176: Lot C24 – 1-1/4-inch A490 – Shear

L16

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 4.25"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.2020 inches

Table A-89: Lot L16 – 1-1/4-inch A490 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate:		0.6375 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2460	152,694	0.35%	1.2450	116,513	1.2454	98,550
2	1.2461	159,448	3.87%	1.2460	124,768	1.2458	97,818
3	1.2470	167,718	4.92%	1.2439	128,925	1.2443	101,178
4	1.2453	167,530	4.52%	1.2451	120,857	1.2464	103,676
5	1.2466	159,217	4.02%	1.2461	120,770	1.2442	101,387
6	1.2450	162,421	3.47%				

Note: The lever arm of the third LVDT was resting on the angle.

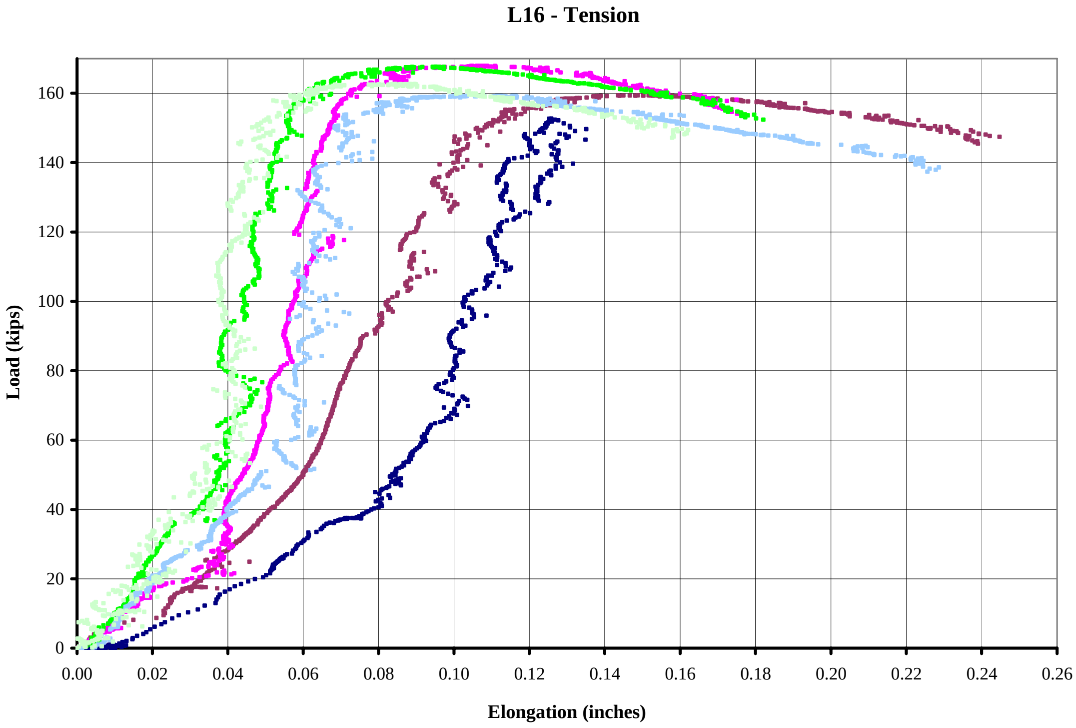

Figure A-177: Lot L16 – 1-1/4-inch A490 – Tension

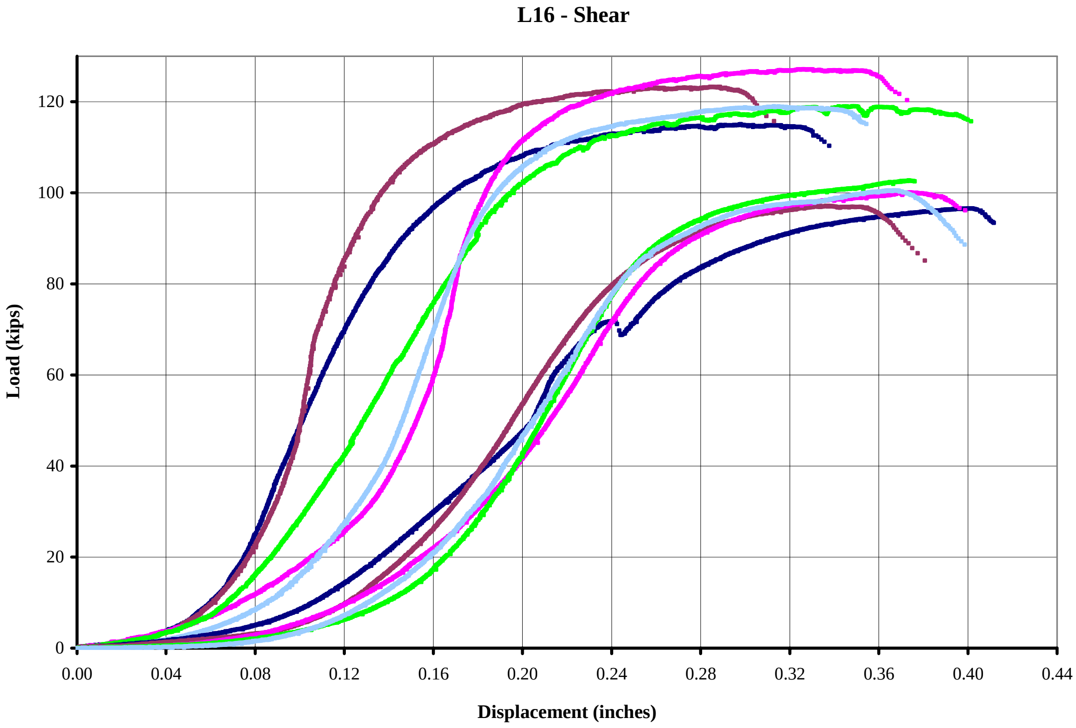

Figure A-178: Lot L16 – 1-1/4-inch A490 – Shear

N20

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/4"-7 x 3.5"
Grade:	A490
Nominal Thread Length:	2 inches
Measured Thread Length:	2.2060 inches

Table A-90: Lot N20 – 1-1/4-inch A490 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.525 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.2448	154,729	6.50%	1.2459	109,066	1.2448	86,309
2	1.2446	151,669	5.38%	1.2460	108,474	1.2440	84,586
3	1.2450	154,729	6.06%	1.2453	105,355	1.2443	88,082
4	1.2454	152,218	6.38%	1.2462	108,547	1.2445	86,680
5	1.2450	156,706	5.74%	1.2448	107,003	1.2456	80,790

Note: The lever arm of the third LVDT was resting on the angle.

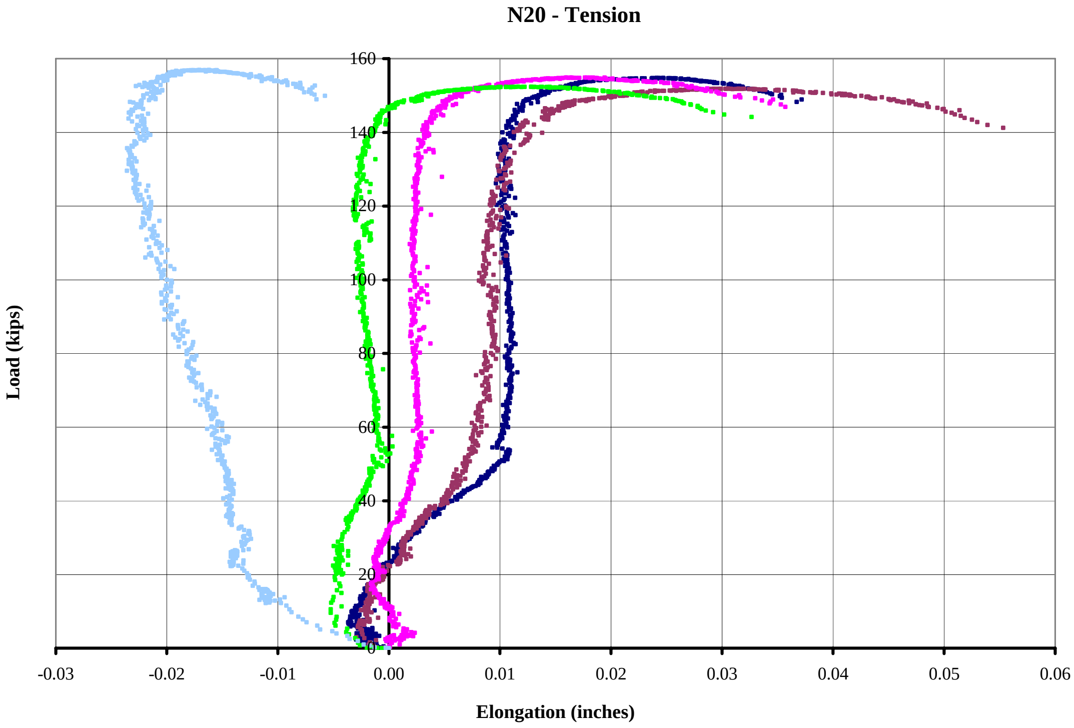

Figure A-179: Lot N20 – 1-1/4-inch A490 – Tension

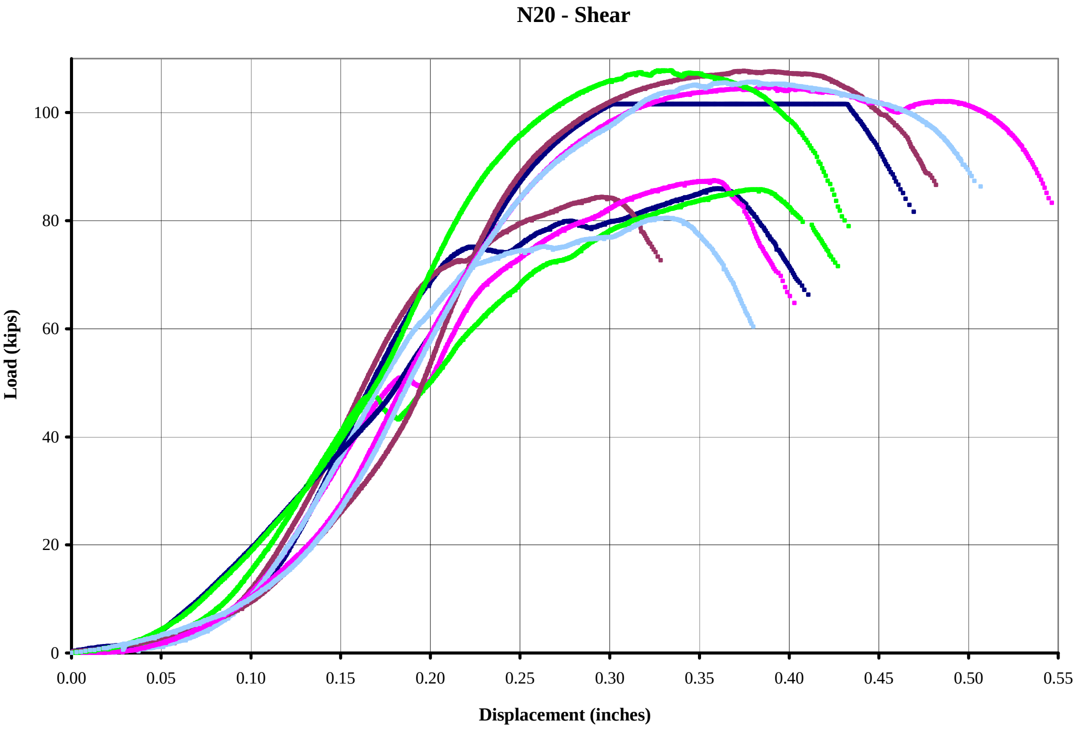

Figure A-180: Lot N20 – 1-1/4-inch A490 – Shear

B12

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 3.5"
Grade:	F2280
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4515 inches

Table A-91: Lot B12 – 3/4-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.525 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7390	56,579	10.99%	0.7403	44,348	0.7406	33,928
2	0.7390	57,519	10.51%	0.7401	44,446	0.7404	34,090
3	0.7390	56,690	10.06%	0.7416	44,489	0.7409	33,975
4	0.7388	57,559	9.09%	0.7412	44,882	0.7397	29,472
5	0.7400	56,943	10.68%	0.7397	45,563	0.7398	32,753

Note: The lever arm of the third LVDT was resting on the bolt head.

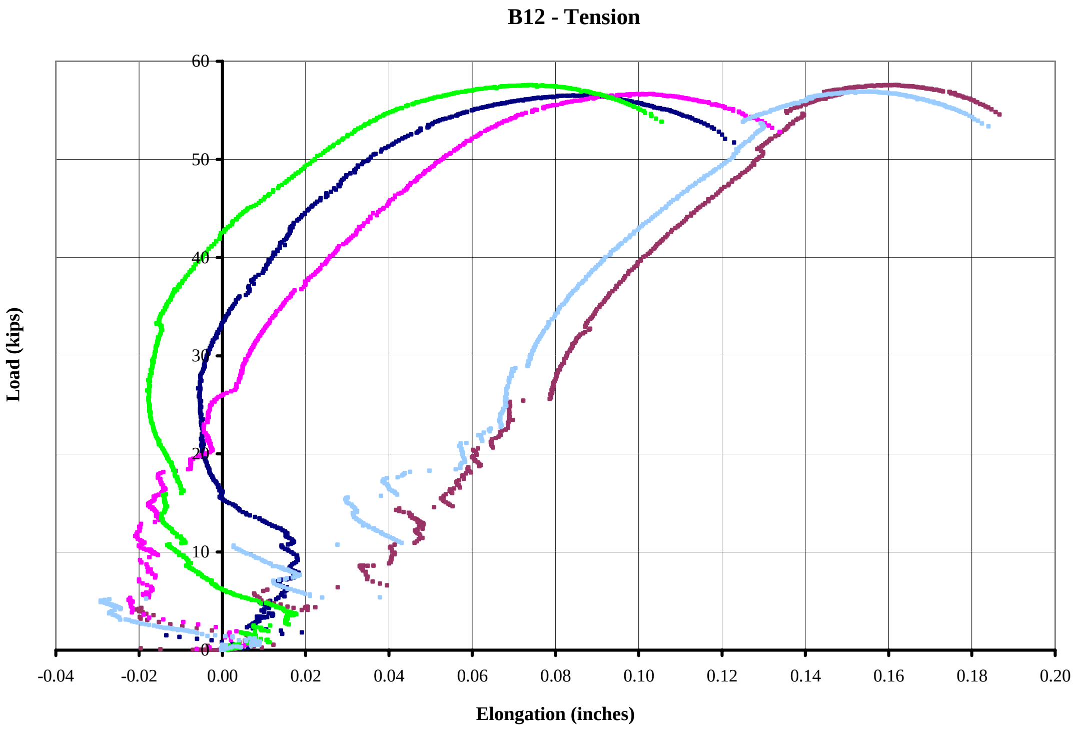

Figure A-181: Lot B12 – 3/4-inch F2280 – Tension

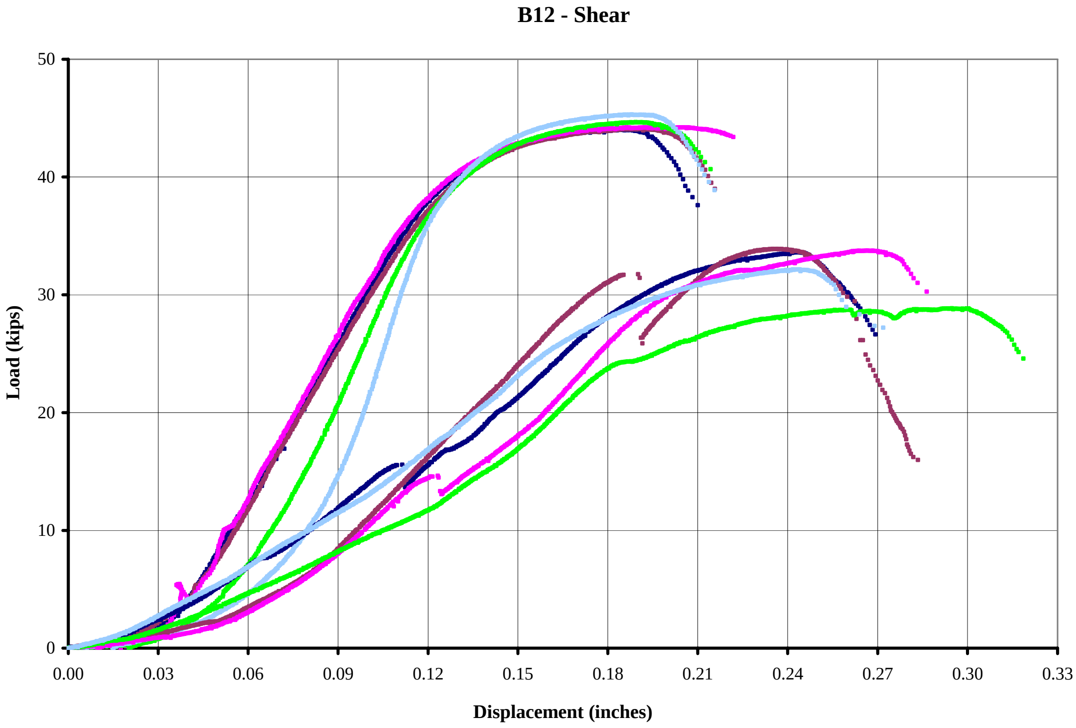

Figure A-182: Lot B12 – 3/4-inch F2280 – Shear

B13

Bolt Properties:

Manufacturer:
Lot Number:
Size: 3/4"-10 x 4"
Grade: F2280
Nominal Thread Length: 1 3/8 inches
Measured Thread Length: 1.4545 inches

Table A-92: Lot B13 – 3/4-inch F2280 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7394	56,939	11.38%	0.7399	44,741	0.7396	34,353
2	0.7388	57,404	13.20%	0.7395	44,875	0.7403	33,715
3	0.7396	57,116	8.32%	0.7395	44,763	0.7394	34,843
4	0.7388	56,507	9.63%	0.7396	44,439	0.7403	34,126
5	0.7384	56,899	9.25%	0.7395	45,030	0.7400	34,021

Note: The lever arm of the third LVDT was resting on the bolt head.

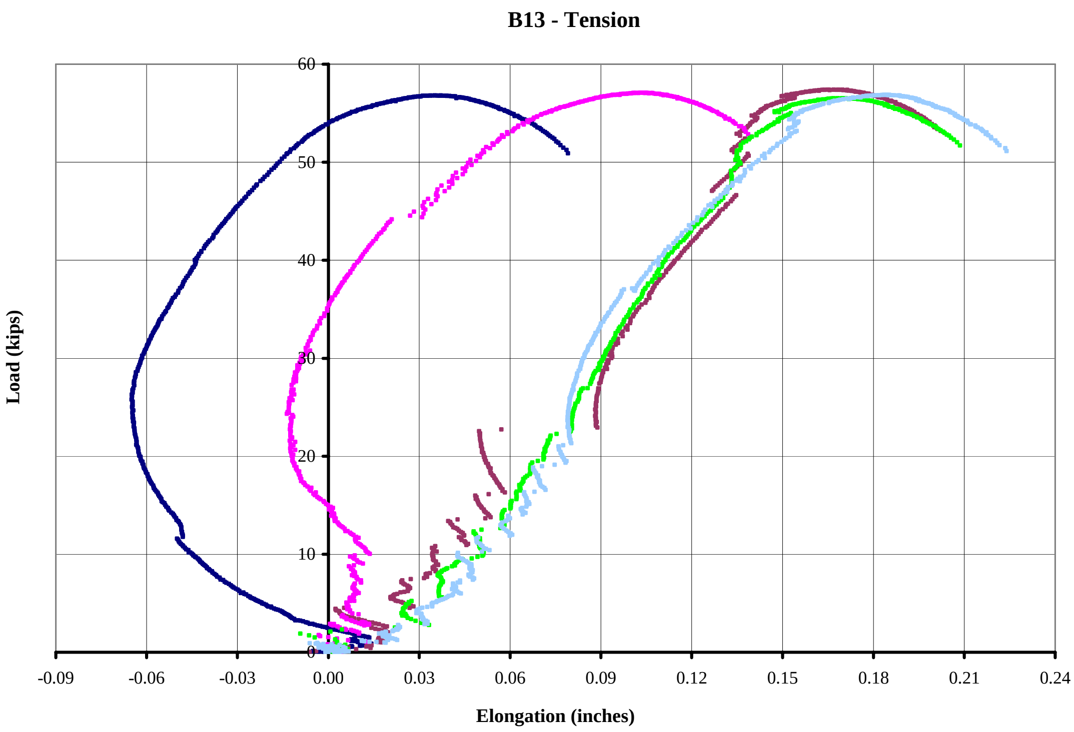

Figure A-183: Lot B13 – 3/4-inch F2280 – Tension

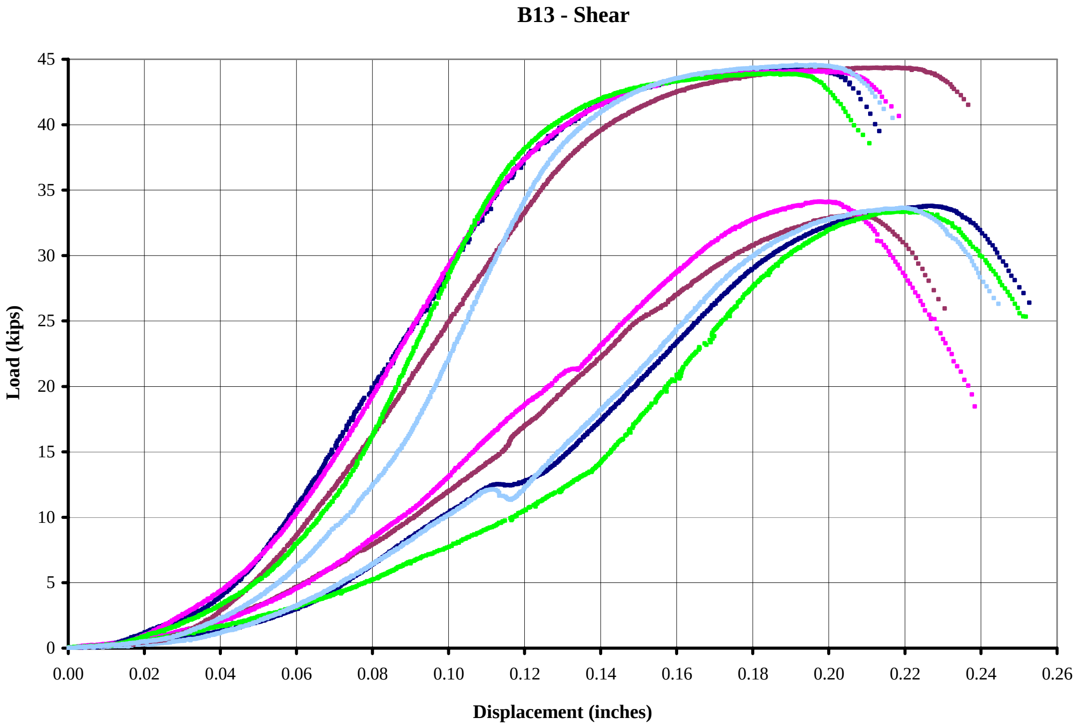

Figure A-184: Lot B13 – 3/4-inch F2280 – Shear

U7

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	3/4"-10 x 4"
Grade:	F2280
Nominal Thread Length:	1 3/8 inches
Measured Thread Length:	1.4500 inches

Table A-93: Lot U7 – 3/4-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate: 0.60 in/min			**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.7350	55,137	7.83%	0.7425	45,105	0.7417	32,468
2	0.7345	56,013	7.07%	0.7422	45,181	0.7427	32,399
3	0.7315	56,564	6.86%	0.7420	43,307	0.7416	33,762
4	0.7325	56,867	10.28%	0.7418	41,166	0.7423	31,228
5	0.7300	56,070	7.62%	0.7414	44,994	0.7420	34,360

Note: The lever arm of the third LVDT was resting on the bolt head.

