An Experimental Analysis of Strength and Ductility of High-Strength Fasteners

AMY M. MOORE, GIAN A. RASSATI, and JAMES A. SWANSON

ABSTRACT

A total of 1,533 structural bolts, consisting of four different bolt grades and six different diameters, up to 5 in. long, were tested in direct tension and shear with the threads excluded and not excluded from the shear plane. Thread lengths, tensile and shear strength, and elongation at failure were measured. The experimental values were then compared to the requirements of the current AISC, RCSC, and ASTM specifications. This paper presents and discusses the results of the experimental tests and of the subsequent comparisons. It is concluded that all fasteners tested meet the minimum strength required by ASTM and RCSC. Furthermore, it is noted that while the strength in tension and in shear with the threads excluded from the shear plane are conservatively assessed by AISC specifications, the strength with the threads not excluded from the shear plane is often not conservatively predicted. As a consequence, an alternative expression for the shear strength with the threads not excluded from the shear plane is proposed. It is also concluded that the actual thread length can be different than the nominal values, potentially affecting the available cross section in shear. Finally, the measurement of the elongation at failure shows that all grades of fastener tested have a satisfactorily ductile behavior.

Keywords: structural bolts, threads excluded, threads included, shear strength, fastener ductility.

INTRODUCTION

High-strength structural bolts started becoming more economical in steel connections, completely replacing the use of rivets, during the 1950s. Installation of rivets required more and more trained manpower and more equipment, compared to that of high-strength bolts, which also offered more strength. The Research Council on Structural Connections (RCSC) was formed in 1947, with the main focus of a rapid development of high-strength fasteners in the United States. American Society of Testing and Materials (ASTM) designation A325 was approved in 1949 and revised in 1951 as a tentative specification for the material for high-strength bolts (Fisher and Beedle, 1967).

Based on Load and Resistance Factor Design, today's engineers are required to account for at most 75% of the bolt's tension and shear strength (AISC, 2005). Based on preliminary analyses on existing data in literature, supported by previous studies (Fischer et al., 1978), the authors believe that the resistance factor of 0.75 is not the direct result of a reliability analysis, but it is rather based on a perceived lack of ductility and on insecurities about consistent strength of fasteners and uncertainties about the force distribution among bolts in connections. This is particularly true for higher-grade bolts. The main goal of this research is to provide a more accurate statistical basis for the calibration of resistance factors for high-strength bolts in order to ensure a safe and potentially more economical design of bolted connections. This was achieved by testing a meaningful, statistical population of A325, F1852, A490, and F2280 bolts in direct tension and in shear, and then calculating resistance factors based on reliability indices and statistical reduction. Some of these results are summarized herein, and a full discussion on resistance factor calculations can be found in (Moore, 2007; Moore et al., 2008). Tensile and shear strengths were compared to the American Institute of Steel Construction *Specification for Structural Steel Buildings* equations (hereafter AISC *Specification;* AISC, 2005), and thread length and elongation at failure were also investigated. In the following, these results are presented and discussed, and some conclusions are drawn.

TENSILE AND SHEAR STRENGTH OF HIGH-STRENGTH FASTENERS

To determine the tensile strength of structural bolts, an effective area, calculated from the mean of the mean root and

Amy M. Moore, Bridge/Structural Engineer, LJB Inc., Dayton, OH. E-mail: amoore@ljbinc.com

Gian A. Rassati, Assistant Professor, Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, OH. E-mail: gian.rassati@uc.edu

James A. Swanson, Associate Professor, Department of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, OH. E-mail: james.swanson@uc.edu

pitch diameters, is used, because the threads are the weakest section of the fastener. The effective area is given by

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

where d is the nominal bolt diameter, and n is the thread pitch, i.e., the number of threads per inch in the fastener (ASTM F606-07, 2007).

Using the effective area, the nominal tensile strength of a structural bolt is given according to Kulak et al. (2001) as

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

where F_u is the ultimate strength of the bolt material.

For easier design purposes, the effective area can be estimated as 75% of the nominal cross-sectional area of the shank, which is conservative for most sizes of structural bolts. AISC specifications follow a slightly different approach, by using nominal tensile stress values F_{nt} calculated as 75% of the tensile strength of the bolt material. Modifying the tensile strength of the bolt material allows the nominal area of the bolt shank to be used in the design calculations. Therefore, based on Section J.3.6 of the AISC *Specification* (AISC, 2005), the nominal tensile strength of a high-strength bolt is given by

$$R_n = F_{nt} A_b = (0.75F_u) A_b = (0.75) F_u \left(\frac{\pi d^2}{4}\right) \tag{3}$$

where A_b is the nominal bolt area.

In both Equations (2) and (3), F_u is the nominal tensile strength of the bolt material, which equals 120 ksi for A325 and F1852 bolts and 150 ksi for A490 and F2280 bolts. ASTM specifications provide a minimum strength value of 105 ksi instead of 120 ksi for A325 fasteners having a diameter larger than 1 in. None of the A325 bolts tested, including 1⅛-in. and 1¼-in.-diameter bolts, resulted in a strength below 120 ksi, thus the lower value is not considered herein.

As for shear, 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 regardless of the bolt grade (Kulak et al., 2001). It should be noted that this value was determined based on bolts tested in double shear in a tension jig. A modification factor of 0.80 is applied in the current specifications to accommodate configurations of fasteners in shear joints up to 50 in. long. This follows the observation that the distribution of shear force amongst bolts is nonuniform when more than two rows of bolts are in the line of force in a lap splice (RCSC, 2004; Moore, 2007). Thus, the nominal strength of a fastener with the threads excluded from the shear plane in a group of fasteners is given by (Section J3, AISC, 2005):

$$R_n = 0.80(0.62 A_b F_u) = 0.50 A_b F_u \tag{4}$$

It was also observed in literature 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 (RCSC, 2004). The nominal shear strength of a fastener with the threads not excluded from the shear plane in a group of fasteners, taking 83% as roughly 80%, is given by (Section J3, AISC, 2005):

$$R_n = 0.80(0.50 A_b F_u) = 0.40 A_b F_u \tag{5}$$

The nominal shear strength of one isolated high-strength bolt, not part of a group of fasteners, can be thus obtained by dividing the AISC and Research Council on Structural Connections (RCSC) equations by 0.80. Therefore, for one bolt with the threads not excluded from the shear plane:

$$R_n = \frac{F_{nv,N} A_b}{0.80} = \frac{0.4 F_u A_b}{0.80} = 0.5 F_u A_b = 0.5 F_u \left(\frac{\pi d^2}{4}\right) \tag{6}$$