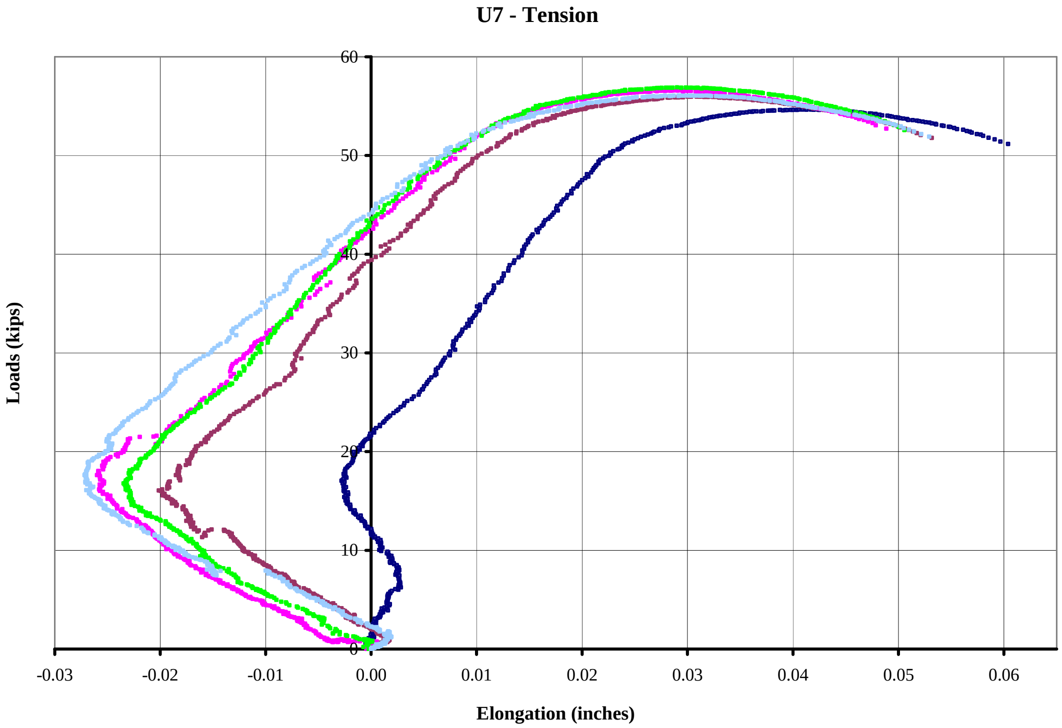

Figure A-185: Lot U7 – 3/4-inch F2280 – Tension

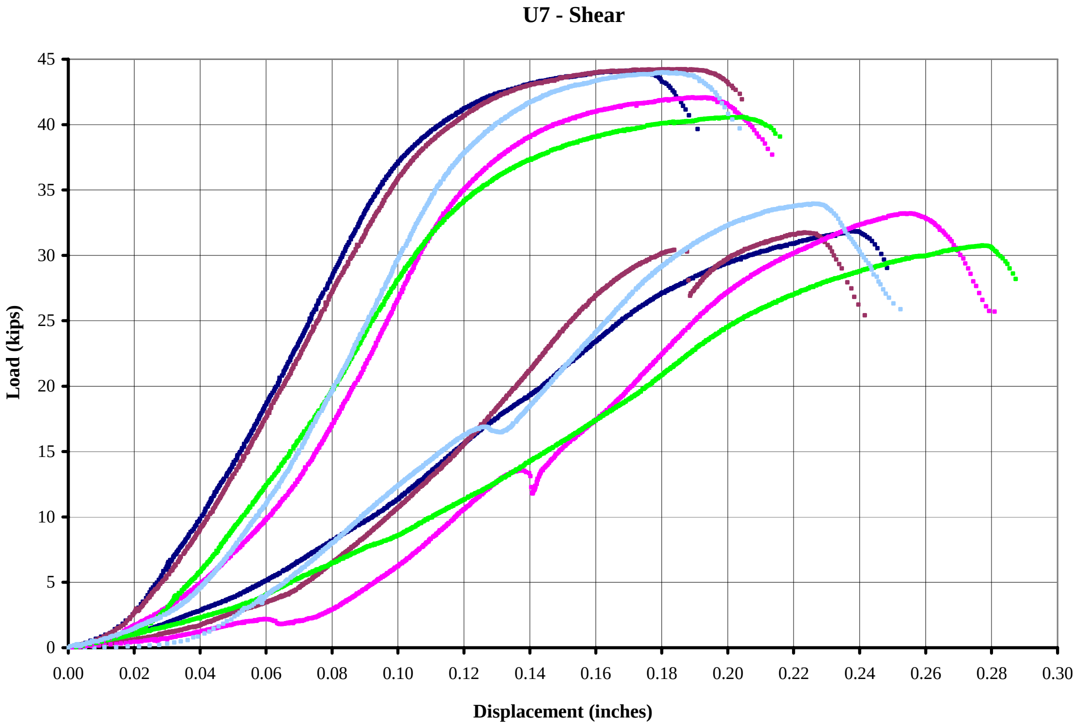

Figure A-186: Lot U7 – 3/4-inch F2280 – Shear

B14

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3.25"
Grade:	F2280
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5410 inches

Table A-94: Lot B14 – 7/8-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.4875 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8746	76,890	9.02%	0.8755	61,946	0.8763	46,879
2	0.8750	76,216	9.28%	0.8751	61,027	0.8758	44,561
3	0.8746	75,935	6.68%	0.8756	61,845	0.8757	45,819
4	0.8740	78,260	8.37%	0.8756	60,273	0.8753	45,549
5	0.8750	77,474	8.21%	0.8752	61,384	0.8751	46,432

Note: The lever arm of the third LVDT was resting on the bolt head.

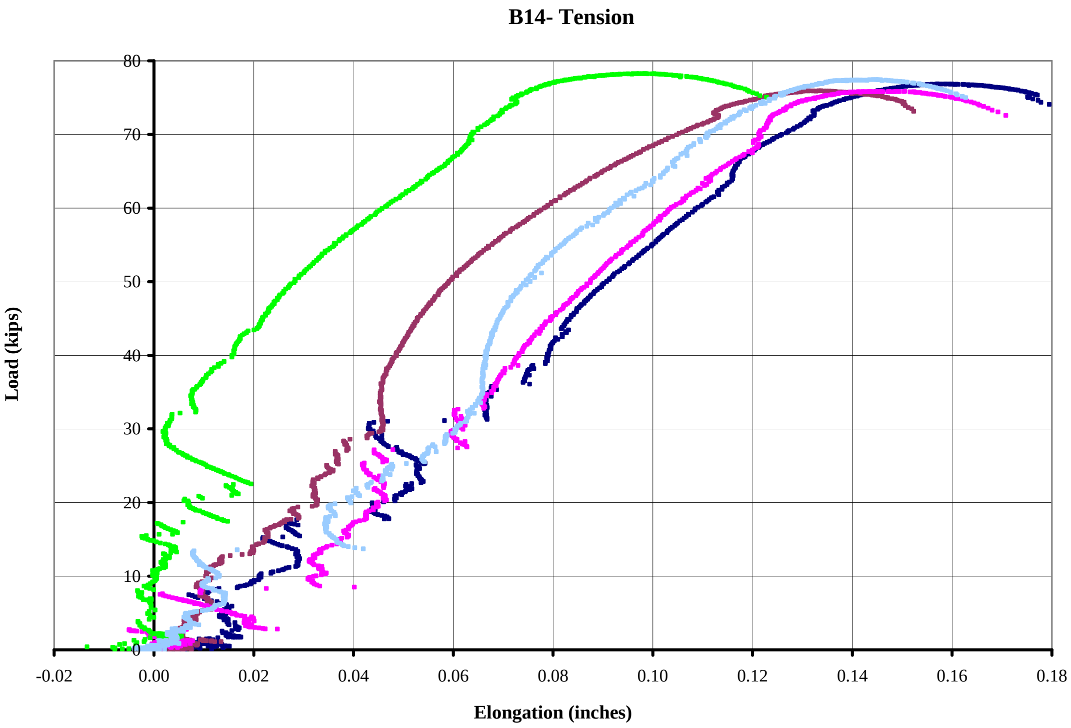

Figure A-187: Lot B14 – 7/8-inch F2280 – Tension

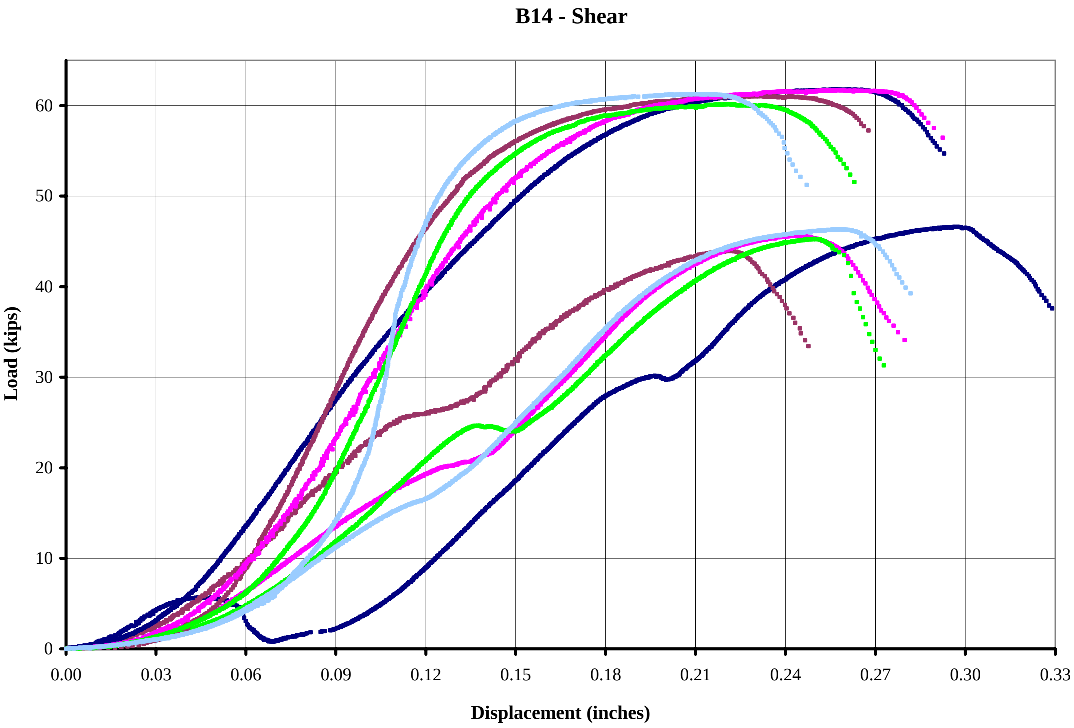

Figure A-188: Lot B14 – 7/8-inch F2280 – Shear

B15

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 3.5"
Grade:	F2280
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5815 inches

Table A-95: Lot B15 – 7/8-inch F2280 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.525 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8742	74,699	11.19%	0.8738	58,608	0.8739	46,025
2	0.8742	77,110	8.63%	0.8737	59,347	0.8745	46,017
3	0.8740	75,092	6.58%	0.8742	58,334	0.8740	44,759
4	0.8742	75,769	5.12%	0.8742	58,918	0.8732	46,327
5	0.8730	75,726	7.62%	0.8741	58,738	0.8740	44,940
6				0.8746	58,911		

Note: The lever arm of the third LVDT was resting on the bolt head.

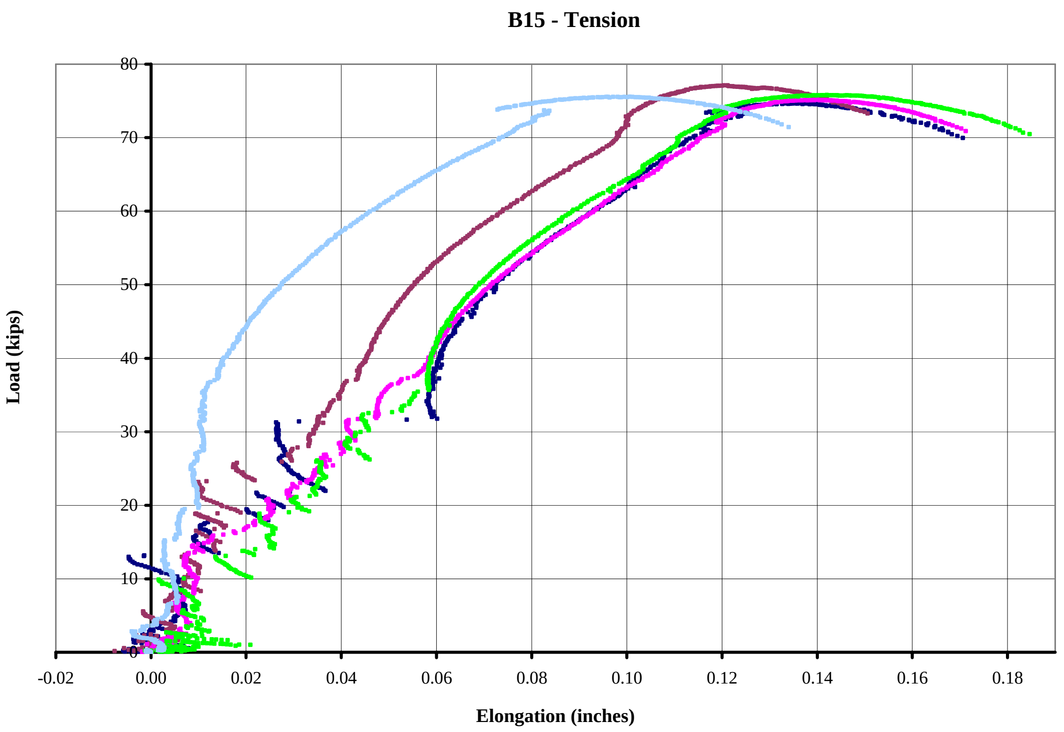

Figure A-189: Lot B15 – 7/8-inch F2280 – Tension

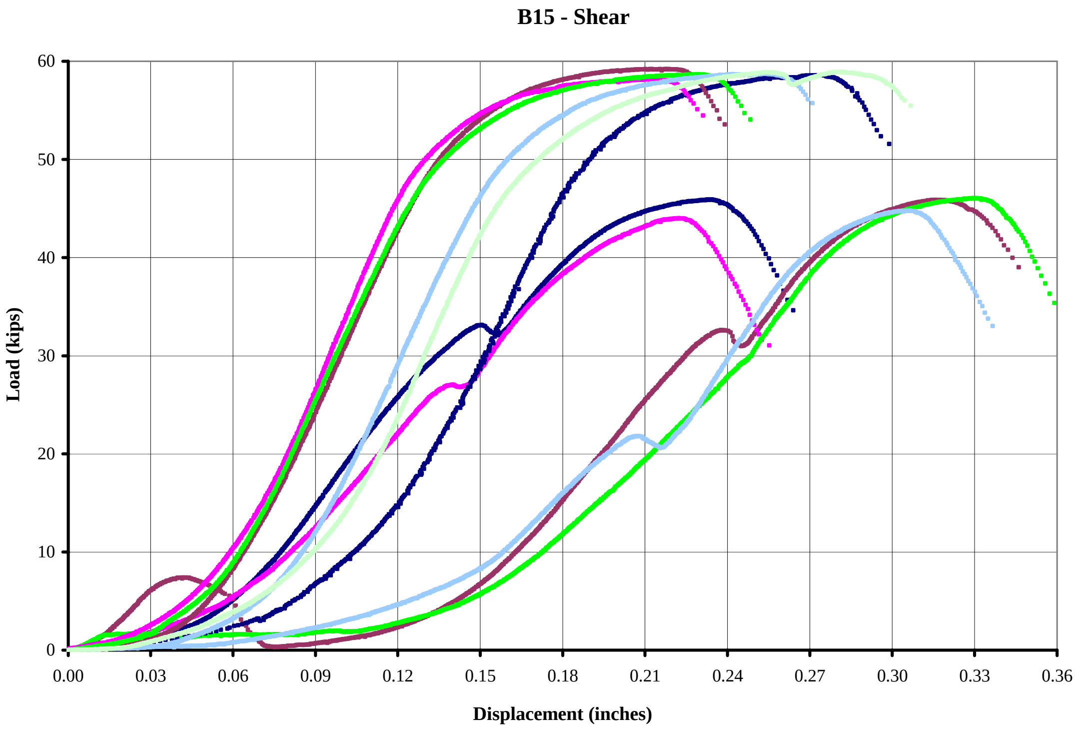

Figure A-190: Lot B15 – 7/8-inch F2280 – Shear

U4

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	7/8"-9 x 4.25"
Grade:	F2280
Nominal Thread Length:	1 1/2 inches
Measured Thread Length:	1.5055 inches

Table A-96: Lot U4 – 7/8-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.6375 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.8707	78,429	6.24%	0.8710	59,552	0.8702	48,133
2	0.8707	77,982	7.14%	0.8698	61,466	0.8704	49,283
3	0.8721	78,786	7.17%	0.8693	62,047	0.8703	48,991
4	0.8742	83,014	5.88%	0.8706	61,492	0.8703	46,944
5	0.8719	77,034	7.24%	0.8700	60,753	0.8703	44,788

Note: The lever arm of the third LVDT was resting on the bolt head.

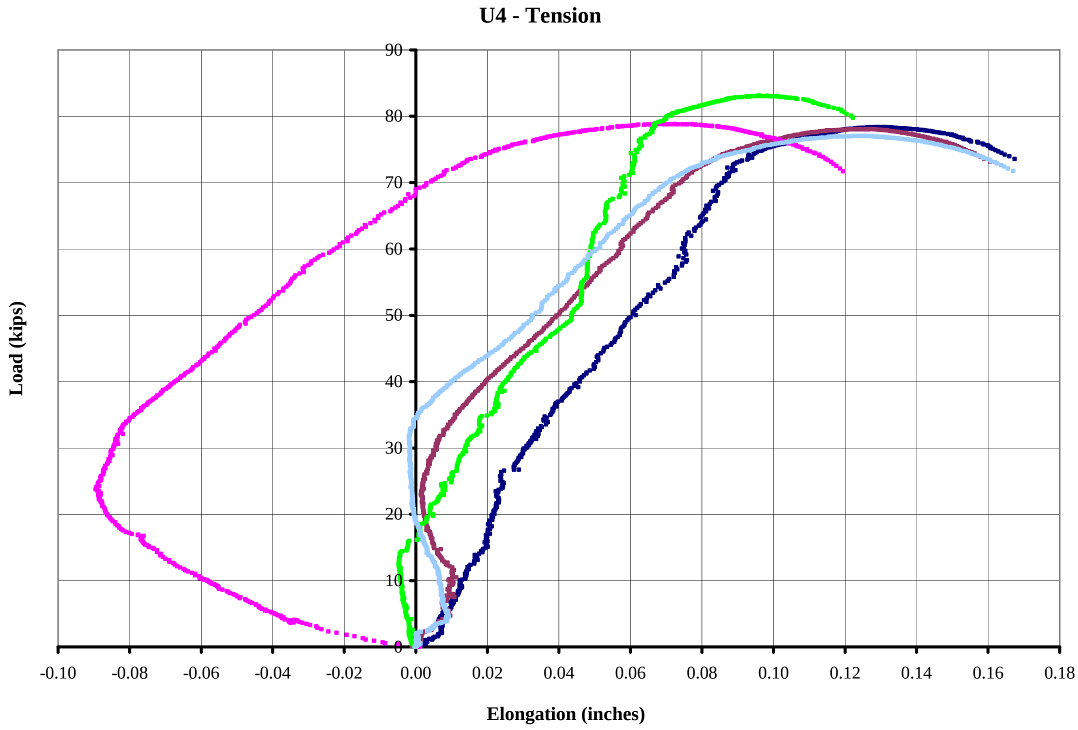

Figure A-191: Lot U4 – 7/8-inch F2280 – Tension

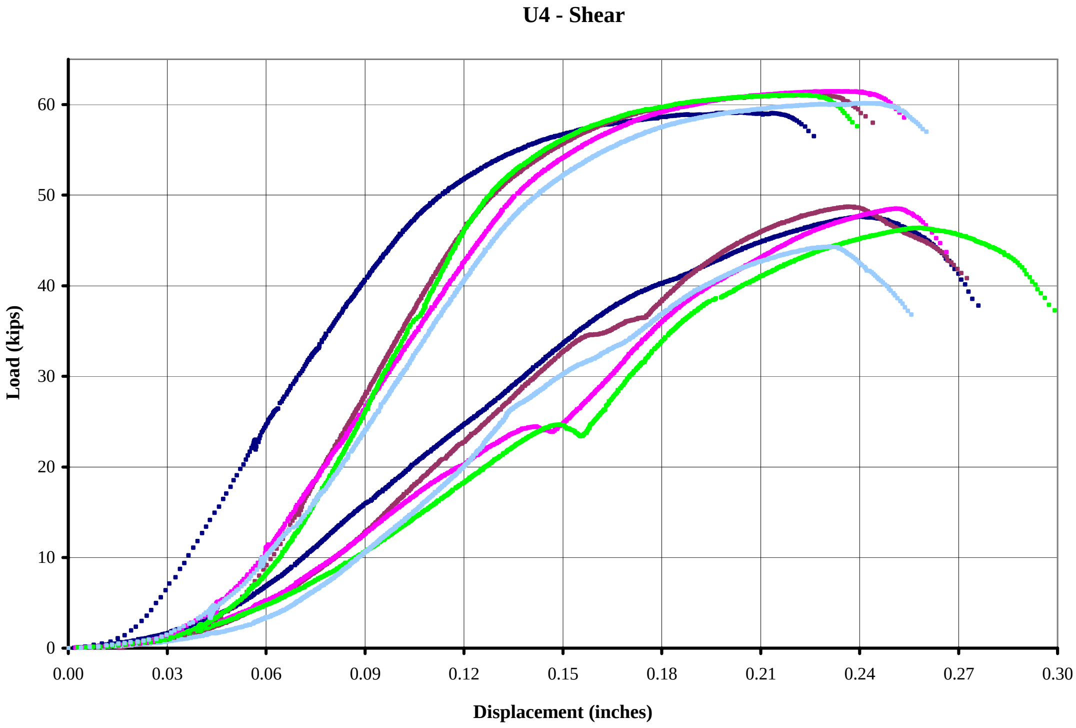

Figure A-192: Lot U4 – 7/8-inch F2280 – Shear

B16

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.5"
Grade:	F2280
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.9185 inches

Table A-97: Lot B16 – 1-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.525 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9864	101,037	7.87%	0.9855	76,948	0.9864	62,187
2	0.9864	99,585	5.50%	0.9861	77,020	0.9858	58,727
3	0.9852	100,086	8.24%	0.9851	76,894	0.9854	58,500
4	0.9866	98,928	7.09%	0.9862	78,296	0.9852	57,988
5	0.9854	100,388	7.38%	0.9861	77,031	0.9855	59,102

Note: The lever arm of the third LVDT was resting on the bolt head.

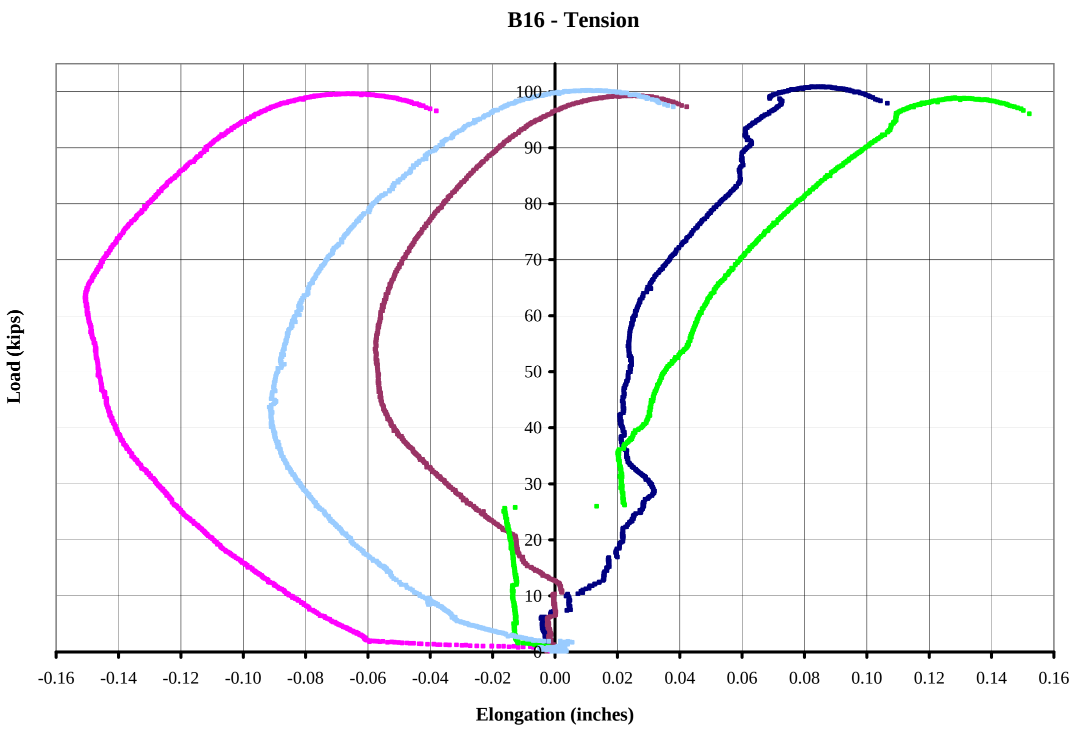

Figure A-193: Lot B16 – 1-inch F2280 – Tension

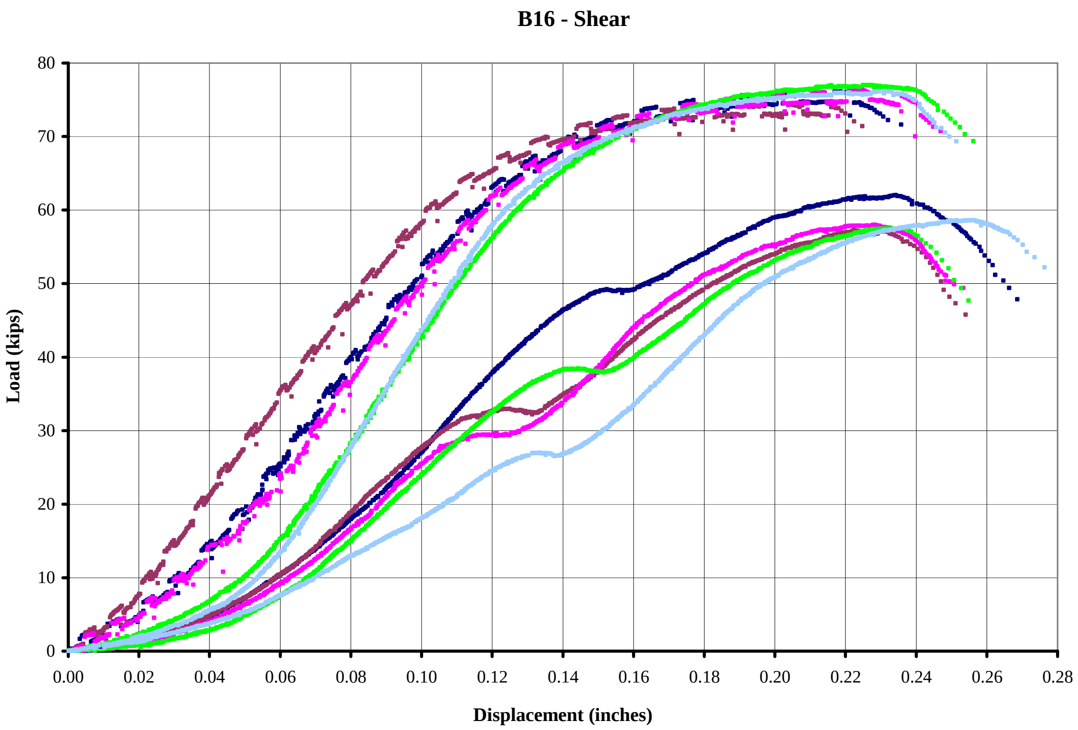

Figure A-194: Lot B16 – 1-inch F2280 – Shear

B17

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.75"
Grade:	F2280
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.9025 inches

Table A-98: Lot B17 – 1-inch F2280 – Data

Test	Tension			Shear			
				Threads Excluded		Threads Not Excluded	
		Load Rate:	0.5625 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9902	100,770	5.52%	0.9880	78,015	0.9887	60,980
2	0.9913	101,621	5.86%	0.9893	77,925	0.9868	58,175
3	0.9915	100,349	4.89%	0.9890	78,368	0.9876	58,651
4	0.9912	101,055	3.76%	0.9888	78,213	0.9862	55,926
5	0.9904	99,174	5.73%	0.9880	78,408	0.9863	56,550

Note: The lever arm of the third LVDT was resting on the bolt head.

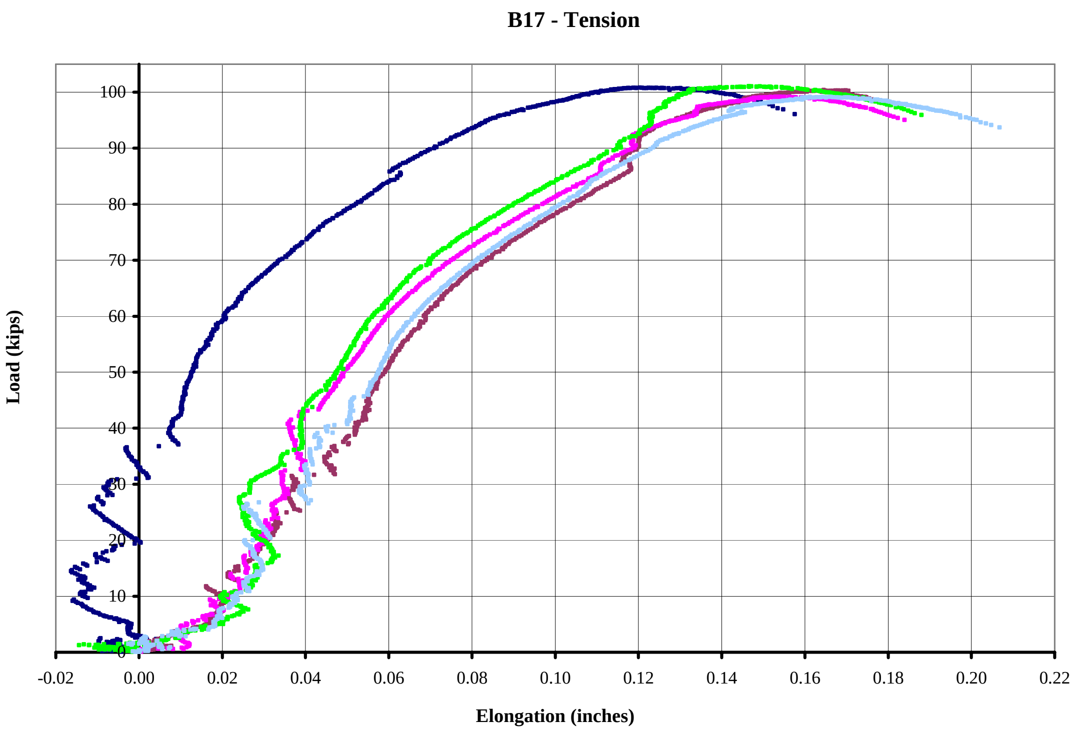

Figure A-195: Lot B17 – 1-inch F2280 – Tension

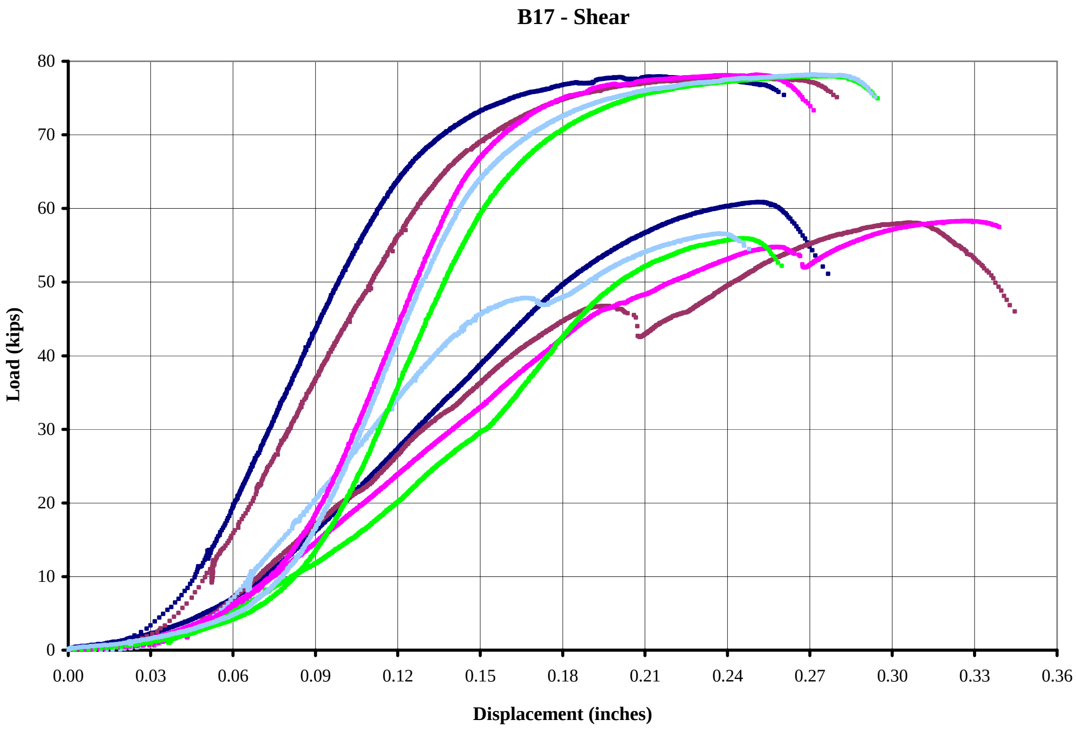

Figure A-196: Lot B17 – 1-inch F2280 – Shear

U8

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1"-8 x 3.5"
Grade:	F2280
Nominal Thread Length:	1 3/4 inches
Measured Thread Length:	1.7735 inches

Table A-99: Lot U8 – 1-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
		Load Rate:	0.525 in/min	**Load Rate:**	0.5 in/min	**Load Rate:**	0.5 in/min
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	0.9953	102,014	4.74%	0.9945	77,139	0.9946	60,219
2	0.9968	102,061	1.35%	0.9943	79,525	0.9947	55,970
3	0.9955	101,059	3.30%	0.9951	77,294	0.9939	59,178
4	0.9963	103,575	6.68%	0.9943	77,283	0.9951	55,559
5	0.9973	101,041	4.74%	0.9945	79,367	0.9943	57,527

Note: The lever arm of the third LVDT was resting on the bolt head.

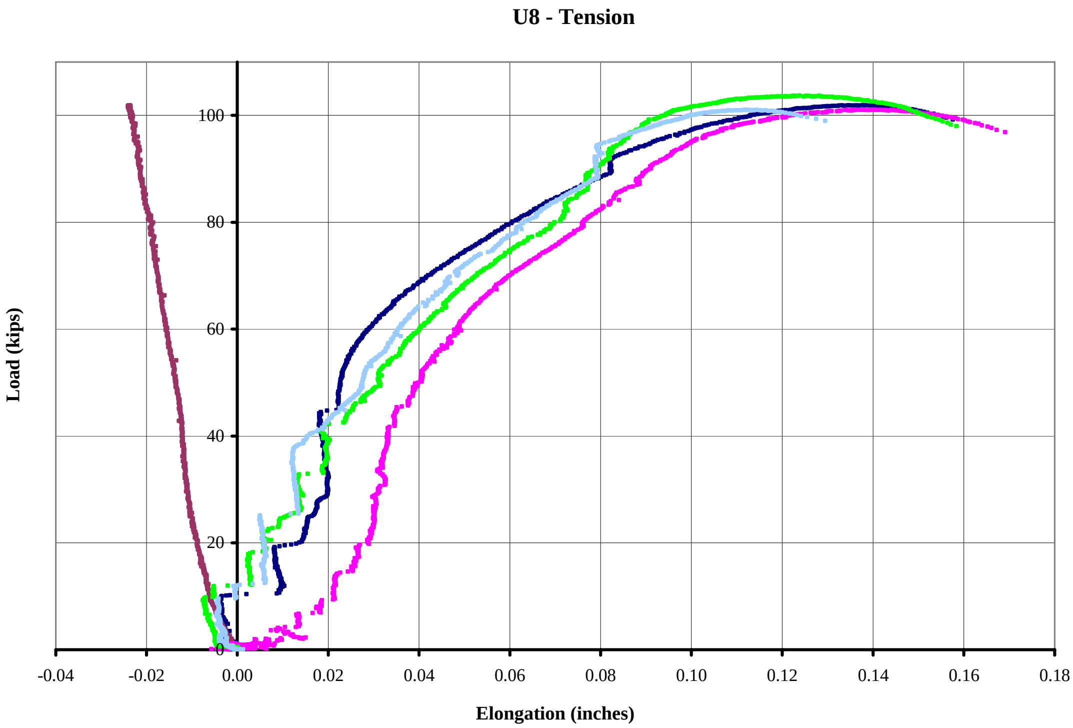

Figure A-197: Lot U8 – 1-inch F2280 – Tension

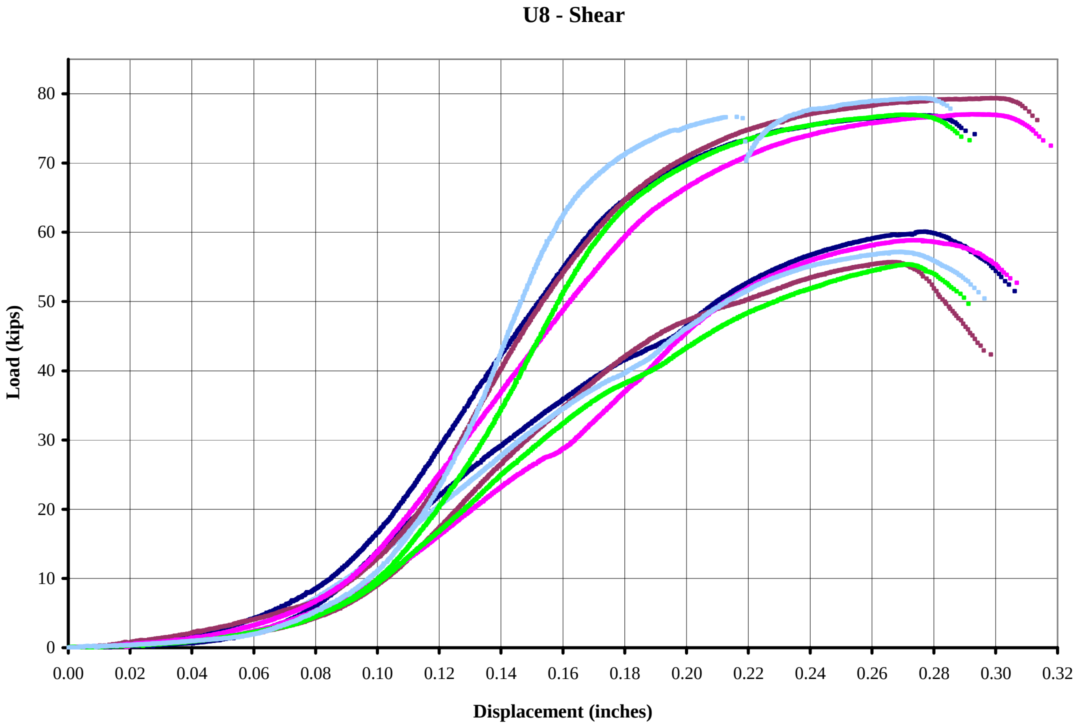

Figure A-198: Lot U8 – 1-inch F2280 – Shear

U9

Bolt Properties:

Manufacturer:	
Lot Number:	
Size:	1-1/8"-7 x 4.25"
Grade:	F2280
Nominal Thread Length:	2 inches
Measured Thread Length:	2.0025 inches

Table A-100: Lot U9 – 1-1/8-inch F2280 – Data

Test	**Tension**			**Shear**			
				Threads Excluded		**Threads Not Excluded**	
	Load Rate:		0.6375 in/min	**Load Rate:** 0.5 in/min		**Load Rate:** 0.5 in/min	
	Average Diameter (inches)	**Failure Load (pounds)**	**Elongation**	**Average Diameter (inches)**	**Failure Load (pounds)**	**Average Diameter (inches)**	**Failure Load (pounds)**
1	1.1120	132,432	2.68%	1.1115	96,200	1.1110	74,428
2	1.1112	127,828	3.12%	1.1115	95,857	1.1114	73,855
3	1.1115	128,088	4.15%	1.1118	96,254	1.1116	69,054
4	1.1114	129,228	5.31%	1.1120	95,082	1.1121	75,917
5	1.1112	128,073	3.51%	1.1123	96,791	1.1116	72,951

Note: The lever arm of the third LVDT was resting on the angle.