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

$$\begin{aligned} R_n &= \frac{F_{nv,X} A_b}{0.80} = \frac{0.5 F_u A_b}{0.80} \\ &= 0.625 F_u A_b \approx 0.62 F_u A_b = 0.62 F_u \left(\frac{\pi d^2}{4}\right) \end{aligned} \tag{7}$$

where $F_{nv,N}$ and $F_{nv,X}$ are the nominal strengths in shear provided in Table J3.2 of the AISC *Specification* (AISC, 2005) for the cases of threads not excluded (N) and excluded (X) from the shear plane, respectively. Equations (6) and (7) reflect the spirit of the shear strength models presented in AISC and RCSC in the context of the strength of a single fastener. It is worth noting that the provisions for tensile and shear strength of fasteners found within the RCSC *Specification* are consistent with those in the AISC *Specification* that are presented herein.

DESCRIPTION OF BOLTS OBTAINED AND TESTED

For this project, 100 lots of A325/F1852 and A490/F2280 high-strength bolts were tested with diameters ranging from ⅝ to 1¼ in. Table 1 shows the number of lots obtained and tested based on the grade of structural bolts. The bolts were acquired from seven different manufacturers or distributors. Approximately half of the bolts were sought from United States manufacturers through donations. The remaining bolts

Table 1. Test Matrix			
Diameter (in.)	Length (in.)	Lots of A325/F1852	Lots of A490/F2280
⅝	2¾ to 5	5	6
¾	2¾ to 5	10	12
⅞	3 to 5	10	13
1	3 to 5	10	12
1⅛	3¾ to 5	5	6
1¼	3¾ to 5	5	6
	Total	45	55

were purchased through local distributors. The decision to purchase half of the bolts was made to limit the possibility of preferential selection by the manufacturers and obtain a statistically sound sample. No differences were noted between donated and purchased fasteners. A larger number of A490/F2280 bolts were tested than A325/F1852 due to the smaller amount of data available from past research on these material grades. For each lot, five bolts were tested in direct tension, five in shear with the threads excluded from the shear plane, and five in shear with the threads not excluded from the shear plane. More details on the selection procedures that were followed to establish number of lots considered and the number of fasteners tested from each lot can be found in Moore (2007).

TEST PROCEDURE

The bolt testing procedure consisted 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. The standards for testing metallic materials in tension are given by ASTM E8-04 and ASTM A370-05. The standard test methods for the tensile and shear strengths of fasteners are given by ASTM F606-05.

Data were collected so that strength and bolt elongation information could be obtained. In tension, the force versus elongation plot provides a better set of information on the bolts' characteristics than a stress-strain curve, because the behavior of a fastener is governed primarily by its threaded part when subjected to an axial load (Kulak et al., 2001).

The tension and shear testing was carried out using a 400-kip universal testing machine in displacement control. More information on the fixtures and the transducers used can be found in Moore (2007).

The speed of testing has to be slow enough so that forces and strains are accurately indicated. Expecting the bolts to elongate more than 5%, per ASTM E8-04, the speed of testing has to be between 0.05 in. and 0.5 in. per inch of the length of reduced section per minute when determining the tensile strength (ASTM E8-04; ASTM A370-05). After conducting several tests using various strain rates, it was observed that the strength of a bolt is not greatly dependant on the strain rate. Therefore, a constant strain rate of 0.15 in./in./min was selected for all tension tests (Moore, 2007).

When testing a bolt in shear, according to F606-07, the speed of testing has to be between 0.25 in./min and 0.5 in./min. Several experiments were conducted using these two extreme load rates with the threads excluded and not excluded from the shear plane to determine the load rate to be used for testing in shear. The load rate was found not to be a factor on the strength of a high-strength fastener, so a load rate of 0.5 in./min was selected for all bolts tested in shear (Moore, 2007).

Tension testing was performed on full-sized fasteners as opposed to coupons machined from fasteners (ASTM A370-05; ASTM F606-07). Coupons were machined from a few fasteners and were tested to validate Equations 1 and 2. The results of this very limited number of experiments are almost identical to those on full-sized fasteners and can be found in Moore (2007).

The bolts tested in tension were tested in a holder with the load axially applied between the bolt head and a threaded fixture. To guarantee a conservative tensile response of the bolt, four complete threads were left unengaged within the grip of the bolt, as per ASTM F606-07, allowing for a complete fracture surface to freely develop in the threads (Moore, 2007). This was accomplished by fully threading the bolt into the holder and then applying four complete rotations to back it out. Tension tests were performed using a wedge washer (ASTM F606-07; ASTM A370-05). 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. The bolt head was oriented on the wedge washer to ensure that a flat edge of the hexagonal head was aligned with the high point of the wedge washer during testing.

Before a bolt was tested in tension, the diameter of the bolt shank was measured at five locations and recorded. The overall length of the bolt and that of its threaded portion were also measured. The bolt was then loaded until fracture occurred. Finally, the maximum load was recorded from the universal testing machine, and the final length of the threaded portion of the bolt was measured and recorded so that the elongation percentage of the fastener at failure could be computed.