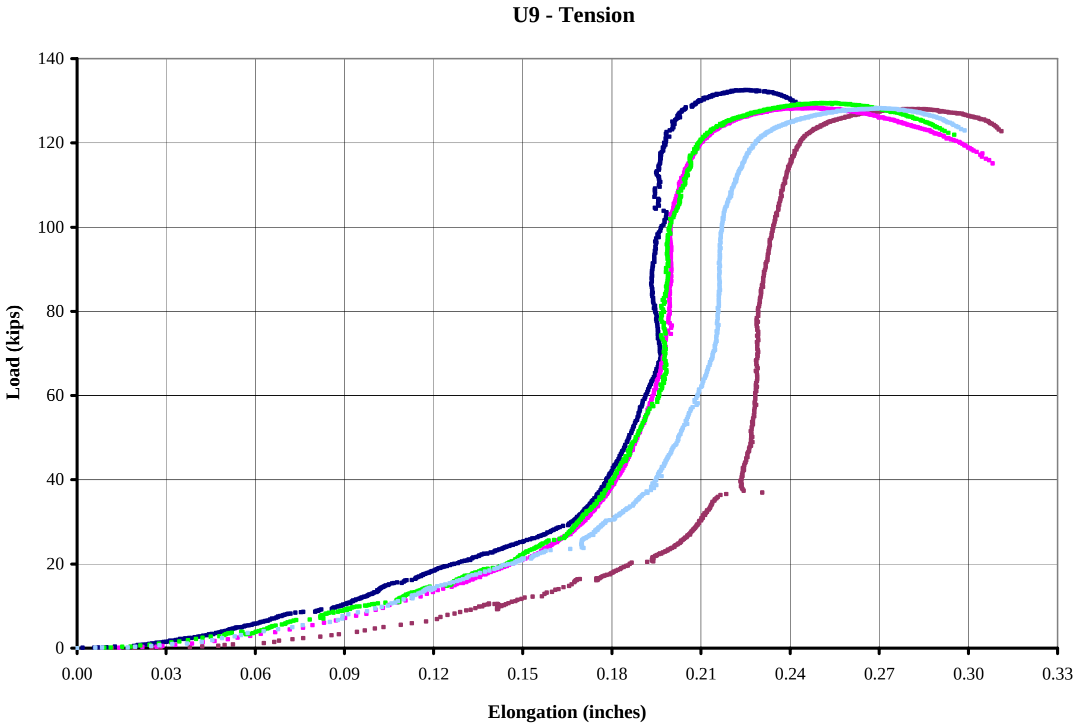

Figure A-199: Lot U9 – 1-1/8-inch F2280 – Tension

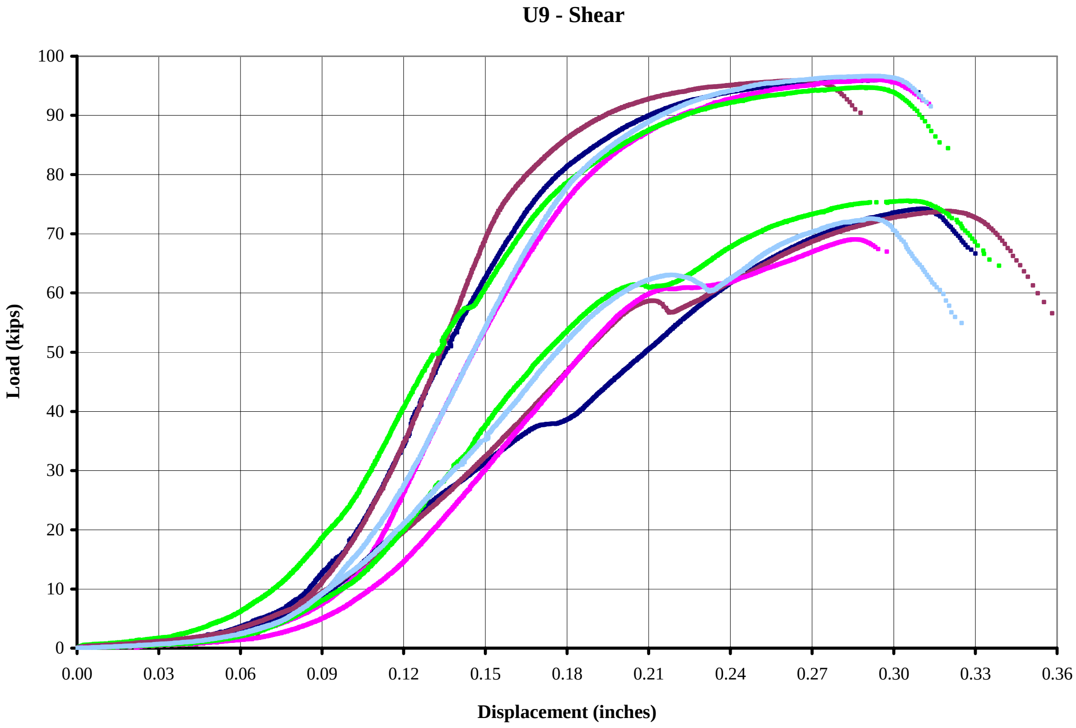

Figure A-200: Lot U9 – 1-1/8-inch F2280 – Shear

APPENDIX B

RESISTANCE FACTOR EXAMPLE CALCULATIONS

This appendix contains examples for calculating a resistance factor in tension and shear with the threads excluded and not excluded from the shear plane for Level V based on the different methods. From Section 2.4.1, Level V resistance factors are calculated for each diameter and grade of bolts. For the eight examples herein the resistance factors will be calculated for 7/8-inch A490 bolts.

B.1 Level V – Tension Resistance Factor – 7/8-inch A490 Bolts

This section calculations the tension resistance factor for 7/8-inch A490 bolts based on the four methods discussed in Section 2.4.1. The average of the bolt diameters and the failure loads in tension for the ten lots of 7/8-inch A490 bolts are summarized in Table B-1.

Table B-1: Raw Tension Data for 7/8-inch A490 Bolts

Bolt Identification	Length (inches)	Average Shank Diameter (inches)	Tension Failure Load (pounds)
C11	3 3/4	0.8676	77669
		0.8679	77665
		0.8677	77593
		0.8664	76195
		0.8673	77182
C12	4 1/2	0.8685	77399
		0.8691	77135
		0.8690	77016
		0.8691	77071
		0.8680	77204
C13	4 3/4	0.8677	73217
		0.8672	73985
		0.8684	73416
		0.8676	73524
		0.8678	73819
C15	5	0.8687	72907
		0.8676	73408
		0.8680	73131
		0.8695	73073
		0.8692	73124
L11	3	0.8759	74591
		0.8747	73877
		0.8730	75185
		0.8722	75196
		0.8729	75070
L12	5	0.8694	79201
		0.8698	78581
		0.8692	78361
		0.8705	78599
		0.8701	77060
N14	3 3/4	0.8719	76944
		0.8750	75315
		0.8743	75629
		0.8721	76670
		0.8733	76494
		0.8757	77060
N15	4	0.8735	73628
		0.8711	71620
		0.8726	74601
		0.8750	73610
		0.8752	72413
T13	4	0.8740	77914
		0.8762	76620
		0.8758	78927
		0.8756	77777
		0.8745	77907
T14	4 1/4	0.8745	75611
		0.8737	74252
		0.8728	76364
		0.8717	75420
		0.8736	75730

B.1.1 Method 1A

The equation to calculate resistance factors for Method 1 was given by equation (2-8), which is repeated here for convenience.

$$\phi = \Phi_{\beta} \frac{R_m}{R_n} \; e^{-\alpha \beta V_R} \tag{2-8}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_{β}, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_{\beta} = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_{\beta} = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-1}$$

STEP 2: Determine the Ratio *R_m/R_n*

The value of R_m, in kips, is the average value of the failure loads, given in Column 4 of Table B-2, of the five or more bolts tested per lot. This value was calculated for each of the ten lots and is shown in Column 5 of Table B-2.

The nominal resistance, R_n, was given by equation (2-4) as previously described in Section 2.2. The equation is repeated here for convenience.

$$R_n = \left(0.75F_u\right)A_b \tag{2-4}$$

The ultimate stress, F_u, equals 150 ksi for A490 bolts. The area, A_b, is the nominal area or area of the shank. Therefore the nominal resistance for a 7/8-inch A490 bolt is

$$R_n = 0.75\left(150^{ksi}\right)\left[\frac{\pi\left(\frac{7}{8}''\right)^2}{4}\right] = 67.649^{kips} \tag{B-2}$$

The ratio ${R_m}/{R_n}$ for each lot is shown in Column 6 of Table B-2 for each of the ten lots.

The ratio of ${R_m}/{R_n}$ used in equation (2-8) is the average value for the ten lots. The average of ${R_m}/{R_n}$ is 1.119199 as shown in Table B-2.

STEP 3: Determine the Coefficient of Variation

The coefficient of variation equals the standard deviation divided by the average of ${R_m}/{R_n}$.

These two values are shown in Table B-2. The coefficient of variation thus equals

$$V_R = \frac{\text{standard deviation}\left({R_m}/{R_n}\right)}{\text{average}\left({R_m}/{R_n}\right)} = \frac{0.029126}{1.119199} = 0.026024 \tag{B-3}$$

Table B-2: Tension – Method 1A

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	R_m **(kips)**	R_m/R_n
C11	3 3/4	0.8676	77669	77.2608	1.142091
		0.8679	77665		
		0.8677	77593		
		0.8664	76195		
		0.8673	77182		
C12	4 1/2	0.8685	77399	77.1650	1.140675
		0.8691	77135		
		0.8690	77016		
		0.8691	77071		
		0.8680	77204		
C13	4 3/4	0.8677	73217	73.5922	1.087861
		0.8672	73985		
		0.8684	73416		
		0.8676	73524		
		0.8678	73819		
C15	5	0.8687	72907	73.1286	1.081008
		0.8676	73408		
		0.8680	73131		
		0.8695	73073		
		0.8692	73124		
L11	3	0.8759	74591	74.7838	1.105475
		0.8747	73877		
		0.8730	75185		
		0.8722	75196		
		0.8729	75070		
L12	5	0.8694	79201	78.3604	1.158346
		0.8698	78581		
		0.8692	78361		
		0.8705	78599		
		0.8701	77060		
N14	3 3/4	0.8719	76944	76.3520	1.128657
		0.8750	75315		
		0.8743	75629		
		0.8721	76670		
		0.8733	76494		
		0.8757	77060		
N15	4	0.8735	73628	73.1744	1.081685
		0.8711	71620		
		0.8726	74601		
		0.8750	73610		
		0.8752	72413		
T13	4	0.8740	77914	77.8290	1.150490
		0.8762	76620		
		0.8758	78927		
		0.8756	77777		
		0.8745	77907		
T14	4 1/4	0.8745	75611	75.4754	1.115699
		0.8737	74252		
		0.8728	76364		
		0.8717	75420		
		0.8736	75730		
				Average	1.119199
				Standard Deviation	0.029126

STEP 4: Calculate the Resistance Factor

Now that everything is known, the resistance factor for 7/8-inch A490 bolts in tension, based on Method 1A, can be determined from equation (2-8).

$$\phi = (0.8991)(1.119199)\ e^{-0.55(4.0)(0.026024)} = 0.950 \tag{B-4}$$

B.1.2 Method 1B

The equation to calculate resistance factors for Method 1 was given by equation (2-8), which is repeated here for convenience.

$$\phi = \Phi_{\beta} \frac{R_m}{R_n}\ e^{-\alpha \beta V_R} \tag{2-8}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_{β}, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_{\beta} = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_{\beta} = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-5}$$

STEP 2: Determine the Ratio *R_m/R_n*

The value of R_m for a lot of bolts, in kips, is the average value of the failure loads, given in Column 4 of Table B-3, of the five or more bolts tested in tension. This value was calculated for each of the ten lots and is shown in Column 5 of Table B-3.

The nominal resistance, R_n, was given by equation (2-31), as previously described in Section 2.4.1.4, with an effective area as given by equation (2-3) of Section 2.2. From these two equations the nominal resistance is given by

$$R_n = F_u A_{eff} = F_u \left[\frac{\pi}{4} \left(d - \frac{0.9743}{n} \right)^2 \right] \tag{B-6}$$

The ultimate stress, F_u, equals 150 ksi for A490 bolts. The diameter, d, is the nominal diameter of the shank. The number of threads per inch, n, equals 9 for a 7/8-inch bolt. Therefore the nominal resistance for a 7/8-inch A490 bolt is

$$R_n = 150^{ksi} \left[\frac{\pi}{4} \left({}^{7}\!/_{8}\text{"} - \frac{0.9743}{9} \right)^2 \right] = 69.26^{kips} \tag{B-7}$$

The ratio ${}^{R_m}\!/_{R_n}$ is shown in Column 6 of Table B-3 for each of the ten lots.

The ratio of ${}^{R_m}\!/_{R_n}$ used in equation (2-8) is the average value for the ten lots. The average of ${}^{R_m}\!/_{R_n}$ is 1.093159 as shown in Table B-3.

Table B-3: Tension – Method 1B

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	R_m **(kips)**	R_m/R_n
C11	3 3/4	0.8676	77669	77.2608	1.115519
		0.8679	77665		
		0.8677	77593		
		0.8664	76195		
		0.8673	77182		
C12	4 1/2	0.8685	77399	77.1650	1.114135
		0.8691	77135		
		0.8690	77016		
		0.8691	77071		
		0.8680	77204		
C13	4 3/4	0.8677	73217	73.5922	1.062550
		0.8672	73985		
		0.8684	73416		
		0.8676	73524		
		0.8678	73819		
C15	5	0.8687	72907	73.1286	1.055856
		0.8676	73408		
		0.8680	73131		
		0.8695	73073		
		0.8692	73124		
L11	3	0.8759	74591	74.7838	1.079755
		0.8747	73877		
		0.8730	75185		
		0.8722	75196		
		0.8729	75070		
L12	5	0.8694	79201	78.3604	1.131395
		0.8698	78581		
		0.8692	78361		
		0.8705	78599		
		0.8701	77060		
N14	3 3/4	0.8719	76944	76.3520	1.102397
		0.8750	75315		
		0.8743	75629		
		0.8721	76670		
		0.8733	76494		
		0.8757	77060		
N15	4	0.8735	73628	73.1744	1.056518
		0.8711	71620		
		0.8726	74601		
		0.8750	73610		
		0.8752	72413		
T13	4	0.8740	77914	77.8290	1.123722
		0.8762	76620		
		0.8758	78927		
		0.8756	77777		
		0.8745	77907		
T14	4 1/4	0.8745	75611	75.4754	1.089740
		0.8737	74252		
		0.8728	76364		
		0.8717	75420		
		0.8736	75730		
				Average	1.093159
				Standard Deviation	0.028448

STEP 3: Determine the Coefficient of Variation

The coefficient of variation equals the standard deviation divided by the average. These two values are shown in Table B-3. The coefficient of variation thus equals

$$V_R = \frac{\text{standard deviation}\left(R_m \big/ R_n \right)}{\text{average}\left(R_m \big/ R_n \right)} = \frac{0.028448}{1.093159} = 0.026024 \tag{B-8}$$

STEP 4: Calculate the Resistance Factor

Now that everything is known, the resistance factor for 7/8-inch A490 bolts in tension, based on Method 1B, can be determined from equation (2-8).

$$\phi = (0.8991)(1.093159)\ e^{-0.55(4.0)(0.026024)} = 0.928 \tag{B-9}$$

B.1.3 Method 2A

The equation to calculate resistance factors for Method 2 was given by equation (2-9), which is repeated here for convenience.

$$\phi = \Phi_{\beta} \rho_R\ e^{-\alpha_R \beta V_R} \tag{2-9}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_β, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_\beta = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_\beta = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-10}$$

STEP 2: Determine the Bias Coefficient and Coefficient of Variation

The bias coefficient, ρ_R, is the average value of the ratio of the measured resistance to the nominal resistance. The bias coefficient for the resistance was given by equation (2-37), which is repeated here for convenience.

$$\rho_R = \rho_G\,\rho_M\,\rho_P \tag{2-37}$$

where ρ_G, ρ_M, and ρ_P are the bias coefficients for the cross-sectional geometry, material strength, and professional factor, respectively.

The coefficient of variation associated with ρ_R, V_R, was given in equation (2-38) and is rewritten here.

$$V_R = \sqrt{(V_G)^2 + (V_M)^2 + (V_P)^2} \tag{2-38}$$

where V_G, V_M, and V_P are the coefficients of variation of the cross-sectional geometry, material strength, and professional factor, respectively. Each coefficient of variation is given by the respective standard deviation divided by the corresponding average.

STEP 2a: Determine the Bias Coefficient and Coefficient of Variation for the Cross-Sectional Geometry

The bias coefficient for the cross-sectional geometry, ρ_G, is the ratio of the average applicable geometric property to the nominal value. The value of the bias coefficient for the cross-sectional geometry was given by equation (2-39) and is restated here, using the appropriate nominal diameter for this example.

$$\rho_G = \frac{\text{Actual Area}}{\text{Nominal Area}} = \frac{\text{Average}\left(\frac{\pi\left(d_{avg}\right)^2}{4}\right)}{\left(\frac{\pi\left(d_{nominal}\right)^2}{4}\right)} = \frac{\text{Average}\left(\left(d_{avg}\right)^2\right)}{\left(d_{nominal}\right)^2} = \frac{\text{Avg}\left(\left(d_{avg}\right)^2\right)}{\left(7/8\text{"}\right)^2} \tag{B-11}$$

Column 3 in Table B-4 is the average shank diameter, d_{avg}. The square of the average shank diameter is shown in Column 5. For each lot of bolts, the numerator of equation (B-11) is shown in Column 6 of Table B-4. Column 7 of Table B-4 shows the bias coefficient for the cross-sectional geometry, ρ_G, for each lot of bolts. The average of these values is the bias coefficient for the cross-sectional geometry, which equals 0.991271.

The average and standard deviation of the bias coefficient for the cross-sectional geometry are shown in Table B-4. From the average and standard deviation of the bias coefficient, the coefficient of variation of the cross-sectional geometry can be determined.

$$V_G = \frac{\text{standard deviation}\left(\rho_G\right)}{\text{average}\left(\rho_G\right)} = \frac{0.0067731}{0.991271} = 0.0068327 \tag{B-12}$$

Table B-4: Tension – Method 2A – Calculation of ρ_G

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	**Squared Average Shank Diameter (in^2)**	**Average of the Squared Average Shank Diameter (in^2)**	**Bias Coefficient for Cross-Sectional Geometry ρ_G**
C11	3 3/4	0.8676	77669	0.75273	0.75235	0.982659
		0.8679	77665	0.75325		
		0.8677	77593	0.75290		
		0.8664	76195	0.75065		
		0.8673	77182	0.75221		
C12	4 1/2	0.8685	77399	0.75429	0.75471	0.985743
		0.8691	77135	0.75533		
		0.8690	77016	0.75516		
		0.8691	77071	0.75533		
		0.8680	77204	0.75342		
C13	4 3/4	0.8677	73217	0.75290	0.75297	0.983475
		0.8672	73985	0.75204		
		0.8684	73416	0.75412		
		0.8676	73524	0.75273		
		0.8678	73819	0.75308		
C15	5	0.8687	72907	0.75464	0.75447	0.985426
		0.8676	73408	0.75273		
		0.8680	73131	0.75342		
		0.8695	73073	0.75603		
		0.8692	73124	0.75551		
L11	3	0.8759	74591	0.76720	0.76342	0.997124
		0.8747	73877	0.76510		
		0.8730	75185	0.76213		
		0.8722	75196	0.76073		
		0.8729	75070	0.76195		
L12	5	0.8694	79201	0.75586	0.75655	0.988150
		0.8698	78581	0.75655		
		0.8692	78361	0.75551		
		0.8705	78599	0.75777		
		0.8701	77060	0.75707		
N14	3 3/4	0.8719	76944	0.76021	0.7634	0.997071
		0.8750	75315	0.76563		
		0.8743	75629	0.76440		
		0.8721	76670	0.76056		
		0.8733	76494	0.76265		
		0.8757	77060	0.76685		
N15	4	0.8735	73628	0.76300	0.7630	0.996532
		0.8711	71620	0.75882		
		0.8726	74601	0.76143		
		0.8750	73610	0.76563		
		0.8752	72413	0.76598		
T13	4	0.8740	77914	0.76388	0.7660	1.000504
		0.8762	76620	0.76773		
		0.8758	78927	0.76703		
		0.8756	77777	0.76668		
		0.8745	77907	0.76475		
T14	4 1/4	0.8745	75611	0.76475	0.7626	0.996028
		0.8737	74252	0.76335		
		0.8728	76364	0.76178		
		0.8717	75420	0.75986		
		0.8736	75730	0.76318		
					Average	0.991271
					Standard Deviation	0.0067731

STEP 2b: Determine the Bias Coefficient and Coefficient of Variation for the Material Strength

As previously defined in equation (2-40), the bias coefficient for the material strength, ρ_M, is the ratio of the average appropriate material property (F_u) to the nominal value given in the AISC manual (2005).

$$\rho_M = \frac{\text{Actual } F_u}{\text{Nominal } F_u} = \frac{F_{u,\,exp}}{F_{u,\,nominal}} \tag{2-40}$$

The nominal ultimate stress, $F_{u,\,nominal}$, equals 150 ksi for A490 bolts.

The ultimate strength, $F_{u,\,exp}$, is determined by

$$F_{u,\,exp} = \frac{P_{exp}}{A'_{eff}} \tag{2-41}$$

where P_{exp} is the experimental load at which the bolt failed in tension, as given in Column 4 of Table B-5. The effective area based on the measured bolt diameters, A'_{eff}, was given by equation (2-42) and is repeated here

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

There are 9 threads per inch, n, for a 7/8-inch bolt. The average diameter per bolt tested, d_{avg}, is given in Column 3 of Table B-5. The effective area using the measured bolt diameters, A'_{eff}, for each bolt tested is shown in Column 5.

Then, from equation (2-41), the ultimate strength, $F_{u,\,exp}$, is determined (Column 4 divided by Column 5). This gives the ultimate strength in pounds per square inch (psi), so dividing that by one thousand gives the ultimate strength in kips per square inch (ksi), which is shown in Column 6 of Table B-5.

Now that the ultimate strength, $F_{u,\,exp}$, and the nominal ultimate stress, $F_{u,\ nominal}$, are known, the bias coefficient for the material strength, ρ_M, can be calculated for each lot.

$$\rho_M = \frac{\text{average}\left(F_{u,\,exp}\right)}{F_{u,\,nominal}} = \frac{\text{average}\left(F_{u,\,exp}\right)}{150} \tag{B-13}$$

The bias coefficient for the material strength of each lot is shown in Column 7 in Table B-5. The bias coefficient for the material strength is the average of these values which equals 1.104213.