Shear testing was performed to determine the failure load due to a load applied perpendicularly to the axis of the bolt according to ASTM F606-07, using a purposely fabricated shear fixture. This test fixture, pictured in Figure 1, was designed to be used with either a tensile or a compressive applied load. The measured shear strength of bolts tested in a shear fixture applying a tensile load is approximately 8 to 13% lower when compared to bolts tested in a compression shear fixture (Kulak et al., 2001). This is 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 has been observed and documented, the tension jig is preferred because it produces a conservative (lower) shear strength value and has more consistent test results when compared to the compression jig (Kulak et al., 2001). Thus, the shear tests were performed with the shear fixture arranged in tension. To provide sufficient durability to the fixture for the large projected number of fasteners to be tested, the fixture was designed so that replaceable inserts could be used as the bearing elements to apply shear forces on the bolts. Two sets of inserts were used: an outer set that would last for approximately 50 shear tests, and an inner set, in sizes corresponding to each bolt diameter that would last for approximately 8 to 10 tests. The outer inserts were made of D2 tool steel, to provide durability, while the inner inserts were made of 1045 steel (a medium carbon steel suitable for machining with mechanical characteristics similar to A36 steel), to provide boundary conditions similar to what would be encountered in an actual bolted connection. More details can be found in Moore (2007).

As was done for tension testing, before a bolt was tested in shear, the diameter of the bolt shank was measured at five locations and recorded. Spacers were used to position the bolt so that it could be tested with the threads excluded or not excluded from the shear plane as required. The bolt was installed in the shear fixture with a finger-tightened nut to hold the bolt in place while it was loaded. The bolt was then loaded until a shear fracture occurred and the maximum load was recorded.

THREAD LENGTH

Variability in the thread length of fasteners was also evaluated. The thread length of one bolt per lot was measured and compared to the values provided in the AISC *Steel Construction Manual* (2005), which are consistent with the values provided in ASME B18.2.6 (2006), to which in turn ASTM A325, F1852, A490 and F2280 make reference. Figure 2 shows the frequency distribution of the percentage error.

The average percent difference in the thread lengths is less than 5% for ⅝-in., ¾-in., and ⅞-in. bolts. However, as the bolt diameter increases, the percent difference in the thread length also increases to as much as 7.41% on average for 1¼-in. bolts (Moore, 2007). The overall average difference in the thread length was found to be 4.82%. The minimum and maximum error in the thread length, based on the 100 lots measured, were −1.34% (indicating that the thread length is shorter than the values provided in AISC's *Manual*) and 10.4%, respectively. This variability in the bolt thread length may be critical in situations in which a bolt is specified in *X* condition (i.e., with threads excluded from the shear plane) but the shear plane is close to the nominal thread run-out.

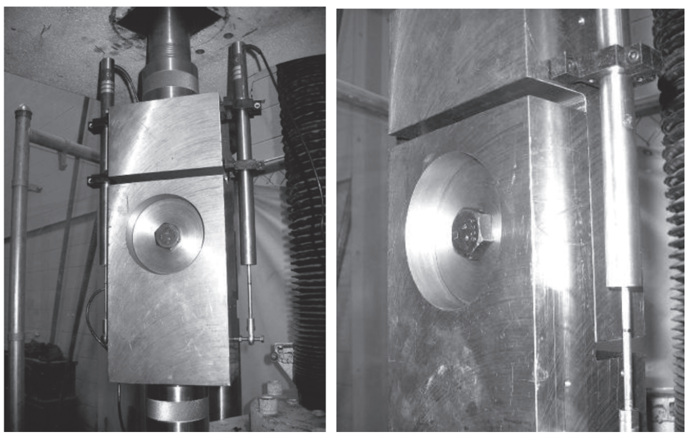

Fig. 1. Fixture used for shear testing.

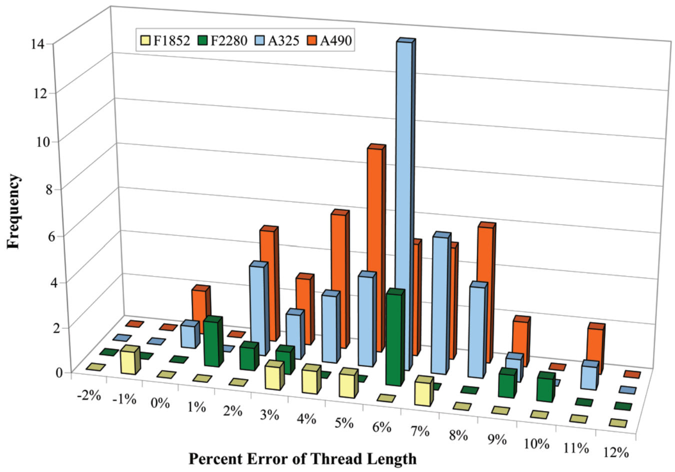

Fig. 2. Frequency distribution of percent error for bolt thread length.

Table 2. Tensile Strength of Bolts Tested Based on Grade											
Grade	Bolts Tested in Tension	Average (ksi)	Grade 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%

EXPERIMENTAL TENSILE STRENGTH COMPARED TO MATERIAL DATA SHEETS

The results of the direct tension tests were compared to the values reported on the material data sheets that were obtained from the manufacturer or distributor. It should be noted that material sheets for only 79 out of the 100 lots were available for comparison (Moore, 2007). The ratio of the experimental tensile strength to the value obtained from the material data sheet was evaluated. Figure 3 shows the frequency distribution of the ratio of experimental tensile strength to the tensile strength reported on the material data sheets for the four grades of bolts investigated. Note that for the 100 lots tested in tension a wedge washer was used, whereas the tensile strength for the material data sheets was obtained using a proof (flat) washer. The experimental tensile strength was on average 99.8% of the strength reported on the manufacturers' material data sheets.

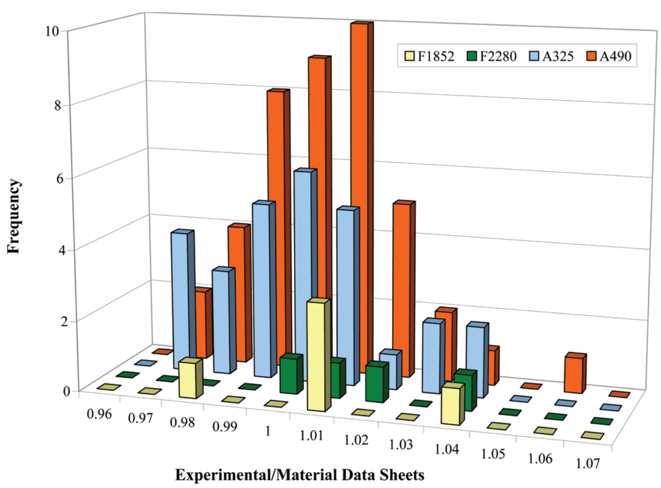

Fig. 3. Frequency distribution of experimental to data sheets strength.