The average and standard deviation of the bias coefficient for the material strength are shown in Table B-5. From the average and standard deviation of the bias coefficient, the coefficient of variation of the material strength can be determined.

$$V_M = \frac{\text{standard deviation}\left(\rho_M\right)}{\text{average}\left(\rho_M\right)} = \frac{0.029680}{1.104213} = 0.026879 \tag{B-14}$$

Table B-5: Tension – Method 2A – Calculation of ρ_M

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	**Effective Area A'_{eff} (in^2)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Bias Coefficient for Material Strength ρ_M**
C11	3 3/4	0.8676	77669	0.45286	171.51	1.138016
		0.8679	77665	0.45322	171.36	
		0.8677	77593	0.45298	171.29	
		0.8664	76195	0.45143	168.78	
		0.8673	77182	0.45251	170.57	
C12	4 1/2	0.8685	77399	0.45394	170.51	1.132555
		0.8691	77135	0.45465	169.66	
		0.8690	77016	0.45454	169.44	
		0.8691	77071	0.45465	169.52	
		0.8680	77204	0.45334	170.30	
C13	4 3/4	0.8677	73217	0.45298	161.63	1.082964
		0.8672	73985	0.45239	163.54	
		0.8684	73416	0.45382	161.77	
		0.8676	73524	0.45286	162.35	
		0.8678	73819	0.45310	162.92	
C15	5	0.8687	72907	0.45418	160.53	1.073712
		0.8676	73408	0.45286	162.10	
		0.8680	73131	0.45334	161.32	
		0.8695	73073	0.45513	160.55	
		0.8692	73124	0.45477	160.79	
L11	3	0.8759	74591	0.46282	161.17	1.083341
		0.8747	73877	0.46137	160.12	
		0.8730	75185	0.45933	163.68	
		0.8722	75196	0.45837	164.05	
		0.8729	75070	0.45921	163.48	
L12	5	0.8694	79201	0.45501	174.06	1.146904
		0.8698	78581	0.45549	172.52	
		0.8692	78361	0.45477	172.31	
		0.8705	78599	0.45633	172.24	
		0.8701	77060	0.45585	169.05	
N14	3 3/4	0.8719	76944	0.45801	168.00	1.106120
		0.8750	75315	0.46173	163.11	
		0.8743	75629	0.46089	164.09	
		0.8721	76670	0.45825	167.31	
		0.8733	76494	0.45969	166.40	
		0.8757	77060	0.46258	166.59	
N15	4	0.8735	73628	0.45993	160.09	1.060718
		0.8711	71620	0.45705	156.70	
		0.8726	74601	0.45885	162.58	
		0.8750	73610	0.46173	159.42	
		0.8752	72413	0.46197	156.75	
T13	4	0.8740	77914	0.46053	169.18	1.123087
		0.8762	76620	0.46318	165.42	
		0.8758	78927	0.46270	170.58	
		0.8756	77777	0.46246	168.18	
		0.8745	77907	0.46113	168.95	
T14	4 1/4	0.8745	75611	0.46113	163.97	1.094713
		0.8737	74252	0.46017	161.36	
		0.8728	76364	0.45909	166.34	
		0.8717	75420	0.45777	164.76	
		0.8736	75730	0.46005	164.61	
					Average	1.104213
					Standard Deviation	0.029680

STEP 2c: Determine the Bias Coefficient and Coefficient of Variation for the Professional Factor

The bias coefficient for the professional factor, ρ_P, is the ratio of the average tested strength, determined experimentally, to the predicted strength, as calculated by a design equation using measured dimensions and material properties, as given in equation (2-43), which is repeated here.

$$\rho_P = \frac{\text{Actual Strength}}{\text{Predicted Strength}} = \frac{\text{Average}\left(P_{exp}\right)}{R_n \ \text{ based on measured values}} \tag{2-43}$$

Model A is based on the approximation that, for commonly used bolt sizes, the effective tensile area is approximately equal to seventy-five percent of the nominal area of the shank. In this case,

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.75A_b^{'}F_{u,exp}} \tag{2-44}$$

where

$$A_b^{'} = \frac{\pi}{4}\left(d_{avg}\right)^2 \tag{2-45}$$

The parameters used to compute the predicted strength in equations (2-44) and (2-45) are measured values. The average of the measured diameters, d_{avg}, is given in Column 3 of Table B-6 for each bolt tested. The value for $F_{u,exp}$ was calculated from equations (2-41) and (2-42) for the bias coefficient for the material strength, and is recalculated and shown in Column 5 of Table B-6. The area of the shank, based on equation (2-45), is calculated using the measured diameters from Column 3 and is shown in Column 6 of Table B-6. Column 7 of Table B-6 is the denominator of equation (2-44), the predicted strength based on the measured values, which is 0.75 times Column 6 times Column 5. Column 8 is the average experimental load, the numerator of equation (2-44). In other words, Column 8 is the average tensile failure load (i.e. average of Column 4) from the bolts tested per lot. Lastly, Column 9 of Table B-6 is the bias coefficient for the professional factor, which is Column 8 divided by the average of Column 7 for each lot. The average of these values is the bias coefficient for the professional factor which equals 1.022546.

The average and standard deviation of the bias coefficient for the professional factor are shown in Table B-6. From the average and standard deviation of the bias coefficient the coefficient of variation of the professional factor can be determined.

$$V_P = \frac{\text{standard deviation}(\rho_P)}{\text{average}(\rho_P)} = \frac{0.00099077}{1.022546} = 0.00096892 \qquad \text{(B-15)}$$

Table B-6: Tension – Method 2A – Calculation of ρ_P

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)	(Column 8)	(Column 9)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Shank Area (in^2)**	**Predicted Strength (kips)**	**Average Experimental Load (kips)**	**Bias Coefficient for Professional Factor ρ_P**
C11	3 3/4	0.8676	77669	171.51	0.5912	76.0450	77.2608	1.021284
		0.8679	77665	171.36	0.5916	76.0335		
		0.8677	77593	171.29	0.5913	75.9681		
		0.8664	76195	168.78	0.5896	74.6312		
		0.8673	77182	170.57	0.5908	75.5756		
C12	4 1/2	0.8685	77399	170.51	0.5924	75.7582	77.1650	1.021738
		0.8691	77135	169.66	0.5932	75.4850		
		0.8690	77016	169.44	0.5931	75.3710		
		0.8691	77071	169.52	0.5932	75.4223		
		0.8680	77204	170.30	0.5917	75.5797		
C13	4 3/4	0.8677	73217	161.63	0.5913	71.6837	73.5922	1.021403
		0.8672	73985	163.54	0.5906	72.4475		
		0.8684	73416	161.77	0.5923	71.8620		
		0.8676	73524	162.35	0.5912	71.9866		
		0.8678	73819	162.92	0.5915	72.2707		
C15	5	0.8687	72907	160.53	0.5927	71.3568	73.1286	1.021691
		0.8676	73408	162.10	0.5912	71.8731		
		0.8680	73131	161.32	0.5917	71.5924		
		0.8695	73073	160.55	0.5938	71.5005		
		0.8692	73124	160.79	0.5934	71.5574		
L11	3	0.8759	74591	161.17	0.6026	72.8344	74.7838	1.023401
		0.8747	73877	160.12	0.6009	72.1651		
		0.8730	75185	163.68	0.5986	73.4832		
		0.8722	75196	164.05	0.5975	73.5131		
		0.8729	75070	163.48	0.5984	73.3732		
L12	5	0.8694	79201	174.06	0.5936	77.4992	78.3604	1.022092
		0.8698	78581	172.52	0.5942	76.8824		
		0.8692	78361	172.31	0.5934	76.6822		
		0.8705	78599	172.24	0.5952	76.8825		
		0.8701	77060	169.05	0.5946	75.3869		
N14	3 3/4	0.8719	76944	168.00	0.5971	75.2293	76.3520	1.023394
		0.8750	75315	163.11	0.6013	73.5627		
		0.8743	75629	164.09	0.6004	73.8861		
		0.8721	76670	167.31	0.5973	74.9565		
		0.8733	76494	166.40	0.5990	74.7553		
		0.8757	77060	166.59	0.6023	75.2501		
N15	4	0.8735	73628	160.09	0.5993	71.9498	73.1744	1.023318
		0.8711	71620	156.70	0.5960	70.0422		
		0.8726	74601	162.58	0.5980	72.9219		
		0.8750	73610	159.42	0.6013	71.8974		
		0.8752	72413	156.75	0.6016	70.7236		
T13	4	0.8740	77914	169.18	0.5999	76.1258	77.8290	1.023892
		0.8762	76620	165.42	0.6030	74.8084		
		0.8758	78927	170.58	0.6024	77.0708		
		0.8756	77777	168.18	0.6021	75.9527		
		0.8745	77907	168.95	0.6006	76.1067		
T14	4 1/4	0.8745	75611	163.97	0.6006	73.8637	75.4754	1.023244
		0.8737	74252	161.36	0.5995	72.5549		
		0.8728	76364	166.34	0.5983	74.6404		
		0.8717	75420	164.76	0.5968	73.7441		
		0.8736	75730	164.61	0.5994	74.0015		
							Average	1.022546
							Standard Deviation	0.00099077

Now that the bias coefficients for the cross-sectional geometry, ρ_G, material strength, ρ_M, and professional factor, ρ_P, are known, the bias coefficient, ρ_R, for the resistance can be calculated.

$$\rho_R = \rho_G \, \rho_M \, \rho_P = 0.991271 \times 1.104213 \times 1.022546 = 1.11925 \tag{B-16}$$

The coefficient of variation associated with ρ_R, V_R, can also be calculated now.

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \tag{2-38}$$

$$V_R = \sqrt{(0.0068327)^2 + (0.026879)^2 + (0.00096892)^2} = 0.027751 \tag{B-17}$$

STEP 3: Calculate the Resistance Factor

Everything is now known, so the resistance factor for 7/8-inch A490 bolts in tension, based on Method 2A, can be calculated.

$$\phi = \Phi_{\beta} \rho_R \; e^{-\alpha_R \beta V_R} \tag{2-9}$$

$$\phi = 0.8991(1.11925)\; e^{-0.55(4.0)0.027751} = 0.947 \tag{B-18}$$

B.1.4 Method 2B

The equation to calculate resistance factors for Method 2 was given by equation (2-9), which is repeated here for convenience.

$$\phi = \Phi_{\beta} \rho_R \; e^{-\alpha_R \beta V_R} \tag{2-9}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_β, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_\beta = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_\beta = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-19}$$

STEP 2: Determine the Bias Coefficient and Coefficient of Variation

The bias coefficient, ρ_R, is the average value of the ratio of the measured resistance to the nominal resistance. The bias coefficient for the resistance was given by equation (2-37), which is repeated here for convenience.

$$\rho_R = \rho_G \, \rho_M \, \rho_P \tag{2-37}$$

where ρ_G, ρ_M, and ρ_P are the bias coefficients for the cross-sectional geometry, material strength, and professional factor, respectively.

The coefficient of variation associated with ρ_R, V_R, was given in equation (2-38) and is rewritten here.

$$V_R = \sqrt{(V_G)^2 + (V_M)^2 + (V_P)^2} \tag{2-38}$$

where V_G, V_M, and V_P are the coefficients of variation of the cross-sectional geometry, material strength, and professional factor, respectively. Each coefficient of variation is given by the respective standard deviation divided by the corresponding average.

STEP 2a: Determine the Bias Coefficient and Coefficient of Variation for the Cross-Sectional Geometry

The bias coefficient for the cross-sectional geometry, ρ_G, is the ratio of the average applicable geometric property to the nominal value. The value of the bias coefficient for the cross-sectional geometry was given by equation (2-39) and is restated here, using the appropriate nominal diameter for this example.

$$\rho_G = \frac{\text{Actual Area}}{\text{Nominal Area}} = \frac{\text{Average}\left(\frac{\pi\left(d_{avg}\right)^2}{4}\right)}{\left(\frac{\pi\left(d_{nominal}\right)^2}{4}\right)} = \frac{\text{Average}\left(\left(d_{avg}\right)^2\right)}{\left(d_{nominal}\right)^2} = \frac{\text{Avg}\left(\left(d_{avg}\right)^2\right)}{\left(7/8\text{"}\right)^2} \qquad \text{(B-20)}$$

Column 3 in Table B-7 is the average shank diameter, d_{avg}. The square of the average shank diameter is shown in Column 5. For each lot of bolts, the numerator of equation (B-20) is shown in Column 6 of Table B-7. Column 7 of Table B-7 shows the bias coefficient for the cross-sectional geometry, ρ_G, for each lot of bolts. The average of these values is the bias coefficient for the cross-sectional geometry, which equals 0.991271.

The average and standard deviation of the bias coefficient for the cross-sectional geometry are shown in Table B-7. From the average and standard deviation of the bias coefficient, the coefficient of variation of the cross-sectional geometry can be determined.

$$V_G = \frac{\text{standard deviation}\left(\rho_G\right)}{\text{average}\left(\rho_G\right)} = \frac{0.0067731}{0.991271} = 0.0068327 \qquad \text{(B-21)}$$

Table B-7: Tension – Method 2B – Calculation of ρ_G

(Column 1) Bolt Identification	(Column 2) Length (inches)	(Column 3) Average Shank Diameter (inches)	(Column 4) Tension Failure Load (pounds)	(Column 5) Squared Average Shank Diameter (in^2)	(Column 6) Average of the Squared Average Shank Diameter (in^2)	(Column 7) Bias Coefficient for Cross-Sectional Geometry ρ_G
C11	3 3/4	0.8676	77669	0.75273	0.75235	0.982659
		0.8679	77665	0.75325		
		0.8677	77593	0.75290		
		0.8664	76195	0.75065		
		0.8673	77182	0.75221		
C12	4 1/2	0.8685	77399	0.75429	0.75471	0.985743
		0.8691	77135	0.75533		
		0.8690	77016	0.75516		
		0.8691	77071	0.75533		
		0.8680	77204	0.75342		
C13	4 3/4	0.8677	73217	0.75290	0.75297	0.983475
		0.8672	73985	0.75204		
		0.8684	73416	0.75412		
		0.8676	73524	0.75273		
		0.8678	73819	0.75308		
C15	5	0.8687	72907	0.75464	0.75447	0.985426
		0.8676	73408	0.75273		
		0.8680	73131	0.75342		
		0.8695	73073	0.75603		
		0.8692	73124	0.75551		
L11	3	0.8759	74591	0.76720	0.76342	0.997124
		0.8747	73877	0.76510		
		0.8730	75185	0.76213		
		0.8722	75196	0.76073		
		0.8729	75070	0.76195		
L12	5	0.8694	79201	0.75586	0.75655	0.988150
		0.8698	78581	0.75655		
		0.8692	78361	0.75551		
		0.8705	78599	0.75777		
		0.8701	77060	0.75707		
N14	3 3/4	0.8719	76944	0.76021	0.7634	0.997071
		0.8750	75315	0.76563		
		0.8743	75629	0.76440		
		0.8721	76670	0.76056		
		0.8733	76494	0.76265		
		0.8757	77060	0.76685		
N15	4	0.8735	73628	0.76300	0.7630	0.996532
		0.8711	71620	0.75882		
		0.8726	74601	0.76143		
		0.8750	73610	0.76563		
		0.8752	72413	0.76598		
T13	4	0.8740	77914	0.76388	0.7660	1.000504
		0.8762	76620	0.76773		
		0.8758	78927	0.76703		
		0.8756	77777	0.76668		
		0.8745	77907	0.76475		
T14	4 1/4	0.8745	75611	0.76475	0.7626	0.996028
		0.8737	74252	0.76335		
		0.8728	76364	0.76178		
		0.8717	75420	0.75986		
		0.8736	75730	0.76318		
					Average	0.991271
					Standard Deviation	0.0067731

STEP 2b: Determine the Bias Coefficient and Coefficient of Variation for the Material Strength

As previously defined in equation (2-40), the bias coefficient for the material strength, ρ_M, is the ratio of the average appropriate material property (F_u) to the nominal value given in the AISC manual (2005).

$$\rho_M = \frac{\text{Actual } F_u}{\text{Nominal } F_u} = \frac{F_{u,\,exp}}{F_{u,\,nominal}} \tag{2-40}$$

The nominal ultimate stress, $F_{u,\,nominal}$, equals 150 ksi for A490 bolts.

The ultimate strength, $F_{u,\,exp}$, is determined by

$$F_{u,\,exp} = \frac{P_{exp}}{A'_{eff}} \tag{2-41}$$

where P_{exp} is the experimental load at which the bolt failed in tension, as given in Column 4 of Table B-8. The effective area based on the measured diameters, A'_{eff}, was given by equation (2-42) and is repeated here

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

There are 9 threads per inch, n, for a 7/8-inch bolt. The average diameter per bolt tested, d_{avg}, is given in Column 3 of Table B-8. The effective area using the measured diameters, A'_{eff}, for each bolt tested is shown in Column 5.

Then, from equation (2-41), the ultimate strength, $F_{u,\,exp}$, is determined (Column 4 divided by Column 5). This gives the ultimate strength in pounds per square inch (psi), so dividing that by one thousand gives the ultimate strength in kips per square inch (ksi), which is shown in Column 6 of Table B-8.

Now that the ultimate strength, $F_{u,\,exp}$, and the nominal ultimate stress, $F_{u,\ nominal}$, are known, the bias coefficient for the material strength, ρ_M, can be calculated for each lot.

$$\rho_M = \frac{\text{average}\left(F_{u,\,exp}\right)}{F_{u,\,nominal}} = \frac{\text{average}\left(F_{u,\,exp}\right)}{150} \tag{B-22}$$

The bias coefficient for the material strength of each lot is shown in Column 7 in Table B-8. The bias coefficient for the material strength is the average of these values which equals 1.104213.

The average and standard deviation of the bias coefficient for the material strength are shown in Table B-8. From the average and standard deviation of the bias coefficient, the coefficient of variation of the material strength can be determined.

$$V_M = \frac{\text{standard deviation}\left(\rho_M\right)}{\text{average}\left(\rho_M\right)} = \frac{0.029680}{1.104213} = 0.026879 \tag{B-23}$$

Table B-8: Tension – Method 2B – Calculation of ρ_M

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	**Effective Area A'_{eff} (in^2)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Bias Coefficient for Material Strength ρ_M**
C11	3 3/4	0.8676	77669	0.45286	171.51	1.138016
		0.8679	77665	0.45322	171.36	
		0.8677	77593	0.45298	171.29	
		0.8664	76195	0.45143	168.78	
		0.8673	77182	0.45251	170.57	
C12	4 1/2	0.8685	77399	0.45394	170.51	1.132555
		0.8691	77135	0.45465	169.66	
		0.8690	77016	0.45454	169.44	
		0.8691	77071	0.45465	169.52	
		0.8680	77204	0.45334	170.30	
C13	4 3/4	0.8677	73217	0.45298	161.63	1.082964
		0.8672	73985	0.45239	163.54	
		0.8684	73416	0.45382	161.77	
		0.8676	73524	0.45286	162.35	
		0.8678	73819	0.45310	162.92	
C15	5	0.8687	72907	0.45418	160.53	1.073712
		0.8676	73408	0.45286	162.10	
		0.8680	73131	0.45334	161.32	
		0.8695	73073	0.45513	160.55	
		0.8692	73124	0.45477	160.79	
L11	3	0.8759	74591	0.46282	161.17	1.083341
		0.8747	73877	0.46137	160.12	
		0.8730	75185	0.45933	163.68	
		0.8722	75196	0.45837	164.05	
		0.8729	75070	0.45921	163.48	
L12	5	0.8694	79201	0.45501	174.06	1.146904
		0.8698	78581	0.45549	172.52	
		0.8692	78361	0.45477	172.31	
		0.8705	78599	0.45633	172.24	
		0.8701	77060	0.45585	169.05	
N14	3 3/4	0.8719	76944	0.45801	168.00	1.106120
		0.8750	75315	0.46173	163.11	
		0.8743	75629	0.46089	164.09	
		0.8721	76670	0.45825	167.31	
		0.8733	76494	0.45969	166.40	
		0.8757	77060	0.46258	166.59	
N15	4	0.8735	73628	0.45993	160.09	1.060718
		0.8711	71620	0.45705	156.70	
		0.8726	74601	0.45885	162.58	
		0.8750	73610	0.46173	159.42	
		0.8752	72413	0.46197	156.75	
T13	4	0.8740	77914	0.46053	169.18	1.123087
		0.8762	76620	0.46318	165.42	
		0.8758	78927	0.46270	170.58	
		0.8756	77777	0.46246	168.18	
		0.8745	77907	0.46113	168.95	
T14	4 1/4	0.8745	75611	0.46113	163.97	1.094713
		0.8737	74252	0.46017	161.36	
		0.8728	76364	0.45909	166.34	
		0.8717	75420	0.45777	164.76	
		0.8736	75730	0.46005	164.61	
					Average	1.104213
					Standard Deviation	0.029680

STEP 2c: Determine the Bias Coefficient and Coefficient of Variation for the Professional Factor

The bias coefficient for the professional factor, ρ_P, is the ratio of the average tested strength, determined experimentally, to the predicted strength, as calculated by a design equation using measured dimensions and material properties, as given in equation (2-43) which is repeated here.

$$\rho_P = \frac{\text{Actual Strength}}{\text{Predicted Strength}} = \frac{\text{Average}\left(P_{exp}\right)}{R_n \text{ based on measured values}} \tag{2-43}$$

Model B is based on the effective area as given by equation (2-46), which is

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{A'_{eff}\,F_{u,exp}} \tag{2-46}$$

where

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

The parameters used to compute the predicted strength, the denominator of equation (2-46), are measured values. The average of the measured diameters, d_{avg}, is given in Column 3 of Table B-9 for each bolt tested. The value for $F_{u,exp}$ was calculated from equations (2-41) and (2-42) for the bias coefficient for the material strength, and is recalculated and shown in Column 5 of Table B-9. The effective area of the shank, based on equation (2-42), is calculated using the measured diameters from Column 3 with n equals 9 threads per inch. The effective area using measured diameters per tested bolt is shown in Column 6 of Table B-9. Column 7 of Table B-9 is the denominator of equation

(2-46), the predicted strength based on the measured values, which is Column 6 times Column 5. Column 8 is the average experimental load, the numerator of equation (2-46). In other words, Column 8 is the average tensile failure load (i.e. average of Column 4) from the bolts tested per lot. Lastly, Column 9 of Table B-9 is the bias coefficient for the professional factor, which is Column 8 divided by the average of Column 7 for each lot. The average of these values is the bias coefficient for the professional factor which equals 1.0000.

The average and standard deviation of the bias coefficient for the professional factor are shown in Table B-9. From the average and standard deviation of the bias coefficient the coefficient of variation of the professional factor can be determined.

$$V_P = \frac{\text{standard deviation}(\rho_P)}{\text{average}(\rho_P)} = \frac{0.00000}{1.0000} = 0.00000 \tag{B-24}$$

Table B-9: Tension – Method 2B – Calculation of ρ_P

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)	(Column 8)	(Column 9)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tension Failure Load (pounds)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Effective Area (in^2)**	**Predicted Strength (kips)**	**Average Experimental Load (kips)**	**Bias Coefficient for Professional Factor ρ_P**
C11	3 3/4	0.8676	77669	171.51	0.4529	77.6690	77.2608	1.00000
		0.8679	77665	171.36	0.4532	77.6650		
		0.8677	77593	171.29	0.4530	77.5930		
		0.8664	76195	168.78	0.4514	76.1950		
		0.8673	77182	170.57	0.4525	77.1820		
C12	4 1/2	0.8685	77399	170.51	0.4539	77.3990	77.1650	1.00000
		0.8691	77135	169.66	0.4547	77.1350		
		0.8690	77016	169.44	0.4545	77.0160		
		0.8691	77071	169.52	0.4547	77.0710		
		0.8680	77204	170.30	0.4533	77.2040		
C13	4 3/4	0.8677	73217	161.63	0.4530	73.2170	73.5922	1.00000
		0.8672	73985	163.54	0.4524	73.9850		
		0.8684	73416	161.77	0.4538	73.4160		
		0.8676	73524	162.35	0.4529	73.5240		
		0.8678	73819	162.92	0.4531	73.8190		
C15	5	0.8687	72907	160.53	0.4542	72.9070	73.1286	1.00000
		0.8676	73408	162.10	0.4529	73.4080		
		0.8680	73131	161.32	0.4533	73.1310		
		0.8695	73073	160.55	0.4551	73.0730		
		0.8692	73124	160.79	0.4548	73.1240		
L11	3	0.8759	74591	161.17	0.4628	74.5910	74.7838	1.00000
		0.8747	73877	160.12	0.4614	73.8770		
		0.8730	75185	163.68	0.4593	75.1850		
		0.8722	75196	164.05	0.4584	75.1960		
		0.8729	75070	163.48	0.4592	75.0700		
L12	5	0.8694	79201	174.06	0.4550	79.2010	78.3604	1.00000
		0.8698	78581	172.52	0.4555	78.5810		
		0.8692	78361	172.31	0.4548	78.3610		
		0.8705	78599	172.24	0.4563	78.5990		
		0.8701	77060	169.05	0.4559	77.0600		
N14	3 3/4	0.8719	76944	168.00	0.4580	76.9440	76.3520	1.00000
		0.8750	75315	163.11	0.4617	75.3150		
		0.8743	75629	164.09	0.4609	75.6290		
		0.8721	76670	167.31	0.4582	76.6700		
		0.8733	76494	166.40	0.4597	76.4940		
		0.8757	77060	166.59	0.4626	77.0600		
N15	4	0.8735	73628	160.09	0.4599	73.6280	73.1744	1.00000
		0.8711	71620	156.70	0.4570	71.6200		
		0.8726	74601	162.58	0.4588	74.6010		
		0.8750	73610	159.42	0.4617	73.6100		
		0.8752	72413	156.75	0.4620	72.4130		
T13	4	0.8740	77914	169.18	0.4605	77.9140	77.8290	1.00000
		0.8762	76620	165.42	0.4632	76.6200		
		0.8758	78927	170.58	0.4627	78.9270		
		0.8756	77777	168.18	0.4625	77.7770		
		0.8745	77907	168.95	0.4611	77.9070		
T14	4 1/4	0.8745	75611	163.97	0.4611	75.6110	75.4754	1.00000
		0.8737	74252	161.36	0.4602	74.2520		
		0.8728	76364	166.34	0.4591	76.3640		
		0.8717	75420	164.76	0.4578	75.4200		
		0.8736	75730	164.61	0.4600	75.7300		
							Average	1.00000
							Standard Deviation	0.00000

Now that the bias coefficients for the cross-sectional geometry, ρ_G, material strength, ρ_M, and professional factor, ρ_P, are known, the bias coefficient, ρ_R, for the resistance can be calculated.

$$\rho_R = \rho_G \, \rho_M \, \rho_P = 0.991271 \times 1.104213 \times 1.000 = 1.094574 \qquad \text{(B-25)}$$

The coefficient of variation associated with ρ_R, V_R, can also be calculated now.

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \qquad \text{(2-38)}$$

$$V_R = \sqrt{(0.0068327)^2 + (0.026879)^2 + (0.00000)^2} = 0.027734 \qquad \text{(B-26)}$$

STEP 3: Calculate the Resistance Factor

Everything is now known, so the resistance factor for 7/8-inch A490 bolts in tension, based on Method 2B, can be calculated.

$$\phi = \Phi_{\beta} \, \rho_R \; e^{-\alpha_R \beta V_R} \qquad \text{(2-9)}$$

$$\phi = 0.8991(1.094574) \; e^{-0.55(4.0)0.027734} = 0.926 \qquad \text{(B-27)}$$

B.2 Level V – Shear Resistance Factor – 7/8-inch A490 Bolts

This section calculations the shear resistance factor for 7/8-inch A490 bolts, with the threads excluded (Section B.2.1) and not excluded (Section B.2.2) from the shear plane, based on the two methods.

B.2.1 Shear Resistance Factor – Threads Excluded

The average of the bolt diameters and the failure loads in shear with the threads excluded from the shear plane for the ten lots of 7/8-inch A490 bolts are summarized in Table B-10.

Table B-10: Raw Shear Excluded Data for 7/8-inch A490 Bolts

Bolt Identification	Length (inches)	Average Shank Diameter (inches)	Shear X Failure Load (pounds)
C11	3 3/4	0.8673	60396
		0.8670	61809
		0.8674	58983
		0.8678	60677
		0.8714	58536
C12	4 1/2	0.8672	59596
		0.8686	59700
		0.8692	59113
		0.8685	59524
		0.8690	59920
C13	4 3/4	0.8680	57491
		0.8677	58179
		0.8693	58028
		0.8683	57653
		0.8679	57401
C15	5	0.8705	56081
		0.8699	56135
		0.8691	56150
		0.8695	54845
		0.8690	55079
L11	3	0.8706	58496
		0.8709	59001
		0.8712	58824
		0.8710	58875
		0.8713	58558
L12	5	0.8692	62674
		0.8686	63326
		0.8689	61827
		0.8694	62537
		0.8684	62274
N14	3 3/4	0.8704	61207
		0.8703	61142
		0.8704	60428
		0.8699	60807
		0.8703	61888
N15	4	0.8696	56921
		0.8692	56867
		0.8699	57963
		0.8698	62714
		0.8693	58042
T13	4	0.8742	61571
		0.8740	61207
		0.8732	61539
		0.8739	60353
		0.8741	61088
T14	4 1/4	0.8701	59902
		0.8701	59617
		0.8704	60169
		0.8703	58485
		0.8703	59996

B.2.1.1 Method 1A

The equation to calculate resistance factors for Method 1 was given by equation (2-8), which is repeated here for convenience.

$$\phi = \Phi_\beta \frac{R_m}{R_n} \; e^{-\alpha \beta V_R} \tag{2-8}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_β, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_\beta = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_\beta = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-28}$$

STEP 2: Determine the Ratio R_m/R_n

The value of R_m, in kips, is the average value of the failure loads, given in Column 4 of Table B-11, of the five or more bolts tested per lot. This value was calculated for each of the ten lots and is shown in Column 5 of Table B-11.

The nominal resistance, R_n, was given by equation (2-36) as previously described in Section 2.4.1.4. The equation is repeated here for convenience.

$$R_n = 0.62 F_u A_b \tag{2-36}$$

The ultimate stress, F_u, equals 150 ksi for A490 bolts. The area, A_b, is the nominal bolt area or area of the shank. Therefore the nominal resistance for a 7/8-inch A490 bolt is

$$R_n = 0.62\left(150^{ksi}\right)\left[\frac{\pi\left(\frac{7}{8}"\right)^2}{4}\right] = 55.9228^{kips} \tag{B-29}$$

The ratio R_m/R_n for each lot is shown in Column 6 of Table B-11.

The ratio R_m/R_n used in equation (2-8) is the average value for the ten lots which equals 1.063464 from Table B-11.

STEP 3: Determine the Coefficient of Variation

The coefficient of variation equals the standard deviation divided by the average of R_m/R_n.

These two values are shown in Table B-11. The coefficient of variation thus equals

$$V_R = \frac{\text{standard deviation}\left(R_m/R_n\right)}{\text{average}\left(R_m/R_n\right)} = \frac{0.034842}{1.063464} = 0.032763 \tag{B-30}$$

Table B-11: Shear Threads Excluded – Method 1A

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear X Failure Load (pounds)**	**R_m (kips)**	**R_m/R_n**
C11	3 3/4	0.8673	60396	60.0802	1.074342
		0.8670	61809		
		0.8674	58983		
		0.8678	60677		
		0.8714	58536		
C12	4 1/2	0.8672	59596	59.5706	1.065229
		0.8686	59700		
		0.8692	59113		
		0.8685	59524		
		0.8690	59920		
C13	4 3/4	0.8680	57491	57.7504	1.032681
		0.8677	58179		
		0.8693	58028		
		0.8683	57653		
		0.8679	57401		
C15	5	0.8705	56081	55.6580	0.995265
		0.8699	56135		
		0.8691	56150		
		0.8695	54845		
		0.8690	55079		
L11	3	0.8706	58496	58.7508	1.050570
		0.8709	59001		
		0.8712	58824		
		0.8710	58875		
		0.8713	58558		
L12	5	0.8692	62674	62.5276	1.118106
		0.8686	63326		
		0.8689	61827		
		0.8694	62537		
		0.8684	62274		
N14	3 3/4	0.8704	61207	61.0944	1.092477
		0.8703	61142		
		0.8704	60428		
		0.8699	60807		
		0.8703	61888		
N15	4	0.8696	56921	58.5014	1.046110
		0.8692	56867		
		0.8699	57963		
		0.8698	62714		
		0.8693	58042		
T13	4	0.8742	61571	61.1516	1.093500
		0.8740	61207		
		0.8732	61539		
		0.8739	60353		
		0.8741	61088		
T14	4 1/4	0.8701	59902	59.6338	1.066359
		0.8701	59617		
		0.8704	60169		
		0.8703	58485		
		0.8703	59996		
				Average	1.063464
				Standard Deviation	0.034842

STEP 4: Calculate the Resistance Factor

Now that everything is known, the resistance factor for shear with the threads excluded for 7/8-inch A490 bolts, based on Method 1A, can be determined from equation (2-8).

$$\phi = (0.8991)(1.063464)\ e^{-0.55(4.0)(0.032763)} = 0.890 \tag{B-31}$$

B.2.1.2 Method 2A

The equation to calculate resistance factors for Method 2 was given by equation (2-9), which is repeated here for convenience.

$$\phi = \Phi_{\beta}\,\rho_R\ e^{-\alpha_R \beta V_R} \tag{2-9}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_{β}, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_{\beta} = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_{\beta} = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-32}$$

STEP 2: Determine the Bias Coefficient and Coefficient of Variation

The bias coefficient, ρ_R, is the average value of the ratio of the measured resistance to the nominal resistance. The bias coefficient for the resistance was given by equation (2-37), which is repeated here for convenience.

$$\rho_R = \rho_G \, \rho_M \, \rho_P \tag{2-37}$$

where ρ_G, ρ_M, and ρ_P are the bias coefficients for the cross-sectional geometry, material strength, and professional factor, respectively.

The coefficient of variation associated with ρ_R, V_R, was given in equation (2-38) and is rewritten here.

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \tag{2-38}$$

where V_G, V_M, and V_P are the coefficients of variation of the cross-sectional geometry, material strength, and professional factor, respectively. Each coefficient of variation is given by the respective standard deviation divided by the corresponding average.

STEP 2a: Determine the Bias Coefficient and Coefficient of Variation for the Cross-Sectional Geometry

The bias coefficient for the cross-sectional geometry, ρ_G, is the ratio of the average applicable geometric property to the nominal value. The value of the bias coefficient for the cross-sectional geometry was given by equation (2-39) and is restated here, using the appropriate nominal diameter for this example.

$$\rho_G = \frac{\text{Actual Area}}{\text{Nominal Area}} = \frac{\text{Average}\left(\frac{\pi\left(d_{avg}\right)^2}{4}\right)}{\left(\frac{\pi\left(d_{nominal}\right)^2}{4}\right)} = \frac{\text{Average}\left(\left(d_{avg}\right)^2\right)}{\left(d_{nominal}\right)^2} = \frac{\text{Avg}\left(\left(d_{avg}\right)^2\right)}{\left(7\!/\!8\,''\right)^2} \tag{B-33}$$

Column 3 in Table B-12 is the average shank diameter, d_{avg}. The square of the average shank diameter is shown in Column 5. For each lot of bolts, the numerator of equation (B-33) is shown in Column 6 of Table B-12. Column 7 of Table B-12 shows the bias coefficient for the cross-sectional geometry, ρ_G, for each lot of bolts. The average of these values is the bias coefficient for the cross-sectional geometry, which equals 0.988233.

The average and standard deviation of the bias coefficient for the cross-sectional geometry are shown in Table B-12. From the average and standard deviation of the bias coefficient, the coefficient of variation of the cross-sectional geometry can be determined.

$$V_G = \frac{\text{standard deviation}\left(\rho_G\right)}{\text{average}\left(\rho_G\right)} = \frac{0.0038788}{0.988233} = 0.0039250 \tag{B-34}$$

Table B-12: Shear Excluded – Method 2A – Calculation of ρ_G

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear X Failure Load (pounds)**	**Squared Average Shank Diameter (in^2)**	**Average of the Squared Average Shank Diameter (in^2)**	**Bias Coefficient for Cross-Sectional Geometry ρ_G**
C11	3 3/4	0.8673	60396	0.75221	0.75372	0.984453
		0.8670	61809	0.75169		
		0.8674	58983	0.75238		
		0.8678	60677	0.75308		
		0.8714	58536	0.75925		
C12	4 1/2	0.8672	59596	0.75204	0.75429	0.985199
		0.8686	59700	0.75447		
		0.8692	59113	0.75551		
		0.8685	59524	0.75429		
		0.8690	59920	0.75516		
C13	4 3/4	0.8680	57491	0.75342	0.75384	0.984609
		0.8677	58179	0.75290		
		0.8693	58028	0.75568		
		0.8683	57653	0.75394		
		0.8679	57401	0.75325		
C15	5	0.8705	56081	0.75777	0.75620	0.987696
		0.8699	56135	0.75673		
		0.8691	56150	0.75533		
		0.8695	54845	0.75603		
		0.8690	55079	0.75516		
L11	3	0.8706	58496	0.75794	0.75864	0.990878
		0.8709	59001	0.75847		
		0.8712	58824	0.75899		
		0.8710	58875	0.75864		
		0.8713	58558	0.75916		
L12	5	0.8692	62674	0.75551	0.75499	0.986106
		0.8686	63326	0.75447		
		0.8689	61827	0.75499		
		0.8694	62537	0.75586		
		0.8684	62274	0.75412		
N14	3 3/4	0.8704	61207	0.75760	0.75735	0.989195
		0.8703	61142	0.75742		
		0.8704	60428	0.75760		
		0.8699	60807	0.75673		
		0.8703	61888	0.75742		
N15	4	0.8696	56921	0.75620	0.75613	0.987604
		0.8692	56867	0.75551		
		0.8699	57963	0.75673		
		0.8698	62714	0.75655		
		0.8693	58042	0.75568		
T13	4	0.8742	61571	0.76423	0.76367	0.997442
		0.8740	61207	0.76388		
		0.8732	61539	0.76248		
		0.8739	60353	0.76370		
		0.8741	61088	0.76405		
T14	4 1/4	0.8701	59902	0.75707	0.75732	0.989150
		0.8701	59617	0.75707		
		0.8704	60169	0.75760		
		0.8703	58485	0.75742		
		0.8703	59996	0.75742		

Average	0.988233
Standard Deviation	0.0038788

STEP 2b: Determine the Bias Coefficient and Coefficient of Variation for the Material Strength

The bias coefficient for the material strength, ρ_M, is the ratio of the average appropriate material property (F_u) to the nominal value given in the AISC manual (2005).

$$\rho_M = \frac{\text{Actual } F_u}{\text{Nominal } F_u} = \frac{F_{u,\,exp}}{F_{u,\,nominal}} \tag{2-40}$$

The nominal ultimate stress, $F_{u,\ nominal}$, equals 150 ksi for A490 bolts. The bias coefficient for the material strength is calculated based on the tension tests of the lot.

The ultimate strength, $F_{u,\,exp}$, is determined by

$$F_{u,\,exp} = \frac{P_{exp}}{A'_{eff}} \tag{2-41}$$

where P_{exp} is the experimental load at which the bolt failed in tension, as given in Column 4 of Table B-13. The effective area based on the measured bolt diameters, A'_{eff}, was given by equation (2-42) and is repeated here

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

There are 9 threads per inch, n, for a 7/8-inch bolt. The average diameter per bolt tested in tension, d_{avg}, is given in Column 3 of Table B-13. The effective area using the measured bolt diameters, A'_{eff}, for each bolt tested is shown in Column 5.

Then, from equation (2-41), the ultimate strength, $F_{u,\,exp}$, is determined (Column 4 divided by Column 5). This gives the ultimate strength in pounds per square inch (psi), so dividing that by one thousand gives the ultimate strength in kips per square inch (ksi), which is shown in Column 6 of Table B-13.

Now that the ultimate strength, $F_{u,\,exp}$, and the nominal ultimate stress, $F_{u,\ nominal}$, are known, the bias coefficient for the material strength, ρ_M, can be calculated for each lot.

$$\rho_M = \frac{\text{average}\left(F_{u,\,exp}\right)}{F_{u,\,nominal}} = \frac{\text{average}\left(F_{u,\,exp}\right)}{150} \tag{B-35}$$

The bias coefficient for the material strength of each lot is shown in Column 7 in Table B-13. The bias coefficient for the material strength is the average of these values which equals 1.104213.

The average and standard deviation of the bias coefficient for the material strength are shown in Table B-13. From the average and standard deviation of the bias coefficient, the coefficient of variation of the material strength can be determined.

$$V_M = \frac{\text{standard deviation}\left(\rho_M\right)}{\text{average}\left(\rho_M\right)} = \frac{0.029680}{1.104213} = 0.026879 \tag{B-36}$$

Table B-13: Shear Excluded – Method 2A – Calculation of ρ_M

(Column 1) Bolt Identification	(Column 2) Length (inches)	(Column 3) Average Shank Diameter (inches)	(Column 4) Tensile Failure Load (pounds)	(Column 5) Effective Area A'_{eff} (in^2)	(Column 6) Ultimate Strength $F_{u,exp}$ (ksi)	(Column 7) Bias Coefficient for Material Strength ρ_M
C11	3 3/4	0.8676	77669	0.45286	171.51	1.138016
		0.8679	77665	0.45322	171.36	
		0.8677	77593	0.45298	171.29	
		0.8664	76195	0.45143	168.78	
		0.8673	77182	0.45251	170.57	
C12	4 1/2	0.8685	77399	0.45394	170.51	1.132555
		0.8691	77135	0.45465	169.66	
		0.8690	77016	0.45454	169.44	
		0.8691	77071	0.45465	169.52	
		0.8680	77204	0.45334	170.30	
C13	4 3/4	0.8677	73217	0.45298	161.63	1.082964
		0.8672	73985	0.45239	163.54	
		0.8684	73416	0.45382	161.77	
		0.8676	73524	0.45286	162.35	
		0.8678	73819	0.45310	162.92	
C15	5	0.8687	72907	0.45418	160.53	1.073712
		0.8676	73408	0.45286	162.10	
		0.8680	73131	0.45334	161.32	
		0.8695	73073	0.45513	160.55	
		0.8692	73124	0.45477	160.79	
L11	3	0.8759	74591	0.46282	161.17	1.083341
		0.8747	73877	0.46137	160.12	
		0.8730	75185	0.45933	163.68	
		0.8722	75196	0.45837	164.05	
		0.8729	75070	0.45921	163.48	
L12	5	0.8694	79201	0.45501	174.06	1.146904
		0.8698	78581	0.45549	172.52	
		0.8692	78361	0.45477	172.31	
		0.8705	78599	0.45633	172.24	
		0.8701	77060	0.45585	169.05	
N14	3 3/4	0.8719	76944	0.45801	168.00	1.106120
		0.8750	75315	0.46173	163.11	
		0.8743	75629	0.46089	164.09	
		0.8721	76670	0.45825	167.31	
		0.8733	76494	0.45969	166.40	
		0.8757	77060	0.46258	166.59	
N15	4	0.8735	73628	0.45993	160.09	1.060718
		0.8711	71620	0.45705	156.70	
		0.8726	74601	0.45885	162.58	
		0.8750	73610	0.46173	159.42	
		0.8752	72413	0.46197	156.75	
T13	4	0.8740	77914	0.46053	169.18	1.123087
		0.8762	76620	0.46318	165.42	
		0.8758	78927	0.46270	170.58	
		0.8756	77777	0.46246	168.18	
		0.8745	77907	0.46113	168.95	
T14	4 1/4	0.8745	75611	0.46113	163.97	1.094713
		0.8737	74252	0.46017	161.36	
		0.8728	76364	0.45909	166.34	
		0.8717	75420	0.45777	164.76	
		0.8736	75730	0.46005	164.61	
					Average	1.104213
					Standard Deviation	0.029680

STEP 2c: Determine the Bias Coefficient and Coefficient of Variation for the Professional Factor

The bias coefficient for the professional factor, ρ_P, is the ratio of the average tested strength, determined experimentally, to the predicted strength, as calculated by a design equation using measured dimensions and material properties, as given in equation (2-43) which is repeated here.

$$\rho_P = \frac{\text{Actual Strength}}{\text{Predicted Strength}} = \frac{\text{Average}\left(P_{exp}\right)}{R_n \ \text{ based on measured values}} \tag{2-43}$$

For the case where the threads are excluded from the shear plane, the bias coefficient for the professional factor was determined in Section 2.4.1.5.3.1 and was given by Equation (2-48), which is repeated here.

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.62 A_b^{'} F_{u,\,exp}} \tag{2-48}$$

where

$$A_b^{'} = \frac{\pi}{4}\left(d_{avg}\right)^2 \tag{2-45}$$

The parameters used to compute the predicted strength, the denominator of equation (2-48), are measured values. The average of the measured diameters, d_{avg}, is given in Column 3 of Table B-14 for each bolt tested. The value for $F_{u,exp}$ was calculated from equations (2-41) and (2-42) for the bias coefficient for the material strength based on the lot's corresponding tensile tests. Column 5 of Table B-14 equals the average of $F_{u,exp}$ for each bolt tested which is the average of Column 6 of Table B-13. The area of the shank, based on equation (2-45), is calculated using the measured diameters from Column 3 and is shown in Column 6 of Table B-14. Column 7 of Table B-14 is the denominator of equation (2-48), the predicted strength based on the measured values, which is 0.62 times Column 6 times Column 5. Column 8 is the average experimental load, the numerator of equation (2-48). In other words, Column 8 is the average failure load (i.e. average of Column 4) from the bolts tested per lot. Lastly, Column 9 of Table B-14 is the bias coefficient for the professional factor, which is Column 8 divided by the average of Column 7 for each lot. The average of these values is the bias coefficient for the professional factor which equals 0.974590.