TENSILE STRENGTH COMPARED TO ASTM AND RCSC

ASTM A325 (ASTM A325-04) and F1852 (ASTM F1852-05) specify a minimum tensile strength of 120 ksi for bolts less than or equal to 1 in. in diameter and of 105 ksi for bolts greater than 1 in. in diameter. Also, ASTM A490 (ASTM A490-04) 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 (2004). As part of this study, the tensile strength of the 515 bolts tested in direct tension was compared to both ASTM and RCSC limits. The tensile strength was calculated using the failure tensile force, divided by the effective area, as given by Equation 1. Figure 4 shows the frequency distribution of the tensile strength for each bolt grade, while Table 2 summarizes the tensile strength of the 515 bolts tested based on the bolt grade.

A325 and F1852 bolts were never below the ASTM minimum tensile strength of 120 ksi, including diameters larger than 1 in., which should have had a minimum strength of 105 ksi. When considering A325 and F1852 bolts together, the average tensile strength of the 237 bolts tested is 143.9 ksi. There are 37 out of the 237 A325 and F1852 bolts tested in direct tension that have a tensile strength greater than 150 ksi. It was observed that the bolts that had a tensile strength greater than 150 ksi were 1 in. in diameter or less (Moore, 2007). AISC and RCSC do not recognize explicitly the 105-ksi strength level and use a minimum strength of 120 ksi regardless of the bolt diameter. The experimental values validate this approach, considering that the tensile strength of the 237 A325 and F1852 bolts tested is always greater than 120 ksi, regardless of the bolt diameter.

The average tensile strength of the 278 A490 and F2280 bolts tested is 164.5 ksi. None of the A490 and F2280 bolts tested in direct tension has a strength smaller than the minimum tensile strength of 150 ksi specified by ASTM. Thirty out of the 278 A490 and F2280 bolts tested in direct tension had a tensile strength greater than the specified RCSC maximum (170 ksi). However, only 3 of the 278 A490 and F2280 bolts have a tensile strength greater than the maximum of 173 ksi as specified by ASTM. Taking into consideration the average tensile strength of the bolts tested per lot, there were 6 out of 55 A490 and F2280 lots that had an average tensile strength greater than 170 ksi. On the other hand, none of the A490 or F2280 lots had an average tensile strength greater than 173 ksi (Moore, 2007).

EXPERIMENTAL TO NOMINAL TENSILE STRENGTH—BASED ON AISC AND RCSC

Figure 5 shows the frequency distributions of the ratio of experimental strength to nominal AISC strength for the direct tension tests. The nominal tensile strength was calculated from Equation 3.

On average, the tensile strength for the A325 and F1852 bolts tested was 22.2% (5.75% standard deviation*) greater than the nominal tensile strength calculated based on AISC/RCSC equations. Also, on average, the measured tensile strength of the A490 and F2280 bolts was 11.9% (3.59%) larger than the nominal tensile strength based on AISC/RCSC equations (Moore, 2007). The ratio of experimental tensile strength to the nominal strength was never less than 1.023. Thus, it can be concluded that the AISC/RCSC equation conservatively predicts the strength of structural bolts in tension based on the 515 bolts tested.

* Henceforth, standard deviations will be reported in parentheses immediately following the average values.

EXPERIMENTAL TO NOMINAL TENSILE STRENGTH—BASED ON EFFECTIVE AREA

The frequency distributions of the ratio of experimental strength to nominal strength calculated based on the effective area are shown in Figure 6. The nominal tensile strength was calculated using the effective area from Equation 2.

On average, the measured tensile strength of the A325 and F1852 bolts tested was 19.9% (5.87%) greater than the

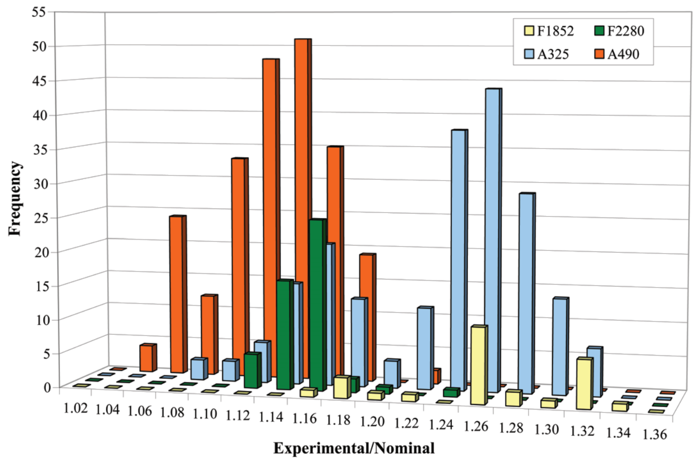

Fig. 5. Frequency distribution of experimental/nominal (AISC) for tensile strength.

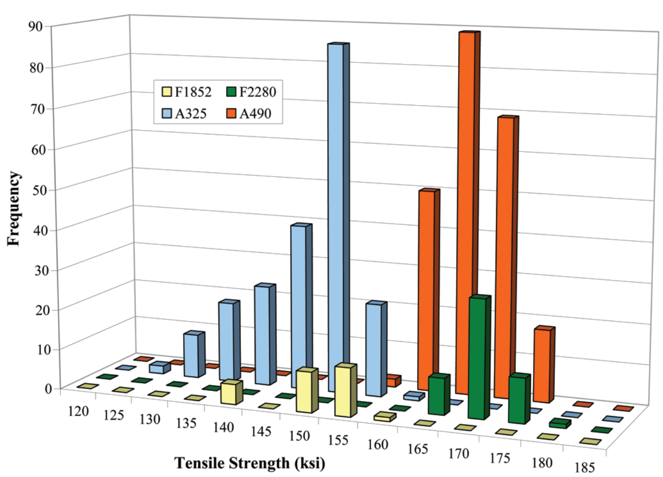

Fig. 4. Frequency distribution of tensile strength.