The average and standard deviation of the bias coefficient for the professional factor are shown in Table B-14. From the average and standard deviation of the bias coefficient, the coefficient of variation of the professional factor can be determined.

$$V_P = \frac{\text{standard deviation}\left(\rho_P\right)}{\text{average}\left(\rho_P\right)} = \frac{0.019573}{0.974590} = 0.020083 \tag{B-37}$$

Table B-14: Shear Excluded – Method 2A – Calculation of ρ_P

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)	(Column 8)	(Column 9)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear X Failure Load (pounds)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Shank Area (in^2)**	**Predicted Strength (kips)**	**Average Experimental Load (kips)**	**Bias Coefficient for Professional Factor ρ_P**
C11	3 3/4	0.8673	60396	170.70	0.59078	62.53	60.0802	0.958957
		0.8670	61809		0.59038	62.48		
		0.8674	58983		0.59092	62.54		
		0.8678	60677		0.59147	62.60		
		0.8714	58536		0.59631	63.11		
C12	4 1/2	0.8672	59596	169.88	0.59065	62.21	59.5706	0.954684
		0.8686	59700		0.59256	62.41		
		0.8692	59113		0.59338	62.50		
		0.8685	59524		0.59242	62.40		
		0.8690	59920		0.59310	62.47		
C13	4 3/4	0.8680	57491	162.44	0.59174	59.60	57.7504	0.968475
		0.8677	58179		0.59133	59.56		
		0.8693	58028		0.59351	59.78		
		0.8683	57653		0.59215	59.64		
		0.8679	57401		0.59160	59.58		
C15	5	0.8705	56081	161.06	0.59515	59.43	55.6580	0.938486
		0.8699	56135		0.59433	59.35		
		0.8691	56150		0.59324	59.24		
		0.8695	54845		0.59378	59.29		
		0.8690	55079		0.59310	59.22		
L11	3	0.8706	58496	162.50	0.59529	59.98	58.7508	0.978677
		0.8709	59001		0.59570	60.02		
		0.8712	58824		0.59611	60.06		
		0.8710	58875		0.59584	60.03		
		0.8713	58558		0.59625	60.07		
L12	5	0.8692	62674	172.04	0.59338	63.29	62.5276	0.988626
		0.8686	63326		0.59256	63.20		
		0.8689	61827		0.59297	63.25		
		0.8694	62537		0.59365	63.32		
		0.8684	62274		0.59228	63.17		
N14	3 3/4	0.8704	61207	165.92	0.59501	61.21	61.0944	0.998454
		0.8703	61142		0.59488	61.19		
		0.8704	60428		0.59501	61.21		
		0.8699	60807		0.59433	61.14		
		0.8703	61888		0.59488	61.19		
N15	4	0.8696	56921	159.11	0.59392	58.59	58.5014	0.998606
		0.8692	56867		0.59338	58.53		
		0.8699	57963		0.59433	58.63		
		0.8698	62714		0.59419	58.62		
		0.8693	58042		0.59351	58.55		
T13	4	0.8742	61571	168.46	0.60022	62.69	61.1516	0.976153
		0.8740	61207		0.59995	62.66		
		0.8732	61539		0.59885	62.55		
		0.8739	60353		0.59981	62.65		
		0.8741	61088		0.60008	62.68		
T14	4 1/4	0.8701	59902	164.21	0.59460	60.54	59.6338	0.984785
		0.8701	59617		0.59460	60.54		
		0.8704	60169		0.59501	60.58		
		0.8703	58485		0.59488	60.56		
		0.8703	59996		0.59488	60.56		

Average 0.974590

Standard Deviation 0.019573

Now that the bias coefficients for the cross-sectional geometry, ρ_G, material strength, ρ_M, and professional factor, ρ_P, are known, the bias coefficient, ρ_R, for the resistance can be calculated.

$$\rho_R = \rho_G \, \rho_M \, \rho_P = 0.988233 \times 1.104213 \times 0.974590 = 1.06349 \tag{B-38}$$

The coefficient of variation associated with ρ_R, V_R, can also be calculated now.

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \tag{2-38}$$

$$V_R = \sqrt{(0.0039250)^2 + (0.026879)^2 + (0.020083)^2} = 0.033782 \tag{B-39}$$

STEP 3: Calculate the Resistance Factor

Everything is now known, so the resistance factor for 7/8-inch A490 bolts in shear with the threads excluded from the shear plan, based on Method 2A, can be calculated.

$$\phi = \Phi_{\beta} \, \rho_R \; e^{-\alpha_R \beta V_R} \tag{2-9}$$

$$\phi = 0.8991(1.06349) \; e^{-0.55(4.0)0.033782} = 0.888 \tag{B-40}$$

B.2.2 Shear Resistance Factor – Threads Not Excluded

The average of the bolt diameters and the failure loads in shear with the threads not excluded from the shear plane for the ten lots of 7/8-inch A490 bolts are summarized in Table B-15.

Table B-15: Raw Shear Not Excluded Data for 7/8-inch A490 Bolts

Bolt Identification	Length (inches)	Average Shank Diameter (inches)	Shear N Failure Load (pounds)
C11	3 3/4	0.8673	46169
		0.8675	44680
		0.8676	44161
		0.8671	48011
		0.8672	45401
C12	4 1/2	0.8687	44179
		0.8686	45451
		0.8690	44049
		0.8691	44392
		0.8694	44291
C13	4 3/4	0.8686	44165
		0.8692	41984
		0.8678	42070
		0.8678	42002
		0.8683	44103
C15	5	0.8698	42193
		0.8697	42283
		0.8691	41267
		0.8702	43491
		0.8689	42312
L11	3	0.8713	46212
		0.8714	46371
		0.8712	44175
		0.8713	46302
		0.8712	43956
L12	5	0.8691	47275
		0.8689	48425
		0.8698	45235
		0.8689	45268
		0.8689	46987
N14	3 3/4	0.8699	45498
		0.8703	46457
		0.8693	46688
		0.8698	46522
		0.8698	45963
N15	4	0.8697	45307
		0.8707	43692
		0.8705	45343
		0.8706	44193
		0.8711	45105
T13	4	0.8743	46219
		0.8739	47823
		0.8737	46587
		0.8741	47881
		0.8737	47697
T14	4 1/4	0.8700	47578
		0.8699	44943
		0.8696	43181
		0.8696	44312
		0.8687	44377

B.2.2.1 Method 1A

The equation to calculate resistance factors for Method 1 was given by equation (2-8), which is repeated here for convenience.

$$\phi = \Phi_{\beta} \frac{R_m}{R_n} e^{-\alpha \beta V_R} \tag{2-8}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_{β}, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_{\beta} = 0.0093\beta^2 - 0.1658\beta + 1.4135 \tag{2-30}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_{\beta} = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \tag{B-41}$$

STEP 2: Determine the Ratio R_m/R_n

The value of R_m for a lot of bolts, in kips, is the average value of the failure loads, given in Column 4 of Table B-16, of the five or more bolts tested. This value was calculated for each of the ten lots and is shown in Column 5 of Table B-16.

The nominal resistance, R_n, for shear with the threads not excluded from the shear plane, was given by equation (2-35) as previously described in Section 2.4.1.4. The equation is repeated here for convenience.

$$R_n = 0.50 F_u A_b \tag{2-35}$$

The ultimate stress, F_u, equals 150 ksi for A490 bolts. The area, A_b, is the nominal bolt area or area of the shank. Therefore the nominal resistance for a 7/8-inch A490 bolt is

$$R_n = 0.50\left(150^{ksi}\right)\left[\frac{\pi\left(\frac{7}{8}"\right)^2}{4}\right] = 45.099^{kips} \tag{B-42}$$

The ratio R_m / R_n is shown in Column 6 of Table B-16 for each of the ten lots.

The ratio R_m / R_n used in equation (2-8) is the average value for the ten lots which equals 0.998791 from Table B-16.

STEP 3: Determine the Coefficient of Variation

The coefficient of variation equals the standard deviation divided by the average of R_m / R_n. These two values are shown in Table B-16. The coefficient of variation thus equals

$$V_R = \frac{\text{standard deviation}\left(R_m / R_n\right)}{\text{average}\left(R_m / R_n\right)} = \frac{0.034657}{0.998791} = 0.034699 \tag{B-43}$$

Table B-16: Shear – Threads Not Excluded – Method 1A

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear N Failure Load (pounds)**	**R_m (kips)**	**R_m/R_n**
C11	3 3/4	0.8673	46169	45.6844	1.012980
		0.8675	44680		
		0.8676	44161		
		0.8671	48011		
		0.8672	45401		
C12	4 1/2	0.8687	44179	44.4724	0.986105
		0.8686	45451		
		0.8690	44049		
		0.8691	44392		
		0.8694	44291		
C13	4 3/4	0.8686	44165	42.8648	0.950459
		0.8692	41984		
		0.8678	42070		
		0.8678	42002		
		0.8683	44103		
C15	5	0.8698	42193	42.3092	0.938140
		0.8697	42283		
		0.8691	41267		
		0.8702	43491		
		0.8689	42312		
L11	3	0.8713	46212	45.4032	1.006744
		0.8714	46371		
		0.8712	44175		
		0.8713	46302		
		0.8712	43956		
L12	5	0.8691	47275	46.6380	1.034124
		0.8689	48425		
		0.8698	45235		
		0.8689	45268		
		0.8689	46987		
N14	3 3/4	0.8699	45498	46.2256	1.024980
		0.8703	46457		
		0.8693	46688		
		0.8698	46522		
		0.8698	45963		
N15	4	0.8697	45307	44.7280	0.991773
		0.8707	43692		
		0.8705	45343		
		0.8706	44193		
		0.8711	45105		
T13	4	0.8743	46219	47.2414	1.047504
		0.8739	47823		
		0.8737	46587		
		0.8741	47881		
		0.8737	47697		
T14	4 1/4	0.8700	47578	44.8782	0.995103
		0.8699	44943		
		0.8696	43181		
		0.8696	44312		
		0.8687	44377		
				Average	0.998791
				Standard Deviation	0.034657

STEP 4: Calculate the Resistance Factor

Now that everything is known, the resistance factor for shear with the threads not excluded for 7/8-inch A490 bolts, based on Method 1A, can be determined from equation (2-8).

$$\phi = (0.8991)(0.998791)\ e^{-0.55(4.0)(0.034699)} = 0.832 \qquad \text{(B-44)}$$

B.2.2.2 Method 2A

The equation to calculate resistance factors for Method 2 was given by equation (2-9), which is repeated here for convenience.

$$\phi = \Phi_{\beta}\,\rho_R\ e^{-\alpha_R \beta V_R} \qquad \text{(2-9)}$$

The coefficient of separation, α, equals 0.55. The safety (reliability) index, β, is taken as 4.0 for this example, as recommended in the commentary to the AISC Specification (2005).

STEP 1: Determine the Adjustment Factor

The adjustment factor, Φ_{β}, which is based on the reliability index, β, and a live-to-dead load ratio of 3.0, was given by equation (2-30) and is repeated here.

$$\Phi_{\beta} = 0.0093\beta^2 - 0.1658\beta + 1.4135 \qquad \text{(2-30)}$$

From this equation, the adjustment factor can be calculated with a reliability index equal to 4.0.

$$\Phi_{\beta} = 0.0093(4.0)^2 - 0.1658(4.0) + 1.4135 = 0.8991 \qquad \text{(B-45)}$$

STEP 2: Determine the Bias Coefficient and Coefficient of Variation

The bias coefficient, ρ_R, is the average value of the ratio of the measured resistance to the nominal resistance. The bias coefficient for the resistance was given by equation (2-37), which is repeated here for convenience.

$$\rho_R = \rho_G \, \rho_M \, \rho_P \tag{2-37}$$

where ρ_G, ρ_M, and ρ_P are the bias coefficients for the cross-sectional geometry, material strength, and professional factor, respectively.

The coefficient of variation associated with ρ_R, V_R, was given in equation (2-38) and is rewritten here.

$$V_R = \sqrt{\left(V_G\right)^2 + \left(V_M\right)^2 + \left(V_P\right)^2} \tag{2-38}$$

where V_G, V_M, and V_P are the coefficients of variation of the cross-sectional geometry, material strength, and professional factor, respectively. Each coefficient of variation is given by the respective standard deviation divided by the corresponding average.

STEP 2a: Determine the Bias Coefficient and Coefficient of Variation for the Cross-Sectional Geometry

The bias coefficient for the cross-sectional geometry, ρ_G, is the ratio of the average applicable geometric property to the nominal value. The value of the bias coefficient for the cross-sectional geometry was given by equation (2-39) and is restated here, using the appropriate nominal diameter for this example.

$$\rho_G = \frac{\text{Actual Area}}{\text{Nominal Area}} = \frac{\text{Average}\left(\frac{\pi\left(d_{avg}\right)^2}{4}\right)}{\left(\frac{\pi\left(d_{nominal}\right)^2}{4}\right)} = \frac{\text{Average}\left(\left(d_{avg}\right)^2\right)}{\left(d_{nominal}\right)^2} = \frac{\text{Avg}\left(\left(d_{avg}\right)^2\right)}{\left(7/8\text{"}\right)^2} \tag{B-46}$$

Column 3 in Table B-17 is the average shank diameter, d_{avg}. The square of the average shank diameter is shown in Column 5. For each lot of bolts, the numerator of equation (B-46) is shown in Column 6 of Table B-17. Column 7 of Table B-17 shows the bias coefficient for the cross-sectional geometry, ρ_G, for each lot of bolts. The average of these values is the bias coefficient for the cross-sectional geometry, which equals 0.988249.

The average and standard deviation of the bias coefficient for the cross-sectional geometry are shown in Table B-17. From the average and standard deviation of the bias coefficient, the coefficient of variation of the cross-sectional geometry can be determined.

$$V_G = \frac{\text{standard deviation}\left(\rho_G\right)}{\text{average}\left(\rho_G\right)} = \frac{0.0041045}{0.988249} = 0.0041533 \tag{B-47}$$

Table B-17: Shear Not Excluded – Method 2A – Calculation of ρ_G

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear N Failure Load (pounds)**	**Squared Average Shank Diameter (in^2)**	**Average of the Squared Average Shank Diameter (in^2)**	**Bias Coefficient for Cross-Sectional Geometry ρ_G**
C11	3 3/4	0.8673	46169	0.752209	0.752279	0.982568
		0.8675	44680	0.752556		
		0.8676	44161	0.752730		
		0.8671	48011	0.751862		
		0.8672	45401	0.752036		
C12	4 1/2	0.8687	44179	0.754640	0.755092	0.986242
		0.8686	45451	0.754466		
		0.8690	44049	0.755161		
		0.8691	44392	0.755335		
		0.8694	44291	0.755856		
C13	4 3/4	0.8686	44165	0.754466	0.754015	0.984835
		0.8692	41984	0.755509		
		0.8678	42070	0.753077		
		0.8678	42002	0.753077		
		0.8683	44103	0.753945		
C15	5	0.8698	42193	0.756552	0.756100	0.987559
		0.8697	42283	0.756378		
		0.8691	41267	0.755335		
		0.8702	43491	0.757248		
		0.8689	42312	0.754987		
L11	3	0.8713	46212	0.759164	0.759129	0.991515
		0.8714	46371	0.759338		
		0.8712	44175	0.758989		
		0.8713	46302	0.759164		
		0.8712	43956	0.758989		
L12	5	0.8691	47275	0.755335	0.755370	0.986605
		0.8689	48425	0.754987		
		0.8698	45235	0.756552		
		0.8689	45268	0.754987		
		0.8689	46987	0.754987		
N14	3 3/4	0.8699	45498	0.756726	0.756587	0.988195
		0.8703	46457	0.757422		
		0.8693	46688	0.755682		
		0.8698	46522	0.756552		
		0.8698	45963	0.756552		
N15	4	0.8697	45307	0.756378	0.757805	0.989786
		0.8707	43692	0.758118		
		0.8705	45343	0.757770		
		0.8706	44193	0.757944		
		0.8711	45105	0.758815		
T13	4	0.8743	46219	0.764400	0.763771	0.997579
		0.8739	47823	0.763701		
		0.8737	46587	0.763352		
		0.8741	47881	0.764051		
		0.8737	47697	0.763352		
T14	4 1/4	0.8700	47578	0.756900	0.756135	0.987605
		0.8699	44943	0.756726		
		0.8696	43181	0.756204		
		0.8696	44312	0.756204		
		0.8687	44377	0.754640		
					Average	0.988249
					Standard Deviation	0.0041045

STEP 2b: Determine the Bias Coefficient and Coefficient of Variation for the Material Strength

The bias coefficient for the material strength, ρ_M , is the ratio of the average appropriate material property (F_u) to the nominal value given in the AISC manual (2005).

$$\rho_M = \frac{\text{Actual } F_u}{\text{Nominal } F_u} = \frac{F_{u,\,exp}}{F_{u,\,nominal}} \tag{2-40}$$

The nominal ultimate stress, $F_{u,\ nominal}$, equals 150 ksi for A490 bolts. The bias coefficient for the material strength is calculated based on the tension tests of the lot.

The ultimate strength, $F_{u,\,exp}$, is determined by

$$F_{u,\,exp} = \frac{P_{exp}}{A'_{eff}} \tag{2-41}$$

where P_{exp} is the experimental load at which the bolt failed in tension, as given in Column 4 of Table B-18. The effective area based on the measured bolt diameters, A'_{eff} , was given by equation (2-42) and is repeated here

$$A'_{eff} = \frac{\pi}{4}\left(d_{avg} - \frac{0.9743}{n}\right)^2 \tag{2-42}$$

There are 9 threads per inch, n, for a 7/8-inch bolt. The average diameter per bolt tested in tension, d_{avg}, is given in Column 3 of Table B-18. The effective area using the measured bolt diameters, A'_{eff} , for each bolt tested is shown in Column 5.

Then, from equation (2-41), the ultimate strength, $F_{u,\,exp}$, is determined by dividing Column 4 by Column 5. This gives the ultimate strength in pounds per square inch (psi), so dividing that by one thousand gives the ultimate strength in kips per square inch (ksi), which is shown in Column 6 of Table B-18.

Now that the ultimate strength, $F_{u,\,exp}$, and the nominal ultimate stress, $F_{u,\ nominal}$, are known, the bias coefficient for the material strength, ρ_M, can be calculated for each lot.

$$\rho_M = \frac{\text{average}\left(F_{u,\,exp}\right)}{F_{u,\,nominal}} = \frac{\text{average}\left(F_{u,\,exp}\right)}{150} \tag{B-48}$$

The bias coefficient for the material strength of each lot is shown in Column 7 in Table B-18. The bias coefficient for the material strength is the average of these values which equals 1.104213.

The average and standard deviation of the bias coefficient for the material strength are shown in Table B-18. From the average and standard deviation of the bias coefficient, the coefficient of variation of the material strength can be determined.

$$V_M = \frac{\text{standard deviation}\left(\rho_M\right)}{\text{average}\left(\rho_M\right)} = \frac{0.029680}{1.104213} = 0.026879 \tag{B-49}$$

Table B-18: Shear Not Excluded – Method 2A – Calculation of ρ_M

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Tensile Failure Load (pounds)**	**Effective Area A'_{eff} (in^2)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Bias Coefficient for Material Strength ρ_M**
C11	3 3/4	0.8676	77669	0.45286	171.51	1.138016
		0.8679	77665	0.45322	171.36	
		0.8677	77593	0.45298	171.29	
		0.8664	76195	0.45143	168.78	
		0.8673	77182	0.45251	170.57	
C12	4 1/2	0.8685	77399	0.45394	170.51	1.132555
		0.8691	77135	0.45465	169.66	
		0.8690	77016	0.45454	169.44	
		0.8691	77071	0.45465	169.52	
		0.8680	77204	0.45334	170.30	
C13	4 3/4	0.8677	73217	0.45298	161.63	1.082964
		0.8672	73985	0.45239	163.54	
		0.8684	73416	0.45382	161.77	
		0.8676	73524	0.45286	162.35	
		0.8678	73819	0.45310	162.92	
C15	5	0.8687	72907	0.45418	160.53	1.073712
		0.8676	73408	0.45286	162.10	
		0.8680	73131	0.45334	161.32	
		0.8695	73073	0.45513	160.55	
		0.8692	73124	0.45477	160.79	
L11	3	0.8759	74591	0.46282	161.17	1.083341
		0.8747	73877	0.46137	160.12	
		0.8730	75185	0.45933	163.68	
		0.8722	75196	0.45837	164.05	
		0.8729	75070	0.45921	163.48	
L12	5	0.8694	79201	0.45501	174.06	1.146904
		0.8698	78581	0.45549	172.52	
		0.8692	78361	0.45477	172.31	
		0.8705	78599	0.45633	172.24	
		0.8701	77060	0.45585	169.05	
N14	3 3/4	0.8719	76944	0.45801	168.00	1.106120
		0.8750	75315	0.46173	163.11	
		0.8743	75629	0.46089	164.09	
		0.8721	76670	0.45825	167.31	
		0.8733	76494	0.45969	166.40	
		0.8757	77060	0.46258	166.59	
N15	4	0.8735	73628	0.45993	160.09	1.060718
		0.8711	71620	0.45705	156.70	
		0.8726	74601	0.45885	162.58	
		0.8750	73610	0.46173	159.42	
		0.8752	72413	0.46197	156.75	
T13	4	0.8740	77914	0.46053	169.18	1.123087
		0.8762	76620	0.46318	165.42	
		0.8758	78927	0.46270	170.58	
		0.8756	77777	0.46246	168.18	
		0.8745	77907	0.46113	168.95	
T14	4 1/4	0.8745	75611	0.46113	163.97	1.094713
		0.8737	74252	0.46017	161.36	
		0.8728	76364	0.45909	166.34	
		0.8717	75420	0.45777	164.76	
		0.8736	75730	0.46005	164.61	
					Average	1.104213
					Standard Deviation	0.029680

STEP 2c: Determine the Bias Coefficient and Coefficient of Variation for the Professional Factor

The bias coefficient for the professional factor, ρ_P, is the ratio of the average tested strength, determined experimentally, to the predicted strength, as calculated by a design equation using measured dimensions and material properties, as given in equation (2-43) which is repeated here.

$$\rho_P = \frac{\text{Actual Strength}}{\text{Predicted Strength}} = \frac{\text{Average}\left(P_{exp}\right)}{R_n \text{ based on measured values}} \tag{2-43}$$

For the case where the threads are not excluded from the shear plane, the bias coefficient for the professional factor was determined in Section 2.4.1.5.3.1 and was given by Equation (2-47), which is repeated here.

$$\rho_P = \frac{\text{Average}\left(P_{exp}\right)}{0.50 A_b^{'} F_{u,\,exp}} \tag{2-47}$$

where

$$A_b^{'} = \frac{\pi}{4}\left(d_{avg}\right)^2 \tag{2-45}$$

The parameters used to compute the predicted strength, the denominator of equation (2-47), are measured values. The average of the measured diameters, d_{avg}, is given in Column 3 of Table B-19 for each bolt tested. The value for $F_{u,exp}$ was calculated from equations (2-41) and (2-42) for the bias coefficient for the material strength based on the lot's corresponding tensile tests. Column 5 of Table B-19 equals the average of $F_{u,exp}$ for each bolt tested which is the average of Column 6 of Table B-18. The area of the shank, based on equation (2-45), is calculated using the measured diameters from Column 3 and is shown in Column 6 of Table B-19. Column 7 of Table B-19 is the denominator of equation (2-47), the predicted strength based on the measured values, which is 0.50 times Column 6 times Column 5. Column 8 is the average experimental load, the numerator of equation (2-47). In other words, Column 8 is the average failure load (i.e. average of Column 4) from the bolts tested per lot. Lastly, Column 9 of Table B-19 is the bias coefficient for the professional factor, which is Column 8 divided by the average of Column 7 for each lot. The average of these values is the bias coefficient for the professional factor, which equals 0.915356.