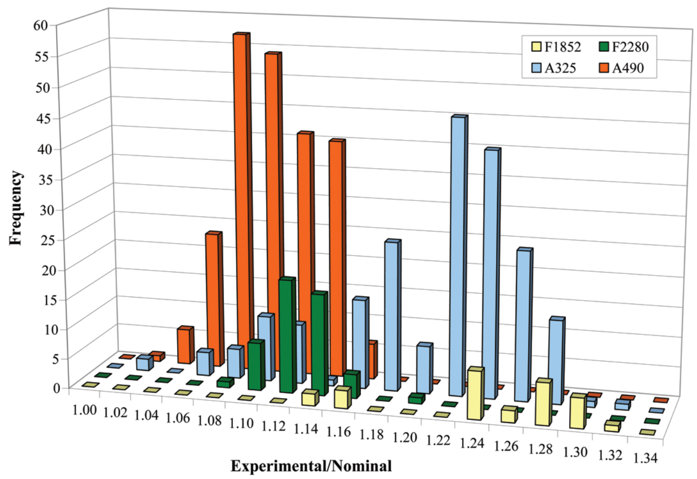

Fig. 6. Frequency distribution of experimental/nominal (effective area) for tensile strength.

nominal tensile strength calculated based on the effective area of the threaded section. The A490 and F2280 bolts had, on average, a measured tensile strength 9.64% (2.91%) larger than the nominal tensile strength based on the effective area (Moore, 2007).

The ratio of experimental tensile strength to nominal strength based on the effective area is 1.013 at a minimum, indicating that none of the high-strength bolts tested in tension had a tensile strength lower than the nominal strength based on the effective area (Moore, 2007). Comparing the ratio of experimental strength to nominal strength, it was determined that, on average, the nominal strength calculated using the effective area better predicts the failure load (i.e., the ratio of experimental to nominal strength is closer to unity, with similar or marginally smaller standard deviations).

EXPERIMENTAL TO NOMINAL SHEAR STRENGTH WITH THE THREADS EXCLUDED

The frequency distributions of the ratio of experimental strength to nominal strength in shear with the threads excluded from the shear plane are shown in Figure 7. Equation 7 was used to calculate the nominal shear strength with the threads excluded from the shear plane.

On average, the measured shear strength of bolts with the threads excluded from the shear plane was 18.1% (6.03%) greater than that specified by AISC/RCSC for the 233 tested A325 and F1852 high-strength bolts. Similarly, on average, a 5.63% (3.70%) greater strength was measured compared to AISC/RCSC's specified shear strength with the threads excluded from the shear plane for the 279 A490 and F2280 bolts tested (Moore, 2007). Of the 512 bolts tested in shear with the threads excluded from the shear plane, about 3.91% of the bolts have a shear strength smaller than the nominal AISC value. These bolts are of Grade A490. Therefore, based on the 512 bolts tested in shear with the threads excluded from the shear plane, it can be observed that the AISC/RCSC equation closely predicts the shear strength with the threads excluded, because less than 4% of the tested bolts were below the AISC nominal value.

EXPERIMENTAL TO NOMINAL SHEAR STRENGTH WITH THE THREADS NOT EXCLUDED

Figure 8 shows the frequency distributions of the ratio of experimental to nominal strength for bolts in shear with the threads not excluded from the shear plane. The nominal shear strength with the threads not excluded from the shear plane was calculated using Equation 6.

The 228 A325 and F1852 bolts tested in shear with the threads not excluded from the shear plane, on average, showed a measured strength 12.1% (6.58%) higher than that specified by AISC/RCSC. On the other hand, the 278 A490 and F2280 bolts had an average measured shear strength with the threads not excluded from the shear plane approximately equal (99.4% ratio with 4.86% standard deviation) to the value provided by the AISC/RCSC specification (Moore, 2007). Compared to the ratios of the same lot of bolts tested in tension and shear with the threads excluded from the shear plane, these averages are somewhat lower.

Of the 203 A325 bolts tested with the threads not excluded from the shear plane, 7 bolts had a strength lower than that specified by AISC/RCSC value (the experimental to nominal ratio is lower than unity). Also there were 132 out of 228 A490 bolts tested and 23 out of 50 F2280 bolts tested that have a ratio less than unity. Consequently, about 55.8% of the A490 and F2280 bolts tested had a measured

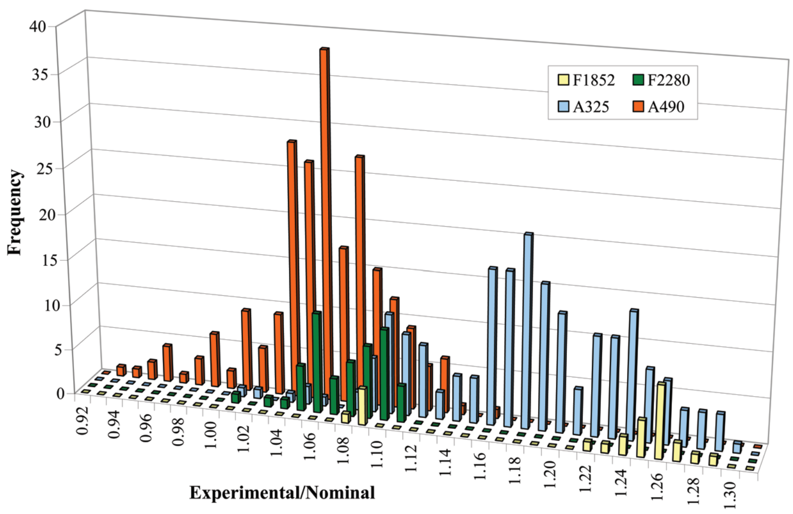

Fig. 7. Frequency distribution of experimental/nominal for strength in shear excluded.

shear strength with the threads not excluded from the shear plane below the AISC/RCSC nominal value. When looking at the 506 total bolts tested in shear with the threads not excluded, 162 (about 32%) had a measured strength below AISC/RCSC's nominal value. Thus, more than 30% of the time, AISC/RCSC's equation overpredicts the shear strength of bolts with the threads not excluded from the shear plane, based on the 506 bolts tested.

SHEAR *X* VERSUS TENSILE STRENGTH

The measured shear strength of fasteners with the threads excluded from the shear plane was compared to the measured tensile strength of bolts from the same lot. For this comparison, the shear strength with the threads excluded from the shear plane is estimated as a percentage of the bolt's tensile strength. Figure 9 shows the plot of the shear strength with the threads excluded from the shear plane versus the tensile strength for all bolts tested. It was found that the ratio of shear excluded to tensile strength is largely independent of the bolt grade (Moore, 2007), thus confirming the findings of Kulak et al. (2001). The average shear strength with the threads excluded from the shear plane is approximately 60.4% (1.49%) of the average tensile strength, based on the 100 lots tested; this compares well with the 0.62 value reported by Kulak et al. (2001).

SHEAR *N* VERSUS SHEAR *X* STRENGTH

Figure 10 shows the plot of the measured shear strength with the threads not excluded from the shear plane versus the measured shear strength with the threads excluded, based on the bolts tested. It was found that the ratio of shear not excluded to shear excluded is largely independent of the bolt grade (Moore, 2007). The average shear strength with the threads not excluded from the shear plane was found to be approximately 76.2% (2.36%) of the average shear strength with the threads excluded from the shear plane. This value is lower than the 0.83 value reported in RCSC (2004), which is approximated in the AISC provisions as 0.80. It is believed that the currently used value is based on a considerably smaller number of data points used in the statistical reduction, which results in the difference between the AISC value and the value obtained from the shear testing.

It is worth observing that the ratio of 0.76 is close to the ratio of the area of the threaded portion to the gross bolt area (which AISC takes indirectly as 0.75, as discussed earlier). This seems reasonable, because the ratio of the shear strength with the threads not excluded from the shear plane (in the threads) to the shear strength with the threads excluded (in the shank) should be proportional to the ratio of the shear areas.

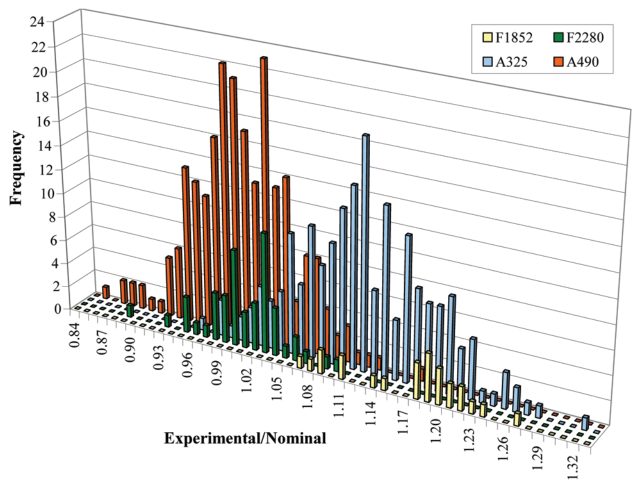

Fig. 8. Frequency distribution of experimental/nominal for strength in shear not excluded.

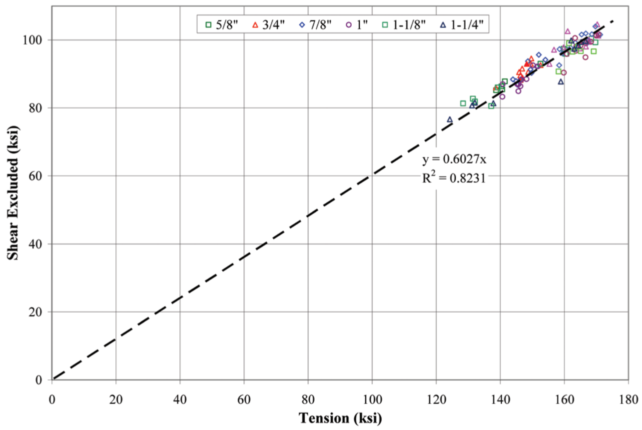

Fig. 9. Shear strength excluded versus tensile strength for all bolts tested.

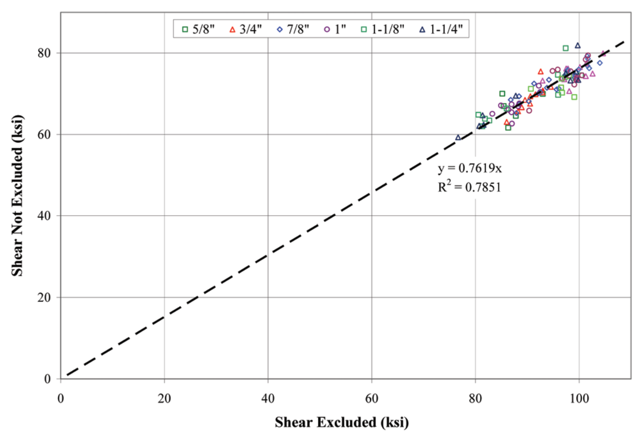

Fig. 10. Shear strength not excluded versus shear strength excluded for all bolts tested.

It is concluded that the equation currently used in the AISC provisions (AISC, 2005) to obtain the nominal value of the shear strength of a fastener with the threads not excluded from the shear plane is not always conservative. As a consequence, the calculation of the corresponding resistance factor to be used in design results in a lower value.

ELONGATION AT FAILURE

The elongation at failure of high-strength bolts was measured for the 515 bolts tested in direct tension. After the bolts were tested, the thread length was measured and compared to the initially measured thread length. This resulted in the percentage of elongation at failure of the tension bolt. Due to the reduced area in the threads, the plastic elongation occurs predominantly in this region and not in the bolt shank. The frequency distribution of the elongation at failure for all high-strength bolts tested is shown in Figure 11. The average percent elongation for A325/F1852 bolts and A490/F2280 bolts are 9.83% and 6.74%, with a standard deviation of 4.24% and 3.00%, respectively (Moore, 2007).

It is concluded that all high-strength fasteners have a considerably ductile behavior. Although higher-grade fasteners (A490 and F2280) show a reduced ductility when compared to A325 and F1852 bolts, failure will still occur after a considerable amount of energy has been absorbed by the fastener.

RELIABILITY STUDY AND RESISTANCE FACTORS

Based on the measured strength values of the 1,533 high-strength fasteners tested, a series of reliability analyses have been performed in order to evaluate resistance factors for the three cases of tension, shear with threads excluded from the shear plane, and shear with threads not excluded from the shear plane. Parameters of these analyses were the desired reliability index β (values used in the investigation were 4.0 and 4.5), the live-to–dead load ratio (values of 1.0 and 3.0 were used), the approach used to calculate the thread area (Equation 2, indicated with A, versus Equation 3, indicated with B in the tables), and the form of the resistance factor equation, chosen between Equations 8 and 9, indicated with Method I and II, respectively, in the tables:

$$\phi = \Phi_\beta \frac{R_m}{R_n} e^{-\alpha\beta V_R} \quad \text{(Fisher et al., 1978; Ravindra and Galambos, 1978)} \tag{8}$$

$$\phi = \Phi_\beta \rho_R e^{-\alpha\beta V_R} \quad \text{(Galambos, 1998)} \tag{9}$$

in which ϕ is the resistance factor; Φ_β is an adjustment factor (function of β); β is the reliability index; R_m and R_n are, respectively, the mean and nominal resistance values; α is the coefficient of separation (accounting for interdependency between loads and resistances); ρ_R is a bias coefficient for the resistance (function of geometry, material properties and equations used); and V_R is the coefficient of variation of the resistance.

A preliminary study was performed on all experimental data available in literature (which was found to be ample for tension and scarce for shear). The outcomes of this preliminary study provide values of resistance factors that compare well with those originally calculated by Fisher et al. (1978). The same approach, applied to the data acquired as part of this study, resulted in the values summarized in Tables 3 and 4. Table 3 contains the resistance factors obtained using various combinations of the parameters listed earlier, performed separately for measured strengths in tension, shear excluded, and shear not excluded (level II). Using a reliability index of 4.0 and a live-to–dead load ratio of 3.0, as recommended in the Commentary to the AISC *Specification* (AISC, 2005), it is possible to recommend a resistance factor of 0.90 for tension, 0.85 for shear excluded, and 0.80 for shear not excluded. Table 4 contains the same values, grouping together all loading cases considered, resulting in a single resistance factor (level I). Even in this case, it is possible to recommend a resistance factor of 0.80 for a live-to–dead load ratio of 3.0 and a reliability index of 4.0. The full study can be found in Moore (2007), and an in-depth summary of the approach and result can be found in Moore et al. (2008). It is concluded that it is indeed possible to increase the values of resistance factors for high-strength fasteners. Also, the resistance values for shear with the threads not excluded from the shear plane negatively affect the value of the corresponding resistance factor. In the next section, a recommendation for modifying the equation to predict the nominal values of shear resistance is presented, and the corresponding changes in resistance factors are noted.

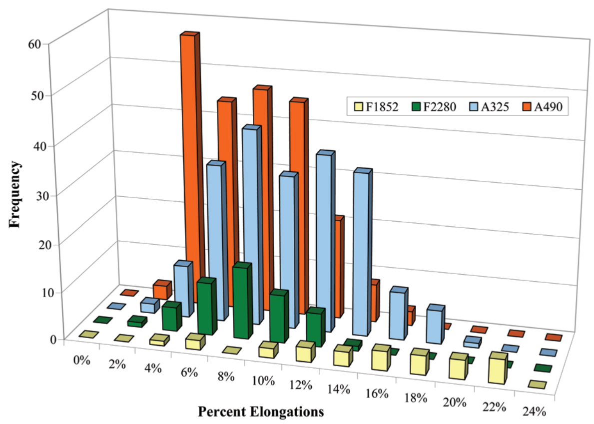

Fig. 11. Frequency distribution of percent elongation for all bolt grades.

Table 3. 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 (0.75A_g)	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 4. 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

RECOMMENDATIONS

After evaluating the resistance factors, it was found that the current values 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. Resistance factors of 0.90, 0.85 and 0.80 were 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 (Moore, 2007).

It was observed that the AISC equation for the shear strength with the threads not excluded from the shear plane does not conservatively predict the strength based on the bolts tested for this research, which is why the recommended resistance factor is lower compared to tension and shear excluded. It is conceivable to modify Equations 6 and 7 using the shear-to-tension strength and shear *N*-to-*X* ratios calculated as part of this study, in the attempt to improve their prediction capabilities.

It was found from the bolts tested that the shear strength of a single high-strength bolt with the threads excluded from

Table 5. Modified 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
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 6. Modified 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	0.903	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

the shear plane is approximately 60% of the tensile strength regardless of the bolt grade. Therefore, based on this ratio, determined experimentally from the 100 lots tested, the nominal shear strength for a single bolt with the threads excluded from the shear plane, previously shown as Equation 7, becomes

$$R_n = 0.60 F_u A_b \tag{10}$$

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. Consequently, modifying Equation 6 to reflect the two new ratios found from the 100 lots tested, the nominal shear strength for a single high-strength bolt with the threads not excluded from the shear plane can be expressed as

$$R_n = 0.76\left(0.6 F_u A_b\right) = 0.456 F_u A_b \approx 0.46 F_u A_b \tag{11}$$

Resistance factors have been evaluated using these modified equations for the shear strength of fasteners. To show the impact the modified shear resistance equations have on the resistance factors, Tables 5 and 6 tabulate the resistance factors based on the modified shear equations for level II and level I, respectively (Moore, 2007).

As can be seen from a comparison of Tables 3 and 4 with Tables 5 and 6, the resistance factors for shear with the threads excluded and not excluded from the shear plane increase with the modified nominal shear equations. Using these modified shear strength equations, a resistance factor of 0.85 can be recommended for bolts in shear with both the threads excluded and not excluded from the shear plane, based on a reliability index equal to 4.0 and a live-to–dead load ratio of 3.0 (Moore, 2007).

CONCLUSIONS

This paper summarizes the results of a study performed on 1,533 high-strength fasteners, measuring their geometric characteristics, strength, and ductility. Single bolts have been tested in direct tension, in shear with the threads excluded from the shear plane, and in shear with the threads not excluded from the shear plane. The main conclusions can be summarized as follows:

- The actual thread length can be considerably different from the nominal length provided in the AISC *Manual* (AISC, 2005). While this will not have any impact for tension bolts, and for most cases of bolts in shear, this variability must be taken into account in situations in which the shear plane is close to the run-out of the threads.
- The comparison of the experimental tensile strength to the data found on the material sheets provided by manufacturers shows an excellent agreement between datasets, even when considering that the experimental data have been obtained using a wedge washer, while the data in the manufacturers' sheets have been obtained using a proof washer.
- A comparison of the experimental tensile strength to the minimum values required in the ASTM specifications and RCSC guide allows one to conclude that for A325/F1852 bolts, the strength is always larger than 120 ksi, irrespective of the diameter of the bolts. The average strength of these grades of fasteners is approximately 144 ksi. Similarly, for A490/F2280 bolts, the strength is always larger than 150 ksi. The average strength of these grades of fasteners is approximately 165 ksi. The RCSC maximum value for A490/F2280 bolts of 170 ksi is exceeded 11% of the time, while only 1% of the bolts exceed the ASTM-mandated limit of 173 ksi.
- Comparing the experimental tensile strength to the nominal values obtained using the equation in the AISC *Specification* (AISC 2005) it can be concluded that the AISC equation conservatively predicts the tensile strength of structural bolts.
- Performing the same comparison, using the effective cross-sectional area in place of the approximate area for the threaded portion of the bolt, it can be concluded that the failure load in tension is more accurately predicted.
- A calculation of the ratio of the experimental to the nominal shear strength with threads excluded from the shear plane, calculated per AISC/RCSC, allows the conclusion that, on average, A325/F1852 bolts are 18.1% stronger than predicted, while A490/F2280 bolts are 5.63% stronger than predicted. Also, 3.91% of the bolts tested (all Grade A490) show a shear strength lower than predicted. The equations in the AISC/RCSC specifications closely predict the shear strength of bolts with the threads excluded from the shear plane.
- Calculating the ratio of the experimental to the nominal shear strength with threads not excluded from the shear plane, calculated per AISC/RCSC, it can be concluded that A325/F1852 bolts are, on average, 12.1% stronger than predicted, while the strength of A490/F2280 bolts is predicted quite closely. It must be noted that 3.45% of the A325 bolts and 57.9% of the A490 bolts that were tested were weaker than predicted. Overall, more than 30% of the time the AISC/RCSC equations for the nominal shear strength with threads not excluded from the shear plane provided an unconservative value.
- The experimental ratio of shear strength with threads excluded to tensile strength is approximately equal to 60%, while the experimental ratio of shear with threads excluded to shear with threads not excluded is equal to 76%.
- The elongation at failure is 9.83% and 6.74% for A325/F1852 and A490/F2280, respectively, showing a considerable ductility in all cases.
- Resistance factors calculated using the equations in the current AISC/RCSC provisions and using the recommended modifications, taking into account the shear ratios obtained as part of this project, can be increased from the current 0.75, without sacrificing safety. Using the proposed modified equations, it is recommended to use a resistance factor of 0.90 for tension and 0.85 for shear, both with threads excluded and not excluded from the shear plane.

ACKNOWLEDGMENTS

This study was funded by the Research Council on Structural Connections, the support and guidance of which the authors gratefully acknowledge.

REFERENCES

AISC (2005), *Specification for Structural Steel Buildings,* 13th Ed., American Institute of Steel Construction, Inc., Chicago, IL.

AISC (2005), *Steel Construction Manual,* 13th Ed., American Institute of Steel Construction, Inc., Chicago, IL.

ASME B18.2.6-2006 (2006), "Fasteners for Use in Structural Applications," American Society of Mechanical Engineers, New York.

ASTM A325-04 (2004), "Standard Specification for Structural Bolts, Steel, Heat Treated, 120/105 Minimum Tensile Strength," ASTM International.

ASTM A370-05 (2002), "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," ASTM International).

ASTM A490-04 (2004), "Standard Specification for Structural Bolts, Alloy Steel, Heat Treated, 150 Minimum Tensile Strength," ASTM International.

ASTM E8-04 (2004), "Standard Test Methods for Tension Testing of Metallic Materials," ASTM International.

ASTM F606-07 (2007), "Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets," ASTM International.

ASTM F1852-05 (2005), "Standard Specification for 'Twist Off' Type Tension Control Structural Bolt/Nut/Washer Assemblies, Steel, Heat Treated, 120/105 ksi Minimum Tensile Strength," ASTM International.

ASTM F2280-06 (2006), "Standard Specification for 'Twist Off' Type Tension Control Structural Bolt/Nut/Washer Assemblies, Steel, Heat Treated, 150 ksi Minimum Tensile Strength," ASTM International.

Fisher, J.W. and Beedle, L.S. (1967). *Bibliography on Bolted and Riveted Joints,* American Society of Civil Engineers, New York, Manuals and Reports on Engineering Practice No. 48.

Fisher, J.W., Galambos, T.V., Kulak, G.L. and Ravindra, M.K. (1978) "Load and Resistance Factor Design Criteria for Connectors," *Journal of the Structural Division,* ASCE, Vol. 104, No. 9.

Galambos, T.V. (1998), *Guide to Stability Design Criteria for Metal Structures,* 5th Ed., John Wiley and Sons, Inc., New York.

Kulak, G.L., Fisher, J.W. and Struik, J.H.A. (2001), *Guide to Design Criteria for Bolted and Riveted Joints*, 2nd Ed., American Institute of Steel Construction, Inc., Chicago, IL.

Moore, A. (2007), "Evaluation of the Current Resistance Factors for High-Strength Bolts," MS Thesis, Department of Civil Engineering, University of Cincinnati, Ohio.

Moore, A.M., Rassati, G.A. and Swanson, J.A. (2008), "A Reliability Analysis of High-Strength Bolts," submitted for review to *Advances in Structural Engineering.*

Ravindra, M.K. and Galambos, T.V. (1978), "Load and Resistance Factor Design for Steel," *Journal of the Structural Division,* ASCE, Vol. 104, No. 9.

RCSC (2004), *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, Research Council on Structural Connections.