The average and standard deviation of the bias coefficient for the professional factor are shown in Table B-19. From the average and standard deviation of the bias coefficient, the coefficient of variation of the professional factor can be determined.

$$V_P = \frac{\text{standard deviation}\left(\rho_P\right)}{\text{average}\left(\rho_P\right)} = \frac{0.023378}{0.915356} = 0.025540 \qquad \text{(B-50)}$$

Table B-19: Shear Not Excluded – Method 2A – Calculation of ρ_P

(Column 1)	(Column 2)	(Column 3)	(Column 4)	(Column 5)	(Column 6)	(Column 7)	(Column 8)	(Column 9)
Bolt Identification	**Length (inches)**	**Average Shank Diameter (inches)**	**Shear N Failure Load (pounds)**	**Ultimate Strength $F_{u,exp}$ (ksi)**	**Shank Area (in^2)**	**Predicted Strength (kips)**	**Average Experimental Load (kips)**	**Bias Coefficient for Material Professional Factor ρ_P**
C11	3 3/4	0.8673	46169	170.70	0.59078	50.42	45.6844	0.905919
		0.8675	44680		0.59106	50.45		
		0.8676	44161		0.59119	50.46		
		0.8671	48011		0.59051	50.40		
		0.8672	45401		0.59065	50.41		
C12	4 1/2	0.8687	44179	169.88	0.59269	50.34	44.4724	0.882837
		0.8686	45451		0.59256	50.33		
		0.8690	44049		0.59310	50.38		
		0.8691	44392		0.59324	50.39		
		0.8694	44291		0.59365	50.43		
C13	4 3/4	0.8686	44165	162.44	0.59256	48.13	42.8648	0.891160
		0.8692	41984		0.59338	48.20		
		0.8678	42070		0.59147	48.04		
		0.8678	42002		0.59147	48.04		
		0.8683	44103		0.59215	48.10		
C15	5	0.8698	42193	161.06	0.59419	47.85	42.3092	0.884742
		0.8697	42283		0.59406	47.84		
		0.8691	41267		0.59324	47.77		
		0.8702	43491		0.59474	47.89		
		0.8689	42312		0.59297	47.75		
L11	3	0.8713	46212	162.50	0.59625	48.45	45.4032	0.937248
		0.8714	46371		0.59638	48.46		
		0.8712	44175		0.59611	48.43		
		0.8713	46302		0.59625	48.45		
		0.8712	43956		0.59611	48.43		
L12	5	0.8691	47275	172.04	0.59324	51.03	46.6380	0.913907
		0.8689	48425		0.59297	51.01		
		0.8698	45235		0.59419	51.11		
		0.8689	45268		0.59297	51.01		
		0.8689	46987		0.59297	51.01		
N14	3 3/4	0.8699	45498	165.92	0.59433	49.31	46.2256	0.937713
		0.8703	46457		0.59488	49.35		
		0.8693	46688		0.59351	49.24		
		0.8698	46522		0.59419	49.29		
		0.8698	45963		0.59419	49.29		
N15	4	0.8697	45307	159.11	0.59406	47.26	44.7280	0.944650
		0.8707	43692		0.59542	47.37		
		0.8705	45343		0.59515	47.35		
		0.8706	44193		0.59529	47.36		
		0.8711	45105		0.59597	47.41		
T13	4	0.8743	46219	168.46	0.60036	50.57	47.2414	0.934964
		0.8739	47823		0.59981	50.52		
		0.8737	46587		0.59954	50.50		
		0.8741	47881		0.60008	50.55		
		0.8737	47697		0.59954	50.50		
T14	4 1/4	0.8700	47578	164.21	0.59447	48.81	44.8782	0.920417
		0.8699	44943		0.59433	48.80		
		0.8696	43181		0.59392	48.76		
		0.8696	44312		0.59392	48.76		
		0.8687	44377		0.59269	48.66		
							Average	0.915356
							Standard Deviation	0.023378

Now that the bias coefficients for the cross-sectional geometry, ρ_G, material strength, ρ_M, and professional factor, ρ_P, are known, the bias coefficient, ρ_R, for the resistance can be calculated.

$$\rho_R = \rho_G\, \rho_M\, \rho_P = 0.988249 \times 1.104213 \times 0.915356 = 0.998871 \tag{B-51}$$

The coefficient of variation associated with ρ_R, V_R, can also be calculated now.

$$V_R = \sqrt{(V_G)^2 + (V_M)^2 + (V_P)^2} \tag{2-38}$$

$$V_R = \sqrt{(0.0041533)^2 + (0.026879)^2 + (0.025540)^2} = 0.037310 \tag{B-52}$$

Everything is now known, so the resistance factor for 7/8-inch A490 bolts in shear with the threads not excluded from the shear plane, based on Method 2A, can be calculated.

$$\phi = \Phi_{\beta}\, \rho_R\, e^{-\alpha_R \beta V_R} \tag{2-9}$$

$$\phi = 0.8991(0.998871)\, e^{-0.55(4.0)0.037310} = 0.827 \tag{B-53}$$

APPENDIX C

MATERIAL DATA SHEETS

The material data sheets obtained from the manufacturers are included in Appendix C.

UC ID#: **C1**

Grade: **A325**

Material Grade: **1036ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.79	0.01	0.022	0.24						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	27.4	32,250	142,699
Low:	25.8	31,260	138,319
Ave:	26.6	31,703	139,823

Notes:

UC ID#: **N1**

Grade: **A325**

Material Grade: **1036ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.79	0.01	0.022	0.24						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	28.1	31,760	140,531
Low:	27.1	31,500	139,381
Ave:	27.4	31,633	139,971

Notes:

UC ID#: **L2**

Grade: **A325**

Material Grade: **1036ML1**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.91	0.011	0.012	0.28						

	Core Hardness	Tensile Strength	Tensile Strength
		(lbs)	(psi)
High:	30.8	51,270	155,898
Low:	29.4	52,070	153,503
Ave:	30.2	51,537	154,301

Notes:

UC ID#: **N0**

Grade: **A325**

Material Grade: **1039M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.42	0.93	0.009	0.007	0.19						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.7	50,440	151,018
Low:	30.5	49,090	146,976
Ave:	31.0	49,587	148,463

Notes:

UC ID#: **N2**

Grade: **A325**

Material Grade: **1036ML1**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.9	0.014	0.018	0.25						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.4	50,360	150,778
Low:	28.9	49,410	147,934
Ave:	29.8	49,853	149,261

Notes:

UC ID#: **L3**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.75	0.008	0.016	0.24	0.35					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.0	67,166	145,381
Low:	27.0	66,174	143,234
Ave:	28.1	66,791	144,569

Notes:

UC ID#: **L4**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.78	0.006	0.018	0.25	0.36					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.8	71,359	154,457
Low:	30.2	68,646	148,584
Ave:	31.0	70,123	151,781

Notes:

UC ID#: **N4**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.84	0.01	0.014	0.25	0.37					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	29.1	70,190	151,926
Low:	26.9	69,350	150,108
Ave:	28.5	69,677	150,815

Notes:

UC ID#: **L5**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.79	0.012	0.009	0.22	0.37					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.9	89,160	147,129
Low:	28.1	86,330	142,459
Ave:	29.8	87,687	144,698

Notes:

UC ID#: **L6**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.78	0.014	0.01	0.22	0.36					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	28.3	89,018	146,881
Low:	26.4	87,530	144,439
Ave:	27.2	88,440	145,941

Notes:

UC ID#: **N6**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.78	0.014	0.01	0.22	0.36					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	29.4	86,690	143,053
Low:	27.2	84,400	139,274
Ave:	28.6	85,760	141,518

Notes:

UC ID#: **N7**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.78	0.014	0.01	0.22	0.36					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.4	90,130	148,729
Low:	29.1	89,650	147,937
Ave:	29.6	89,920	148,383

Notes:

UC ID#: **F1**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.79	0.018	0.016	0.24	0.44					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	27.1	103,000	134,993
Low:	24.4	100,210	131,337
Ave:	25.8	101,735	133,359

Notes: Material sheet difficult to read

UC ID#: **L8**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.74	0.007	0.022	0.24	0.47					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	27.8	104,021	136,332
Low:	25.1	102,419	134,232
Ave:	26.4	102,986	134,975

Notes:

UC ID#: **N8**

Grade: **A325**

Material Grade: **10B30**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	1.01	0.008	0.012	0.21					0.03	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	28.7	106,430	139,489
Low:	27.2	105,510	138,283
Ave:	27.6	105,927	138,829

Notes:

UC ID#: **T8**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.74	0.007	0.022	0.24	0.47					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	27.8	104,021	136,332
Low:	25.1	102,419	134,232
Ave:	26.4	102,986	134,975

Notes: Duplicate of UC ID #L8

UC ID#: **C3**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.77	0.011	0.021	0.24	0.45					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	25.0	123,980	127,946
Low:	23.8	123,570	127,523
Ave:	24.4	123,743	127,702

Notes:

UC ID#: **C8**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.73	0.011	0.017	0.24	0.66					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.8	57,340	171,677
Low:	34.8	56,950	170,509
Ave:	35.4	57,100	170,958

Notes:

UC ID#: **N13**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.42	0.79	0.008	0.015	0.26	0.64					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.6	53,790	161,048
Low:	32.8	52,640	157,605
Ave:	33.5	53,390	159,850

Notes:

UC ID#: **N10**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.75	0.012	0.014	0.26	0.64					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.7	38,480	170,265
Low:	34.9	38,160	168,850
Ave:	35.4	38,270	169,336

Notes:

UC ID#: **N11**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.75	0.012	0.014	0.26	0.64					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.8	38,520	170,442
Low:	34.2	38,260	169,292
Ave:	34.5	38,403	169,926

Notes:

UC ID#: **C6**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.76	0.01	0.018	0.24	0.65					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.8	36,960	163,540
Low:	25.8	36,780	162,743
Ave:	30.8	36,870	163,142

Notes:

UC ID#: **C5**

Grade: **A490**

Material Grade: **5039H**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.43	0.77	0.009	0.021	0.29	0.64					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.7	37,920	167,788
Low:	33.7	37,250	164,823
Ave:	34.3	37,523	166,033

Notes: Material sheet difficult to read

UC ID#: **N9**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.74	0.011	0.011	0.24	0.42					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	37.1	126,200	130,237
Low:	25.0	118,280	122,064
Ave:	26.0	121,227	125,105

Notes:

UC ID#: **T9**

Grade: **A325**

Material Grade: **1039ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.72	0.007	0.014	0.23	0.47					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	25.5	133,474	137,744
Low:	25.2	132,796	137,044
Ave:	25.3	133,135	137,394

Notes:

UC ID#: **T2**

Grade: **A325**

Material Grade: **1039M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.86	0.013	0.009	0.25						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.7	51,060	152,874
Low:	28.8	50,000	149,701
Ave:	30.2	50,453	151,058

Notes:

UC ID#: **N5**

Grade: **A325**

Material Grade: **1037ML**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.76	0.013	0.006	0.26	0.41					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.4	69,250	149,892
Low:	28.0	68,380	148,009
Ave:	28.9	68,913	148,163

Notes:

UC ID#: **C9**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.8	0.007	0.018	0.24	0.66					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.1	55,470	166,078
Low:	33.1	55,010	164,701
Ave:	33.7	55,237	165,379

Notes:

UC ID#: **C10**

Grade: **A490**

Material Grade: **5039M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.72	0.011	0.011	0.2	0.63					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	32.3	52,768	157,988
Low:	30.5	51,064	152,886
Ave:	31.4	51,882	155,335

Notes:

UC ID#: **N12**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.74	0.007	0.015	0.21	0.63					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	355.0	56,710	169,790
Low:	361.0	56,340	169,401
Ave:	108.0	56,543	169,291

Notes: Core Hardness Rockwell B. Average value of 108 is as it is written on sheets

UC ID#: **T12**

Grade: **A490**

Material Grade: **5039**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.74	0.01	0.024	0.21	0.65					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.4	54,670	163,683
Low:	33.3	52,920	158,443
Ave:	33.9	54,003	161,687

Notes:

UC ID#: **C11**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.88	0.011	0.018	0.23	0.95	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.2	76,470	165,519
Low:	33.5	75,510	163,442
Ave:	34.5	75,993	164,488

Notes:

UC ID#: **C13**

Grade: **A490**

Material Grade: **5140LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.75	0.012	0.024	0.24	0.72					0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.6	74,614	161,502
Low:	33.4	73,254	158,558
Ave:	33.8	73,952	160,070

Notes: Material sheet difficult to read

UC ID#: **C15**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.82	0.012	0.014	0.18	0.94	0.15				0.01

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.5	75,980	164,459
Low:	30.2	72,875	157,738
Ave:	31.7	73,534	159,380

Notes:

UC ID#: **L11**

Grade: **A490**

Material Grade: **4135**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.81	0.007	0.011	0.19	0.95	0.16				0.011

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.3	75,625	163,690
Low:	33.8	74,427	161,097
Ave:	34.6	75,026	162,394

Notes:

UC ID#: **N14**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.91	0.009	0.023	0.25	0.95	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.3	77,500	167,749
Low:	34.2	76,880	166,407
Ave:	34.7	77,243	167,193

Notes:

UC ID#: **N15**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.85	0.012	0.011	0.19	0.95	0.16				

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.1	73,880	159,913
Low:	33.4	73,050	158,117
Ave:	33.9	73,587	159,278

Notes:

UC ID#: **T13**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.88	0.011	0.018	0.23	0.95	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	36.3	78,490	169,892
Low:	33.4	76,620	165,844
Ave:	34.8	77,393	167,518

Notes:

UC ID#: **C16**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.87	0.009	0.024	0.23	0.94	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.6	98,770	162,987
Low:	33.3	97,470	160,842
Ave:	33.8	98,063	161,821

Notes:

UC ID#: **C17**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.89	0.013	0.015	0.24	0.94	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.7	99,240	163,762
Low:	33.4	98,040	161,782
Ave:	33.9	98,727	162,915

Notes:

UC ID#:	**L13**
Grade:	**A490**
Material Grade:	**4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.87	0.015	0.015	0.23	0.95	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.9	96,120	158,914
Low:	33.2	95,540	157,657
Ave:	33.5	95,883	158,223

Notes:

UC ID#: **L14**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.87	0.013	0.015	0.24	0.96	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.0	97,700	161,221
Low:	34.1	97,560	160,990
Ave:	34.5	97,647	161,133

Notes:

UC ID#: **N16**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.87	0.009	0.024	0.23	0.94	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.7	101,470	167,442
Low:	35.0	101,150	166,914
Ave:	35.3	101,310	167,178

Notes:

UC ID#: **N17**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.87	0.009	0.024	0.23	0.94	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.0	97,740	161,287
Low:	33.5	97,080	160,198
Ave:	33.8	97,410	160,743

Notes:

UC ID#: **N18**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.85	0.016	0.02	0.22	0.95	0.16				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.3	102,720	169,505
Low:	35.0	101,940	168,218
Ave:	35.2	102,430	169,026

Notes:

UC ID#: **T15**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.9	0.014	0.02	0.24	0.96	0.15				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.8	96,780	159,703
Low:	34.2	96,010	158,432
Ave:	34.5	96,360	159,010

Notes:

UC ID#: **C18**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.88	0.008	0.018	0.24	0.94	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.8	127,200	166,710
Low:	33.8	125,680	164,613
Ave:	34.4	126,380	165,635

Notes:

UC ID#: **C19**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.86	0.019	0.009	0.19	0.94	0.16				0.013

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.3	128,840	168,860
Low:	32.2	126,420	165,688
Ave:	33.3	127,610	167,248

Notes:

UC ID#: **C20**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.88	0.012	0.014	0.25	0.97	0.18				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.2	123,295	161,592
Low:	32.2	119,729	156,919
Ave:	32.8	121,288	158,962

Notes:

UC ID#: **L15**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.82	0.013	0.01	0.19	0.92	0.16				0.011

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.1	125,460	164,430
Low:	30.8	123,330	161,638
Ave:	32.5	124,293	162,634

Notes:

UC ID#: **N19**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.84	0.015	0.1	0.2	0.95	0.15				0.013

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	32.9	122,220	160,183
Low:	30.4	119,240	156,278
Ave:	32.2	120,587	158,278

Notes:

UC ID#: **C21**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.88	0.009	0.02	0.25	0.98	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.1	160,360	165,490
Low:	34.0	159,488	164,582
Ave:	33.4	159,884	164,999

Notes:

UC ID#: **C22**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.88	0.009	0.02	0.25	0.98	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.2	161,340	166,502
Low:	34.5	159,730	164,840
Ave:	33.2	160,587	165,724

Notes:

UC ID#: **C23**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.88	0.009	0.02	0.25	0.98	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	33.7	167,420	172,776
Low:	33.1	163,310	168,535
Ave:	33.4	164,980	170,258

Notes:

UC ID#: **C24**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.35	0.88	0.009	0.02	0.25	0.98	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.4	165,260	170,547
Low:	33.0	164,050	169,298
Ave:	34.0	164,655	169,923

Notes:

UC ID#: **L16**

Grade: **A490**

Material Grade: **4135MLV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.34	0.86	0.008	0.02	0.24	0.95	0.17				0.02

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.4	166,450	171,775
Low:	33.6	161,520	166,687
Ave:	34.5	163,893	169,136

Notes:

UC ID#: **N20**

Grade: **A490**

Material Grade: **4135MOD**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.33	0.82	0.01	0.009	0.2	0.91	0.15				0.007

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.8		
Low:	33.8		
Ave:	34.5		

Notes: Material sheet notes that bolts were too short to test.

UC ID#: **L9**

Grade: **A490**

Material Grade: **5039M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.75	0.005	0.011	0.22	0.64					

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.8	36,260	160,442
Low:	30.6	35,540	157,257
Ave:	32.9	35,785	158,341

Notes:

UC ID#: **C7**

Grade: **A490**

Material Grade: **5039LV**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.78	0.007	0.022	0.25	0.67					0.022

	Core Hardness	Tensile Strength	Tensile Strength
		(lbs)	(psi)
High:	36.0	55,741	166,883
Low:	33.2	54,854	164,234
Ave:	33.9	55,210	165,238

Notes: Material sheet difficult to read

UC ID#: **T11**

Grade: **A490**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.98	0.01	0.007	0.23	0.38	0.26	0.02	0.02	0.027	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	35.0		168,000
Low:	33.0		162,000
Ave:	34.4		165,625

Notes:

UC ID#: **T5**

Grade: **A325**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.42	0.99	0.013	0.01	0.27		0.24	0.38	0.06	0.038	0.003

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	32.0		150,000
Low:	30.0		147,000
Ave:	31.2		148,600

Notes:

UC ID#: **T7**

Grade: **A325**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.42	1.01	0.012	0.006	0.26	0.37	0.25	0.02	0.03	0.039	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.0		146,000
Low:	29.0		144,000
Ave:	30.0		145,125

Notes:

UC ID#: **T4**

Grade: **A325**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.99	0.01	0.007	0.24	0.37	0.25	0.02	0.03	0.034	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.0		145,000
Low:	29.0		142,000
Ave:	30.0		143,625

Notes:

UC ID#: **T3**

Grade: **A325**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.98	0.01	0.007	0.23	0.38	0.26	0.02	0.02	0.027	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	31.0		156,000
Low:	29.0		151,000
Ave:	29.8		152,750

Notes:

UC ID#: **T16**

Grade: **A490**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.42	1.01	0.012	0.006	0.26	0.37	0.25	0.02	0.03	0.039	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	36.0		165,000
Low:	34.0		163,000
Ave:	34.9		164,000

Notes:

UC ID#: **T1**

Grade: **A325**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.37	0.98	0.011	0.005	0.21	0.36	0.22	0.02	0.02	0.038	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	30.0		140,000
Low:	26.0		137,000
Ave:	28.1		138,875

Notes:

UC ID#: **L12**

Grade: **A490**

Material Grade: **4037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.39	0.96	0.008	0.004	0.23	0.36	0.251	0.014	0.02	0.035	

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	36.0		170,000
Low:	33.0		169,000
Ave:	34.6		169,500

Notes:

UC ID#: **L1**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.31	0.8	0.006	0.009	0.23	0.05	0.02	0.01	0.02		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	31.5	33,000	146,017

Notes:

UC ID#: **U1**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.31	0.8	0.012	0.008	0.26	0.09	0.01	0.02	0.02		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	30.7	33,250	147,124

Notes:

UC ID#: **U2**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.33	0.84	0.01	0.011	0.25	0.07	0.01	0.08	0.04		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	31.2	50,960	152,575

Notes:

UC ID#: **U3**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.32	0.83	0.008	0.008	0.28	0.07	0.01	0.08	0.06		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	32.5	70,500	152,597

Notes:

UC ID#: **U5**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.32	0.83	0.01	0.009	0.26	0.06	0.02	0.09	0.04		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	32.5	91,500	150,990

Notes:

UC ID#: **U6**

Grade: **A325**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.32	0.82	0.005	0.006	0.25	0.05	0.04	0.04	0.05		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	27.6	104,525	136,992

Notes:

UC ID#: **U7**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.88	0.013	0.011	0.25	1	0.22	0.09	0.05		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	35.0	55,250	165,419

Notes:

UC ID#: **U4**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.4	0.89	0.013	0.013	0.23	0.93	0.21	0.09	0.06		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	34.1	76,475	165,530

Notes: A325 is typed on the sheet but A490 is written in

UC ID#: **U8**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.43	0.88	0.012	0.01	0.24	0.96	0.19	0.08	0.05		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	34.7	101,175	165,955

Notes:

UC ID#: **U9**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.41	0.91	0.012	0.022	0.22	0.89	0.19	0.1	0.05		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:			
Low:			
Ave:	34.2	129,875	170,216

Notes:

UC ID#: **C12**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.38	0.95	0.011	0.018	0.026	0.55	0.02	0.31	0.36		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	34.7	78,542	163,875
Low:	33.4	70,271	152,102
Ave:	33.9	75,225	159,889

Notes:

UC ID#: **L10**

Grade: **A490**

Material Grade:

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.36	0.97	0.012	0.019	0.25	0.64	0.02	0.29	0.35		

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	36.4	56,518	169,216
Low:	34.3	55,122	165,036
Ave:	35.6	55,832	167,162

Notes:

UC ID#: **C4**

Grade: **A325**

Material Grade: **1037M**

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al	V
0.36	1.04	0.007	0.011	0.17						

	Core Hardness	Tensile Strength (lbs)	Tensile Strength (psi)
High:	28.5		142,000
Low:	27.9		136,000
Ave:	28.2		139,333

Notes: