EFFECTS OF HEAD SIZE ON THE PERFORMANCE OF TWIST-OFF BOLTS

by

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(ABSTRACT)

This study examines a specific application of button-head type twist-off bolts. Currently, the Research Council on Structural Connections Specification (2000) removes the requirement for ASTM F436 washers (ASTM 2000a) under the bolt head of twist-off bolts where the head diameter equals or exceeds that of an ASTM F436 washer when oversized and slotted holes are used. The need for washers is also removed for A490 strength bolts used on steels with specified yield strengths less than 40 ksi provided that the head diameter equals or exceeds an ASTM F436 washer.

The ASTM F1852 Specification (ASTM 2000b) allows for head diameter dimensions that are slightly smaller than an ASTM F436 washer. Following the RCSC Specification, manufacturers that produce bolts using the ASTM F1852 dimensions are required to use ASTM F436 washers under the bolt head. The discrepancies between the specifications lead to this study, which involved the testing of button-head type twist-off bolts with two different head diameters, both of which were smaller than an ASTM F436 washer.

Five bolt diameters between 5/8 in and 1-1/8 in. were tested in standard, oversized, and long-slotted holes. The performance of the twist-off bolts was determined by measuring and comparing the achieved relaxed pretension force in the bolt after tightening. It was found that twist-off bolts with head diameters less than an ASTM F436 washer had no trouble attaining their required minimum pretension force. Bolt head diameter and hole size were found to have no significant influence on the pretension force that was achieved for all bolts tested.

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1. INTRODUCTION

The head diameter of button-head type twist-off bolts necessary for adequate and reliable performance has been brought into question. Following the Research Council on Structural Connections (RCSC) Specification (2000), ASTM (2000a) F436 washers are not required under the bolt head when the bolt head diameter equals or exceeds the diameter of a standard ASTM F436 washer when used on oversized and slotted holes. The same is true for A490 strength bolts that are used with steels that have minimum specified yield strengths less than 40 ksi provided that the head diameter equal or exceeds an ASTM F436 washer. The intent of this study was to determine if the RCSC Specification should be modified to allow for ASTM (2000b) F1852 minimum bolt head diameter twist-off bolts without washers for both of these conditions.

Minimum head diameters that are smaller than an ASTM F436 washer are allowed under the ASTM F1852-00 Specification (ASTM 2000b). Some manufacturers produce twist-off bolts that have head diameters that are larger than that required by ASTM F1852, but are less than the ASTM F436 washer diameter. These bolts are required to have a washer under the bolt head on oversized and slotted holes if the current RCSC Specification is followed.

The purpose of this research is to determine if bolts with ASTM F1852 minimum head diameters are comparable to those with a diameter equal to or larger than an ASTM F436 washer. Testing was done on bolt diameters ranging from 5/8 in. to 1-1/8 in. for both F1852/A325 and A490 strength bolts. Bolt heads having the minimum required diameter permitted by ASTM F1852 were tested against those having larger head diameters. Bearing plates with hole sizes including standard, oversized, and slotted holes were used in the testing.

2. PREVIOUS RESEARCH

Previous research dealing with twist-off bolts is very limited. Much of the reported work did not deal specifically with the effects of bolt-head size on pretension forces. However, some work is related to the findings contained in this report.

Research was conducted by Chesson and Munse (1965) in the early 1960's at the University of Illinois dealing with the effect of washers on the clamping force of 3/4 in. A325 strength bolts. Regular and heavy semi-finished hexagon head bolts were used along with finished, heavy, and flanged nuts. The heavy semi-finished hexagon head was permitted as an alternate design fastener at this time. Hole sizes ranged from a standard 13/16 in. diameter hole to an oversized hole of 7/8 in. diameter. The majority of the bolts were tightened using the turn-of-nut method. The tightening procedure involved snugging the bolt with an impact wrench to an approximate tension of 5,000 pounds, then turning the nut or bolt head an additional one-half turn. Bolts that were tightened with washers under the bolt head were compared to those tightened without washers.

Test results for all hole sizes showed that the presence of a washer under the bolt head had no significant effect on the clamping or pretension force achieved in the bolts. The type and hardness of the nut had a greater effect on the clamping force than the washers. The torque required to achieve the measured pretension forces was found to be higher for the bolts without washers due to the galling of the nut into the soft plate material. Galling occurs when the nut tears into the plate material, damaging the outer integrity of the hole. Hole size did not influence the achieved pretension by a significant amount. All clamping forces on oversized holes without washers were well above the required minimum, and comparable to the tests conducted on standard holes with washers. Long-term relaxation of the bolts was also studied and it was found that the inclusion or exclusion of washers had no influence on relaxation. It was found that most of the relaxation that occurs in the bolt happens within the first few minutes after tightening. The major difference between the testing conducted by Chesson and Munse (1965) at the University of Illinois and the testing contained in this report is the type of bolts and the method of tightening used -- hexagon head bolts compared to twist-off bolts and turn-of-nut procedure versus twist-off torque control.

Allan and Fisher (1968) performed studies on oversized and slotted holes in the late 1960's. They were primarily concerned with holes having larger clearances, above the 1/16 in. and 1/8 in. tested by Chesson and Munse (1965). Bolts of 1 in. diameter and A325 strength were tested in hole sizes of 1/4 in. and 5/16 in. greater than the nominal bolt diameter and compared against the standard 1/16 in. clearance. The bolts were installed with and without washers using the turn-of-nut method. The results obtained were analyzed to observe what effects oversized and slotted holes had on achieved bolt pretension, bolt relaxation, and joint slip resistance. The data was used to determine if washers should be required under the bolt head.

The 1 in. bolts tested in the 1-1/16 in. standard hole without washers were able to attain pretensions well above the minimum, as shown in the previous tests by Chesson and Munse (1965). Bolts tested in the 1-1/4 in. oversized hole without washers had the same average pretension as bolts tested with washers in the same hole size. The measured pretensions however were slightly lower than those obtained in the plus 1/16 in. hole size. The increased hole size increased galling around the hole in the test setups that did not include washers under the bolt head. The 5/16 in. oversized holes required washers under both the head and nut to attain the necessary pretension. The relaxation of the bolts was not affected by oversized and slotted holes.

Allan and Fisher (1968) also concluded that the slip coefficient for the 1-1/4 in. holes were comparable to the standard holes, however the coefficient decreased for the 1-5/16 in. and slotted holes. Omitting washers from the 1-1/4 in. oversized hole did not affect bolt pretension greatly but it was suggested that they be used to prevent plate galling.

Other research relating hole size and joint slip coefficients can be found in "Bolted Connections with Varied Hole Diameters" by Shoukry and Haisch (1970). Their tests involved determining the effects oversized holes had on bolted connections. Both 3/4 in. and 7/8 in. A325 strength bolts were used in butt and lap joints and were tightened using the calibrated wrench and the turn-of-the-nut methods with washers only under the turned element. Hole clearances ranged from 1/16 in. to 1/4 in. Testing concentrated on the initial slip of the joints which was needed for slip coefficient calculations. After this data

was collected, the specimens were loaded until failure to find the ultimate shear load of the joint. Results showed that the slip coefficients and ultimate shear strengths of the joints were not significantly affected by hole clearances up to 3/16 in. This result was also found to be true for the 3/4 in. and 7/8 in. A325 strength bolts tested in the butt and lap joints.

More recent testing, specifically with twist-off bolts, was performed by Kulak and Undershute (1998) who studied factors that affect the achievable pretension force in twist-off bolts. They stated, "Factors that affect the preload of a tension control bolt are bolt material strength, thread conditions (such as lubrication, dirt, and thread damage), the diameter of the annular groove at the splined end, and friction conditions at the nut-washer interface." The main factors investigated were the effects of storage and aging conditions as well as friction conditions on the achieved pretension force in the bolt. Bolts of 3/4 in. diameter and A325 strength were received from seven different manufacturers. The bolts were of different ages upon receipt and were purposely subjected to different storage conditions prior to tightening. Some of these conditions included sealing the bolts in a container for up to 4 weeks, fully exposing others to the elements and subjecting additional bolts to humid environments. The friction tests involved testing bolts with different lubrication arrangements.

All of the bolts in the storage tests were able to attain the required pretension force. Sealing in containers and exposing to humidity had little effect on the ultimate pretension. Average pretension values for these tests were 16% to 20% higher than required by the RCSC Specification (2000). Full exposure to weather, and weathered snugged bolts in a steel joint produced the lowest acceptable pretension values, around 5% to 10% above the required. The friction tests revealed how loss of lubrication on the bolt assembly affects pretension values. These bolts were found to be unacceptable with an average that was 20% below the required preload force. On the high end, bolts and washers that were cleaned and relubricated resulted in a pretension 52% above required. The tests performed by Kulak and Undershute (1998) show how important storage conditions and proper lubrication is on the final pretension force in twist-off bolts.

Research by Oswald, et al (1996) deals with large-diameter bolts and the effects of grip length on pretension forces. Their work found that many 1 in. and 1-1/8 in. bolts that had grip length longer than 7 in. were unable to attain the required preload. Shorter length bolts had no problem attaining this value. Reasons for the low pretensions attained were stated as "greater difficulty in snugging the plies in the connections with the longer bolts and the very high pretension forces that the large-diameter, high-strength bolts required to develop specified pretension stresses". They suggested that "designers should consider alternatives to the use of large diameter A490 bolts in slip-critical joints, especially if the bolts have a long effective bolt length (greater than 178 mm or 7 in.) and are installed through more than one interface".

The research that is most related to this study is that performed by Chesson and Munse (1965) and by Allan and Fisher (1968). Both studies looked at the need for washers under the bolt head in oversized holes. The main difference is the type of tightening procedure used and the type of bolts tested. The work by Allan and Fisher (1968) and Shoukry and Haisch (1970) added insight on effects of hole size on pretension forces and slip coefficients.

3. DESCRIPTION OF BOLTS

A single twist-off bolt manufacturer provided all of the bolts tested in the project. They supplied both ASTM F1852 minimum head diameter and their standard head diameter in both F1852/A325 and A490 strengths. Specifics for these bolts can be found in the bolt certificates that are provided in Appendix A.

The minimum head diameter bolts that were used were machined from the manufacturer's standard head diameters down to the minimum ASTM F1852 diameter. Table 3.1 lists the average measured head diameters for the minimum head diameter (ASTM F1852), the as-manufactured bolts, and the nominal ASTM F436 washer diameters. Figure 3.1 shows photos of minimum and standard head diameters as supplied.

Table 3.1: Average Head Diameters for Supplied F1852/A325 and A490 Strength Bolts, and F436 Washer Diameters

Bolt Diameter	Average Measured Minimum Head Diameter (ASTM F1852)	Average Measured Manufacturer's Standard Head Diameter	Nominal F436 Washer Diameter
5/8" (A325 only)	1.099"	1.166"	1.313"
3/4"	1.340"	1.394"	1.469"
7/8"	1.534"	1.578"	1.750"
1"	1.771"	1.846"	2.000"
1-1/8"	1.992"	2.178"	2.250"

(Seven to ten bolt head diameters were measured for above averages)

Figure 3.1: Photo of Manufacturer's Standard and Machined F1852 Minimum Diameter 1-1/8" Bolts

4. TEST SETUP AND PROCEDURE

The achieved pretension force in the bolt after tightening was used as the standard of comparison between the minimum ASTM F1852 and the manufacturer's standard head diameters. A Skidmore Wrench Calibrator, (Model ML), was used to measure the tension in the twist-off bolt after tightening. Bolts ranging in diameters from 5/8 in. to 1-1/8 in. were tested with plates having standard, oversized, and slotted holes. The steel plates were of A36 minimum yield strength and measured 4 in. square by 1/4 in. thick. Tensile coupon tests produced an average plate yield strength of 34.9 ksi and tensile strength of 51.3 ksi. Plate holes ranged from 1/16 in. to 3/8 in. greater than the bolt diameter. All plate holes were measured prior to testing to ensure correct diameters.

The test setup involved placing the bolt head along with a plate on the front of the Skidmore Calibrator with a flat bushing on the rear. A washer and nut were then placed on the bolt and tightening was done from the back of the calibrator. A typical setup from the front of the Skidmore Calibrator is shown in Figure 4.1. Additional photographs of the test setup are in Appendix E. Two electrically powered Tone wrenches were to tighten the bolts; Model S-60EZA for the 5/8 in. through 7/8 in. bolts and Model S-110EZ for the 1 in. and 1-1/8 in. bolts.

Once the bolts were installed in the Skidmore Calibrator, the Tone wrench was used to snug the bolts against the plate. After waiting several seconds, the wrench was then used to tighten the bolts until the splined end sheared off. An initial measurement of bolt pretension was taken 5-10 seconds after tip twist-off. A second reading was taken 30-45 seconds later, after most of the bolt relaxation had occurred. The bolt was then removed using an air impact wrench. All bolts and plates were visually inspected after testing for concerns such as plate embedment depths which occur when the bolt head recesses into the plate.

The test plate matrices used for each bolt diameter are given in Tables 4.1 and 4.2. Bolt strengths of F1852/A325 and A490 were used for bolts with diameters ranging from 3/4 in. through 1-1/8 in. Only 5/8 in. diameter F1852/A325 strength bolts were tested, due to the lack of availability of A490 strength twist-off bolts in this diameter.

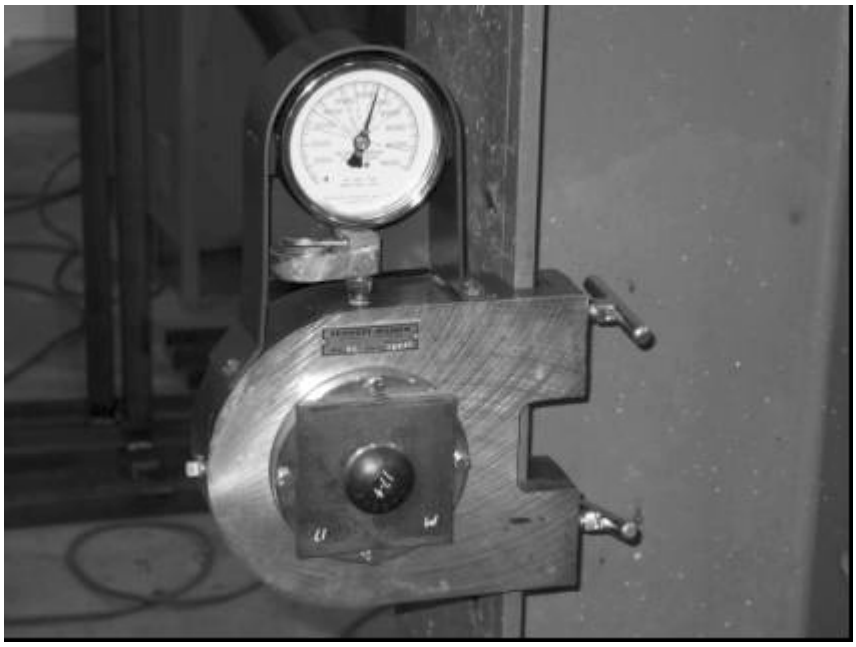


Figure 4.1: Typical Skidmore Calibrator Setup with Test Sample

The first set of tests was conducted with the bolts centered in the hole. The holes in these plates were punched, which resulted in a slightly larger hole diameter on one side of the plate. All bolt diameters except the 7/8 in. were placed in the Calibrator with the larger diameter facing the bolt head. The plates used for the 7/8 in. bolts were reversed so that the smaller diameter was now facing the bolt head. This was done to determine if there would be any noticeable difference in performance. The effects of reversing the plates for the 7/8 in. bolts will be discussed subsequently.

After the first set of tests was completed, a second set of tests was conducted placing the bolt to one side of the holes. This was done to determine if there were any deviations in performance compared to tests performed with the bolts centered in the holes. Bolt diameters of 3/4 in. through 1-1/8 in. were used for these tests, as shown in Table 4.2. The holes in these plates were punched as well as drilled. Additional plates were needed for the 5/16 in. and 3/8 in. oversized holes so more were drilled from leftover smaller diameter punched plates. All plates were placed with the larger hole diameter facing the bolt head.

Table 4.1: Test Matrix with Bolts Centered in Holes

	Hole Size					
Bolt Diameter	**Standard Holes**	**3/16" Oversized**	**1/4" Oversized**	**5/16" Oversized**	**3/8" Oversized**	**Long-Slotted**
5/8" (A325 only)	11/16"	13/16"	7/8"	15/16"		11/16" x 1-9/16"
3/4"	13/16"		1"	1-1/16"		13/16" x 1-7/8"
7/8"	15/16"		1-1/8"	1-3/16"		15/16" x 2-3/16"
1"	1-1/16"		1-1/4"	1-5/16"		1-1/16" x 2-1/2"
1-1/8"	1-3/16"			1-7/16"	1-1/2"	1-3/16" x 2-13/16"

(Five bolts were tested on each hole size for both head diameters and strengths in the above matrix, 370 total tests)

Table 4.2: Test Matrix with Bolts Placed to One Side of Hole

	Hole Size		
Bolt Diameter	**5/16" Oversized**	**3/8" Oversized**	**Short-Slotted**
3/4"			1-1/16" x 1-5/16"
7/8"	1-3/16"		
1"			1-3/16" x 1-9/16"
1-1/8"		1-1/2"	

(Four bolts were tested on each hole size for both head diameters and strengths in the above matrix, 64 total tests)

As previously explained, the F1852 minimum and manufacturer's standard bolt heads were tested in standard, oversized, and long-slotted holes in centered and off-centered positions. With a change in hole size along with bolt position, there is a change in the bearing area between the plate and the underside of the bolt head. The influence of bearing area on the achievable pretension force for twist-off bolts is discussed further in the following sections.

5. EXPERIMENTAL RESULTS

5.1 Overview

Results for the tests on the F1852/A325 and A490 strength bolts are summarized in Appendices C and D, respectively. The data shows initial and relaxed bolt pretension strengths that were read directly from the Skidmore Calibrator. Usually a drop of one to two kips occurred between the initial and relaxed readings. All of the plots that are presented use the achieved relaxed pretension.

5.2 Results for F1852/A325 Strength, Centered Bolts

In Figures 5.1 through 5.3, F1852/A325 strength, ASTM F1852 minimum head diameter relaxed bolt tensions are compared against those for the manufacturer's standard bolts. The three figures are for standard, oversized, and long-slotted holes with all of the bolts centered in the holes. Each of these figures clearly indicates that the F1852 minimum head diameter bolts are able to achieve the pretension equivalent to that for the manufacturer's standard bolt. All of the F1852/A325 strength bolts, minimum and standard, were above the necessary required bolt pretension force. The minimum head diameter bolts are all within reasonable scatter, as well.

More significantly, the size of the hole in the plate caused no significant effect on the achieved bolt pretensions. The bolt forces developed in the standard, oversized, and long-slotted holes are all randomly distributed within the normal scatter for both minimum and standard bolt diameters. Figures C.1 and C.2 in Appendix C further illustrate this conclusion. A more in-depth look at the pretension forces for each bolt diameter is available in Figures C.3 through C.7. Individual graphs for each F1852/A325 strength bolt diameter are provided which show the achieved relaxed pretension for each specific hole size. The F1852 minimum and the manufacturer’s standard bolt heads are compared. Pretension forces for the minimum and standard bolt heads for each hole clearance have been averaged and are connected by the solid and dashed lines. The lack of significant change in the lines illustrates the similar pretension averages between different hole sizes as well as between the minimum and standard bolt heads.

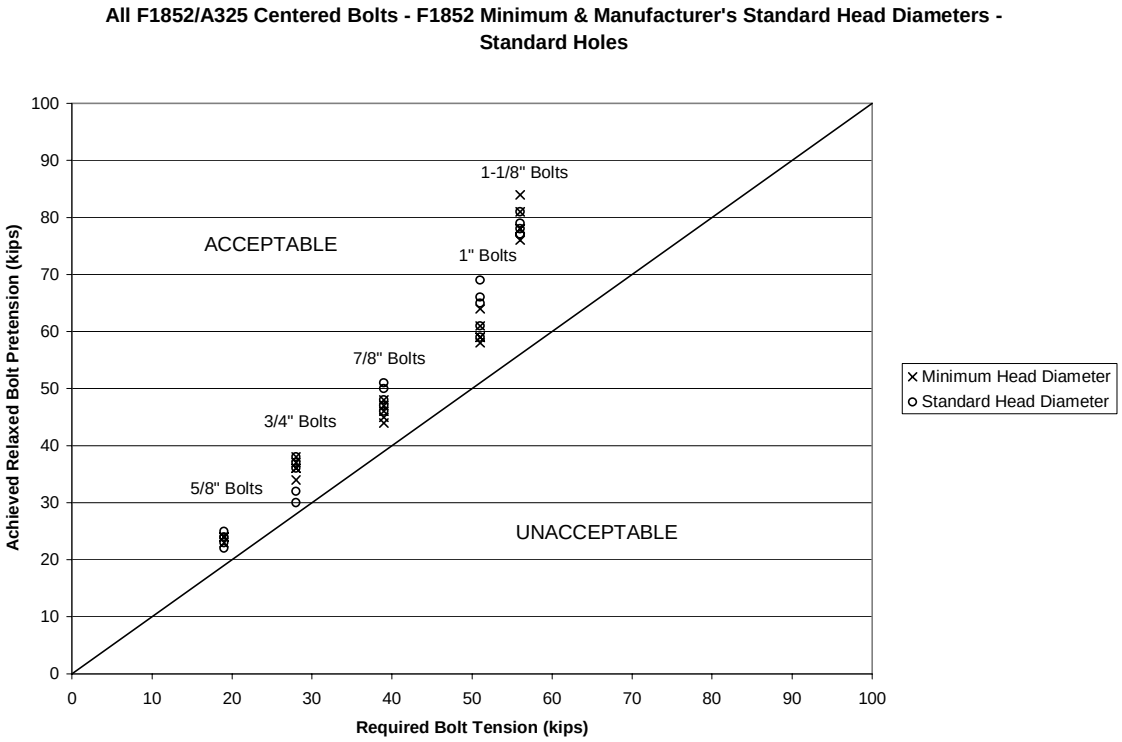


Figure 5.1: F1852/A325 Strength, Centered Bolts, Standard Holes

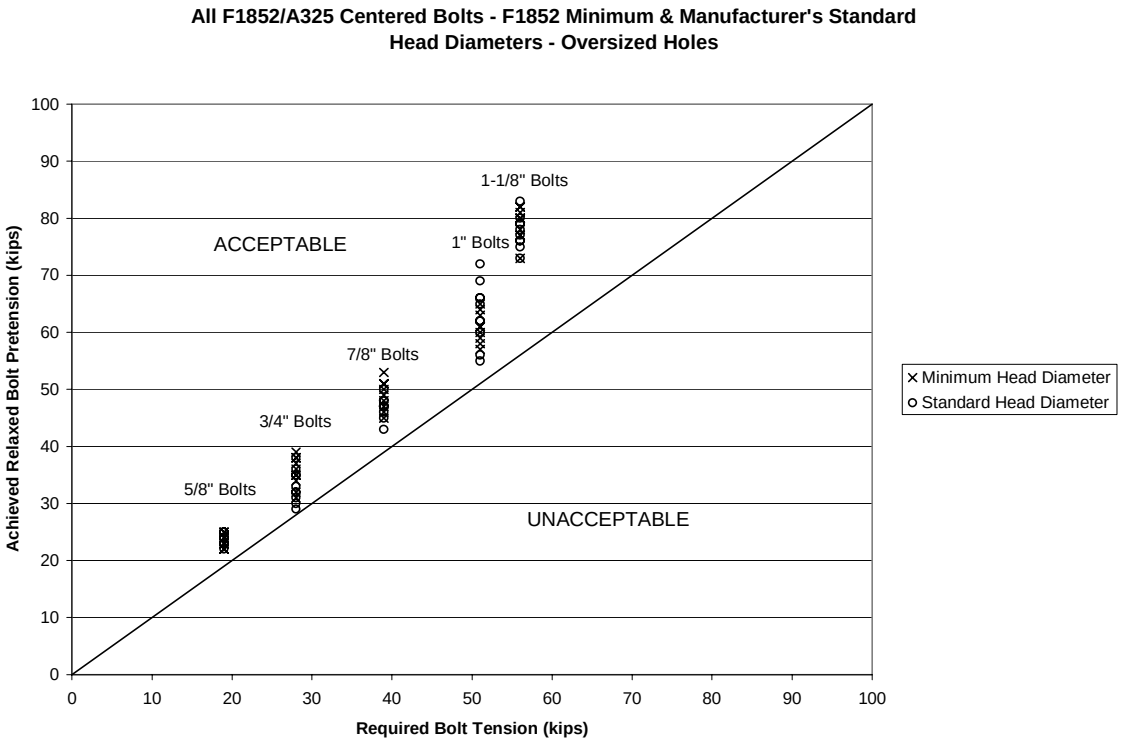


Figure 5.2: F1852/A325 Strength, Centered Bolts, Oversized Holes

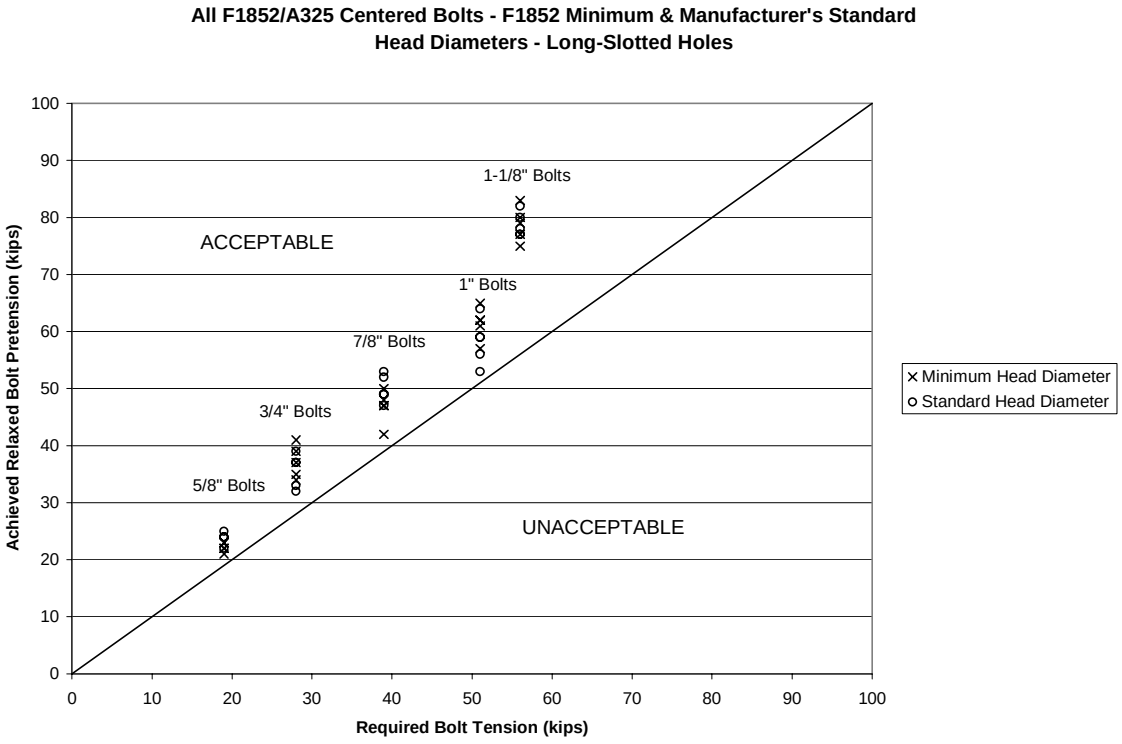


Figure 5.3: F1852/A325 Strength, Centered Bolts, Long-Slotted Holes

5.3 Results for A490 Strength, Centered Bolts

In Figures 5.4 through 5.6, the relaxed pretension achieved using A490 strength bolts with the ASTM F1852 minimum head diameter are compared against the manufacturer's standard bolts. The figures are divided by standard, oversized, and long-slotted holes with all of the bolts centered in the holes. All three plots are consistent with the results from the F1852/A325 strength tests. The F1852 minimum head diameter bolt results show no indication that such bolts are unable to achieve as much pretension as the manufacturer's standard head bolt. A single 7/8 in. manufacturer's standard head bolt was found to have a relaxed pretension of 42 kips which is well below the required pretension of 49 kips. It is believed that this bolt was damaged in some way. In spite of this, it still has been included in the averages and statistical results. The 7/8 in. bolts were closest to the required pretension for both the minimum and manufacturer's standard bolt heads. The range of minimum and maximum pretension increased as the hole sizes increased from standard to oversized to long-slotted. This is most evident for the 1-1/8 in. bolts.

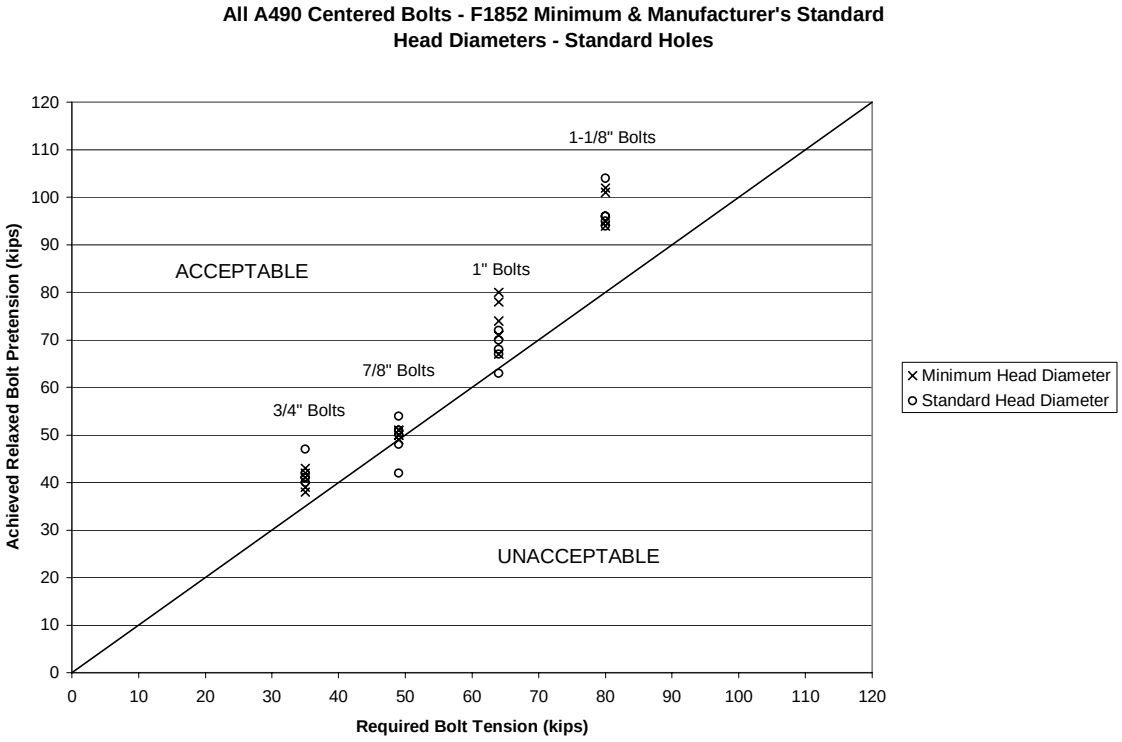


Figure 5.4: A490 Strength, Centered Bolts, Standard Holes

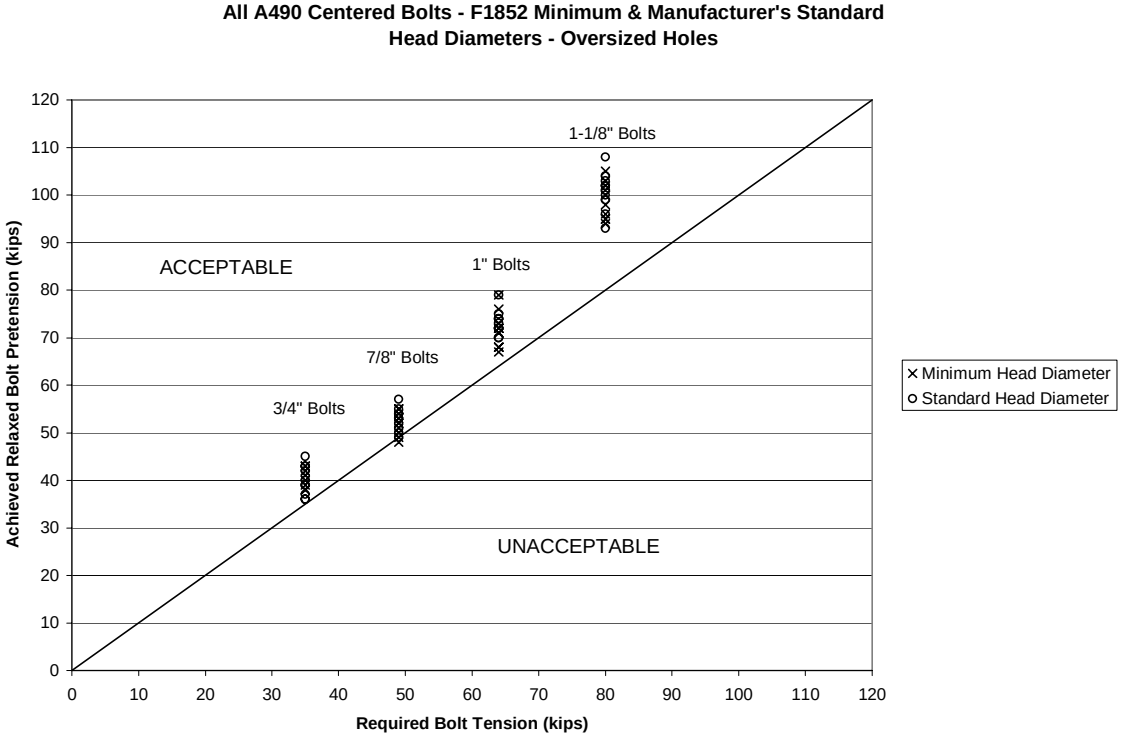


Figure 5.5: A490 Strength, Centered Bolts, Oversized Holes

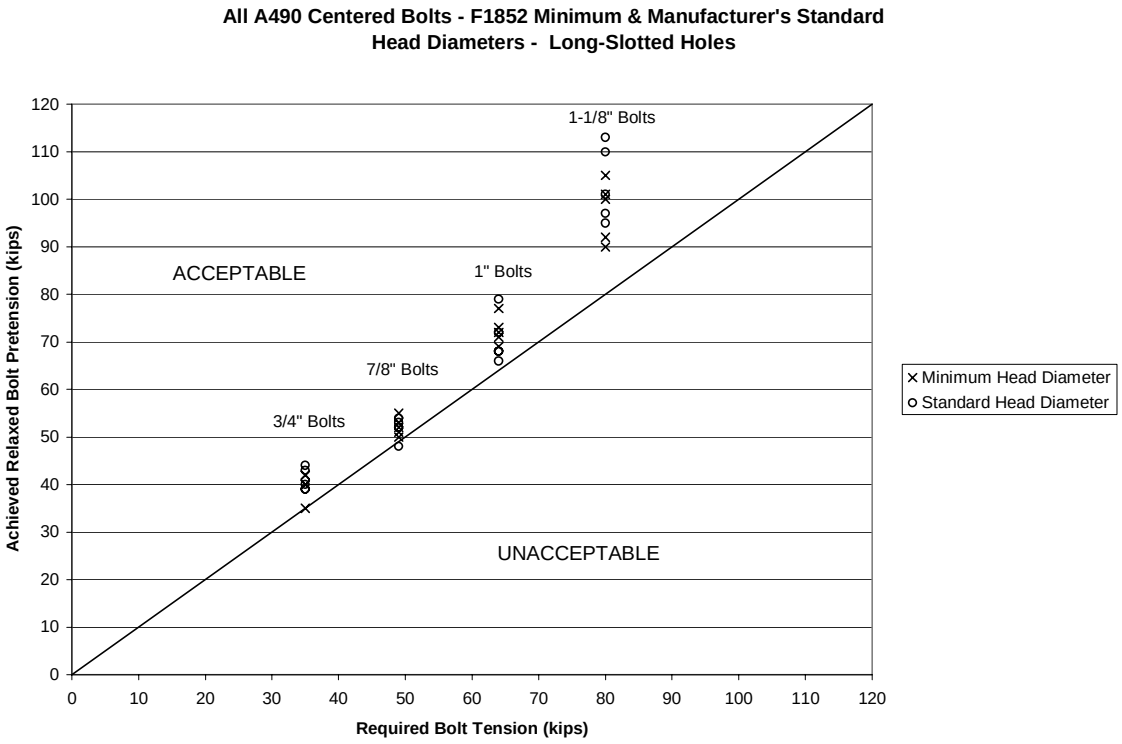


Figure 5.6: A490 Strength, Centered Bolts, Long-Slotted Holes

The effect of hole size on the relaxed pretension of the A490 bolts can be seen in Figures D.1 and D.2 in Appendix D. The effect of standard, oversized, and long-slotted holes on relaxed pretension force is minimal. The achieved pretensions for all four hole sizes are within the expected distributions for both the minimum and standard head diameters. A possible reason for the lower results on the 7/8 in. A490 strength bolts is the reversal of the test plates for this diameter, as explained in the previous chapter. Available in Figures D.3 through D.6 are individual graphs for each A490 bolt diameter showing the achieved relaxed pretension for each specific hole size. F1852 minimum and the manufacturer's standard bolt heads are compared against each other. Pretension forces for the minimum and standard bolt heads on each hole clearance have been averaged and are indicated by the solid and dashed lines. Like the F1852/A325 strength results, there is a lack of significant change in the lines which illustrates the similar pretension averages between different hole sizes as well as between the minimum and standard bolt heads.

5.4 Results for F1852/A325 and A490 Strength, Off-Centered Bolts

After all of the testing with the various bolts centered in the plate holes was complete, a second set of tests was run with bolts set in off-centered positions. This was done with 3/4 in. through 1-1/8 in. bolts with the plate holes shown in Table 4.2. Results of these tests are in Figures 5.7 and 5.8 as well as in Appendix C and D. The achieved relaxed pretensions for minimum and standard bolt diameters were not affected significantly by this alteration. All of the F1852/A325 strength bolts were well above the required pretension. A few of the A490 strength, 7/8 in. bolts were just below the required pretension, which is consistent with the previous tests. The pretension in the 3/4 in. and 1 in. bolts was not affected significantly by the short-slotted holes. Average relaxed pretensions for both bolt diameters were well within the limits of the centered bolt tests. Comparing Figures 5.7 and 5.8 with Figures C.1, C.2, D.1 and D.2 also shows the minor effects of off-centering the bolt.

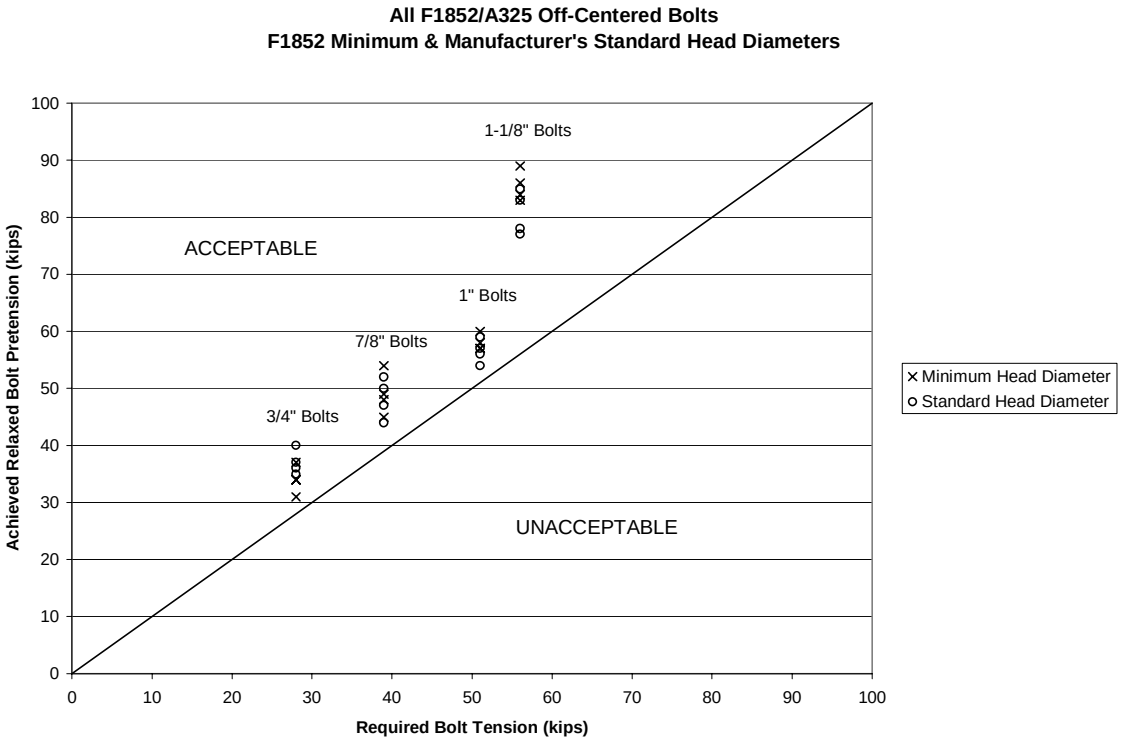


Figure 5.7: F1852/A325 Strength, Off-Centered Bolts

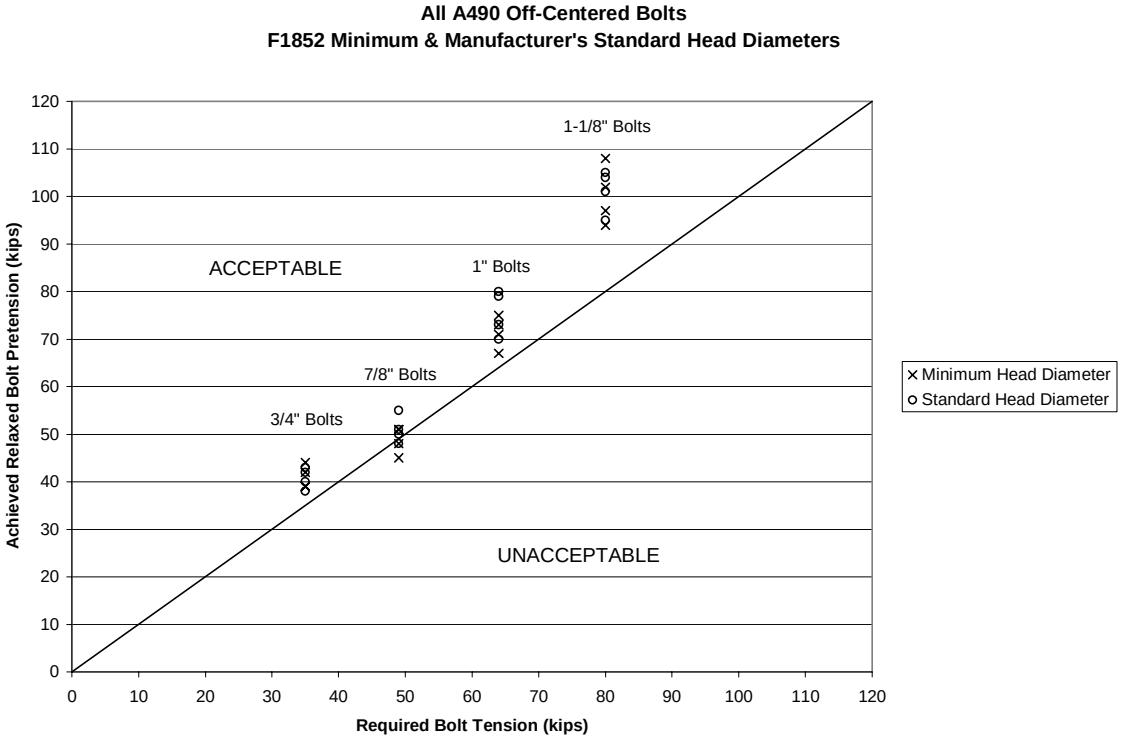


Figure 5.8: A490 Strength, Off-Centered Bolts

The tests conducted on the F1852/A325 and A490 strength, centered and off-centered bolts demonstrate the lack of influence that bolt location in an oversize or slotted hole has on achieved pretension. The hole diameter, whether standard, oversized, or long-slotted relates directly to bearing area under the twist-off bolt head. Whether the bearing area is large or small, the data shows that the achieved pretension force in a twist-off bolt is not significantly affected. The excessively large oversized holes that were tested are almost double of what is allowed by the RCSC Specification yet favorable results are still attainable even at these large clearances.

6. STATISTICAL ANALYSIS

6.1 Overview

For further comparison, a statistical analysis was performed on all of the data. The results are presented in Appendix E. All statistical analysis was performed on the relaxed pretension values obtained. A normalized pretension value is used for the comparisons. This value was calculated as a ratio of relaxed achieved pretension divided by minimum required pretension provided in the RCSC Specification (2000). Values equal to 1.0 are minimum and anything above 1.0 is acceptable. The normalized values were calculated to facilitate comparison between bolt diameters and bolt strengths. For example, the results from a 5/8 in. diameter F1852/A325 strength bolt can be compared against a 1-1/8 in. diameter A490 strength bolt. Evaluating the different standard, oversized, and long-slotted hole performances is also possible.

Figures E.1 through E.9 show the average normalized relaxed pretension value for each centered bolt diameter in the respective hole clearances. The F1852 minimum head is compared against the manufacturer's standard. An overall average for all hole clearances is shown on each table. The overall averages are also presented in Figures E.13 and E.14, which can be used for comparisons between differing bolts diameters and strengths. Figures E.10 through E.12 average all of the normalized values for all of the centered bolts in each specific hole. This was done as a way to compare the different hole clearances for the minimum and standard head diameters. Lastly, Figures E.15 and E.16 compare the results for the off-centered tests that were performed.

Tables from the statistical analyses follow the figures in Appendix E. Tables E.1 through E.5 present average relaxed pretensions, normalized values, and standard deviations for each bolt type tested in the various hole clearances. Table E.6 can be used to relate average normalized values and average standard deviations for F1852/A325, A490 or all bolt strengths for each hole clearance. Table E.7 is a final analysis for the off-centered tests and presents the same type of data discussed for the centered bolts.

6.2 Observations

Looking at Figure E.1, the 5/8 in. F1852/A325 centered bolt performed very well for both the minimum and standard head types in all hole clearances. The normalized values for the minimum and standard head types are consistent with one another and had overall averages of 1.22 and 1.25 respectively. Standard deviations shown in Table E.1 show little variability for each hole clearance. The 5/8 in. F1852/A325 strength bolts had very favorable results with pretension values well above the minimum required.

Figures E.2 and E.3 are for the 3/4 in. F1852/A325 and A490 strength bolts. Both of these strengths show good results for each head type. The normalized values are slightly larger for the F1852/A325 bolts compared to the A490 strength. Standard deviations shown in Table E.2 are noticeably larger for the 3/4 in. as compared to the 5/8 in. centered bolts.

The results for the 7/8 in. centered bolts are presented in Figures E.4 and E.5. The F1852/A325 strength bolts were well above the required minimum. The A490 strength values were much lower, but still above the minimum required. The 7/8 in. A490 strength bolts had the lowest normalized values for all the bolts tested, but the standard deviations for both strengths in Table E.3 are consistent with those from the 3/4 in. bolts. As discussed previously, a cause of these low pretension values for the A490 strength 7/8 in. bolts may be related to the reversal of the test plates for this diameter.

The 1 in. bolts in Figures E.6 and E.7 show positive results as well. Again, the pretension for the minimum and standard head bolts were consistent with each other for both strengths. Like the 3/4 in. and 7/8 in. bolts, the A490 strength bolts had lower overall averages for normalized pretension. Table E.4 reflects the slightly higher variability in the 1 in. bolts.

Figures E.8 and E.9 show very favorable pretension values for the 1-1/8 in. bolts. The F1852/A325 strength bolts performed the best for all bolts tested. The pretension for the minimum and standard heads have average normalized values of 1.41 and 1.39 respectively. The A490 strength was the highest as well for all bolts of that strength with minimum and standard average normalized values of 1.23 and 1.26. Comparisons

between all bolt diameters are in Figures E.13 and E.14. The F1852/A325 strength 1-1/8 in. bolt pretensions had lower standard deviations compared to the A490 strength tests.

The off-centered test results are summarized in Figures E.15 and E.16 and in Table E.7. The F1852/A325 strength bolt pretensions are consistent with the centered bolts, having normalized values that were well above 1.0. The A490 strength bolt pretensions once again were lower but still acceptable. The 7/8 in. A490 strength minimum head diameter bolt pretensions have a normalized value of 0.995. This average includes one pretension force of 45 kips which, when eliminated, raises the normalized value up over 1.0. Standard deviations for the off-centered tests ranged from a low of 1.414 to a high of 6.131. Comparing each of the off-centered deviations to the centered deviations shows little difference between the two.

The best performing F1852/A325 and A490 strength bolts were of 1-1/8 in. diameter. Overall, all bolt diameters and bolt strengths performed well. The 7/8 in. A490 strength bolt pretensions were very close to the minimum required, yet still an average of 5% above the minimum for both head types. The standard deviation or variability of achieved pretension increased as bolt diameter increased. This can be seen in the data tables in Appendix E as well as the figures in Appendix C and D, which reflect the larger range of pretension values as bolt diameter increases.

Figures E.10 through E.12 show that the best performing tests were with hole clearances of 3/8 in. oversized. The data however, is a bit misleading since the 3/8 in. oversized was only tested on the 1-1/8 in. bolts which had the highest normalized values of all bolts.

Figure E.12 reinforces the fact that the minimum head diameter performs just as well as the manufacturer's standard head diameter for all hole clearances. The effects of off-centering the bolts proved to be insignificant.

The statistical analysis performed for this study reinforces the results discussed in Chapter 5. Normalizing the pretension values for all bolt diameters and strengths allows for straightforward comparisons to be made. The best and worst performing bolt diameters, hole clearances, and bolt strengths for the minimum and standard heads were established using the figures and tables available in Appendix E.

Final overall averages for all of the F1852 minimum and manufacturer's standard head bolts in both centered and off-centered positions in all hole clearances have been calculated as well. The averages combine the results for the F1852/A325 and A490 strength tests.

The average normalized relaxed pretension for the F1852 minimum head bolts in centered positions equals 1.211 with an average standard deviation of 2.610 kips. The average normalized relaxed pretension for the manufacturer's standard head bolts in centered positions equals 1.213 with an average standard deviation of 3.224 kips.

The off-centered tests of the F1852 minimum head diameter bolts resulted in an average normalized relaxed pretension of 1.209 with an average standard deviation of 3.140 kips. The off-centered tests of the manufacturer's standard head diameter bolts resulted in an average normalized relaxed pretension of 1.220 with an average standard deviation of 3.258 kips.

7. CONCLUSIONS

The purpose of this investigation was to determine if the RCSC Specification (2000) should be modified to allow for smaller bolt heads on twist-off bolts. The current specification removes washer requirements for bolts with a head bearing diameter equal to that of an ASTM F436 washer (2000a). The ASTM F1852 Specification (2000b) allows for smaller bolt head diameters thus, the conflict.

Testing was conducted on bolts with both minimum and a manufacturer's standard head diameter. The bolts ranged in bolt size from 5/8 in. to 1-1/8 in. and included both F1852/A325 and A490 strength. The bolts were tightened using 1/4 in. plates under the head with various hole sizes and in both centered and off-centered positions. A total of 434 bolt tests were conducted, half with minimum head diameter, the other half with the manufacturer's standard head diameter. Of the 217 minimum head diameter bolts, only three were under the required pretension force and deemed unacceptable. Of those with the manufacturer's standard head diameter, five of the 217 bolts were found to be unacceptable. Seven of these eight unacceptable bolts were 7/8 in. diameter, A490 strength. Overall, bolts with both head diameters performed well in all circumstances, regardless of type, hole size, and location.

Appendix E provides statistical results which can be used for comparisons between bolt diameters, strengths, and hole clearances. The figures and tables also reinforce the fact that bolts with the minimum ASTM F1852 head diameter are comparable to the manufacturer’s standard head diameter, and that both types are able to achieve the necessary pretension required without washers under the head of the bolt on all hole clearances tested in this study.

Final analysis of the data has shown that there is no significant difference in the achieved pretension force between the manufacturer's standard head and minimum bolt head diameter. The data clearly indicates that the minimum head diameter is able to attain the same pretension force as the manufacturer's standard head diameter.

More significantly to the issue of the RCSC Specification (2000) provisions regarding twist-off bolt head diameter, the size of the hole has also been shown not to affect the

pretension force in the bolt. The pretension expected to be achieved using a bolt with the minimum F1852 head diameter is the same as that of a bolt with a larger head diameter equal to the size of a F436 washer, if the hole size does not exceed the clearance limitations in the RCSC Specification. This conclusion can be drawn from the fact that amount of bearing surface under the twist-off bolt head does not affect achieved bolt pretension up to the hole clearances tested in this study. This was demonstrated by measuring bolt pretension with bolts in grossly oversized round holes, centered in long-slotted holes, and off-centered in slotted holes and without the presence of a washer beneath the head as called for in the RCSC Specification. There was no significant reduction in achieved bolt pretension from that of a standard hole diameter, even with minimum bolt head diameters, when these bolts were used in bolt holes that exceeded the oversized diameter permitted by the RCSC Specification. Similarly, the bolt bearing area was at a minimum when used centered in long-slotted holes, yet the achieved bolt pretension was virtually identical to that achieved in a standard hole.

Tests using A490 strength level twist-off bolts in very low-strength steel plate also demonstrated that the achieved pretension was not significantly reduced with either oversized or slotted holes, compared to standard holes.

Because the twist-off bolt uses torque control to establish the shearing of the bolt spline, the resulting pretension is not affected by the amount of embedment in the steel plate that occurs beneath the bolt head. There is a reduction in achieved pretension if turn-of-nut methods are used, as embedment depths increase, as demonstrated by prior University of Illinois tests conducted by Chesson and Munse (1965). The amount of embedment of the steel beneath the bolt head increases with smaller bolt head size, with increasing bolt hole diameter, higher strength (A490 strength compared to F1852/A25 strength) bolts, and lower strength plate material, but there is no correlation with bolt pretension associated with the amount of embedment when the twist-off bolt method is used.

It is recommended that footnote (a) to Table 6.1 of the RCSC Specification (2000) should be revised to reflect that washers are not required beneath the bolt head of a twist-off bolt provided that the bolt head diameter meets the minimum head diameter requirements of ASTM F1852, rather than provide a bearing circle equal to or greater than that of an F436 washer. Similarly, it is recommended that section 6.2.1 be revised to state that a washer is not required beneath the head of an A490 strength twist-off bolt when used in steels with a specified minimum yield strength less than 40 ksi, provided the bolt head diameter meets the minimum head diameter requirements of ASTM F1852.

8. REFERENCES

Allan, R.N., and Fisher, J.W. (1968). "Bolted Joints with Oversize and Slotted Holes." *Journal of the Structural Division, ASCE,* Vol. 94, ST9, pp. 2061-2080.

American Society for Testing and Materials. (2000a). ASTM F 436-93 (2000) "Standard Specification for Hardened Steel Washers." *ASTM Annual Book of Standards,* Vol. 01.08, ASTM, West Conshohocken, PA.

American Society for Testing and Materials. (2000b). ASTM F 1852-00 "Standard Specification for "Twist-off" Type Tension Control Structural Bolt/Nut/Washer Assemblies, Steel, Heat Treated, 120/105 ksi Minimum Tensile Strength." *ASTM Annual Book of Standards,* Vol. 01.08, ASTM, West Conshohocken, PA.

Chesson, E., Jr., and Munse, W.H. (1965). *Studies on the Behavior of High-Strength Bolts and Bolted Joints.* Engineering Experiment Bulletin 469, University of Illinois, Urbana.

Kulak, G.L., and Undershute, S.T. (1998). "Tension Control Bolts: Strength and Installation." *Journal of Bridge Engineering, ASCE,* Vol. 3, No. 1, pp. 15-20.

Oswald, C.J., Dexter, R.J., and Brauer, S. K. (1996). "Field Study of Pretension in Large Diameter A490 Bolts." *Journal of Bridge Engineering, ASCE,* Vol. 1, No. 3, pp. 121-126

Research Council on Structural Connections. (2000). *Specification for Structural Joints Using ASTM A325 or A490 Bolts.* RCSC, Chicago.

Shoukry, Z., and Haisch, W.T. (1970). "Bolted Connections with Varied Hole Diameters." *Journal of the Structural Division, ASCE,* Vol. 96, ST6, pp. 1105-1118.

APPENDIX A

BOLT INSPECTION CERTIFICATES

60501A

INSPECTION CERTIFICATE

SET LOT NO. _____

Specification	Size	Quantity
ASTM F1852 Type 1 -00 ASTM A563 Grade DH +00 ASTM F436 Type 1	5/8-11 UNC X 3	7,920 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

60501

BOLT LOT NO. _____

Date: Aug. 26,'02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %								
	Tensile Strength		PROOF LOAD	Hardness				C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
	Load (lbf)	Position of fracture	19200 lbf. (Length Method)	HRC	Quench	Temper	A325TC ASU										
Spec.	Min. 27100	Part of Screw	Max. +/- 0.0005 in.	25 - 34	--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average	34972	Part of Screw	ALL PASS	32.7	1580	860	7325902	30	25	82	11	14	1	2	8	2	18

05051

NUT LOT NO. _____

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper		C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89	0	--	Min. 850	Heat No.	20 55	—	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	26.9	—	ALL PASS	1562	1067	7309118	44	22	75	13	20	1	2	6

J823

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. _____

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
			C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	39.6	208143	48	12	70	7	4	-	-	-

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 19950
Mean / 5 sets	22512
Standard Deviation	977

REMARKS

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

D. Swift

Figure A.1: Bolt Certificate for 5/8", F1852/A325 Strength Bolts

SET LOT NO. 66201A

INSPECTION CERTIFICATE

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

Specification	Size	Quantity
ASTM F1852 Type 1 -00 ASTM A563 Grade DH -00 ASTM F436 Type 1 -00	3/4-10 UNC X 3-1/4	12,464 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

BOLT LOT NO. 66201

Date: Nov.15,'02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		Proof Load 28400 lbf.	Hardness			USA A325TC										
	Load (lbf)	Position of fracture	(Length Method)	HRC	Quench	Temper		C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
Spec.	Min. 40100	Part of Screw	Max. +/− 0.0005 in.	25 - 34	--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average	48484	Part of Screw	ALL PASS	31.4	1580	900	7240470	30	25	82	11	13	1	3	8	2	14

NUT LOT NO. 08051

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper	DH	C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89	58450	--	Min. 850	Heat No.	20 55	—	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	28.7	—	ALL PASS	1562	1112	7242139	46	21	79	7	24	5	10	11

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. J921

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
		P	C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	42.2	125495	33	18	78	14	5	-	-	-

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 29400
Mean / 5 sets.	37324
Standard Deviation	1727

REMARKS

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.2: Bolt Certificate for 3/4", F1852/A325 Strength Bolts

INSPECTION CERTIFICATE

SET LOT NO. 71821A

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-

Specification	Size	Quantity
ASTM A490 Type 1 -00 ASTM A563 Grade DH -00 ASTM F436 Type 1 -00	3/4-10 UNC X 3-1/4	300 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

BOLT LOT NO. 71821

Date: Mar. 07,'03

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %								
	Tensile Strength		Proof Load	Hardness			A490 USA									
	Load (lbf)	Position of fracture	40,100lbf. (Length Method)	HRC	Quench	Temper		C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100
Spec.	50,100 56,800	Part of Screw	Max. +/- 0.0005 in.		–	Min. 800	Heat No.	30 52	..	Min. 60	Max. 40	Max. 50	–	–	–	–
Average 8 pcs	54636	Part of Screw	ALL PASS	33.5	1580	1031	7442286	40	24	93	8	4	2	6	102	22

NUT LOT NO. 09682

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper	U DH	C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89	58450	–	Min. 850	Heat No.	20 55	–	Min. 60	Max. 40	Max. 50	–	–	–
Mean/5pcs	28.2	—	ALL PASS	1562	1220	S55542	45	21	71	11	28	25	9	14

Thread Accura	
(Bolt & Nut)	
Bolt	ASME I Class 2
Nut	ASME I Class 2

WASHER LOT NO. J926

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
		E	C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	–	–	–	Max. 40	Max. 50	–	–	–
Mean/5 Pcs.	41.4	221761	34	20	79	15	5	–	–	–

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 36,750
Mean / 5 sets.	41,200
Standard Deviation	2,200

REMARKS

THESE BOLTS HA' BEEN MAGNETIC PARTICLE INSPECT IN ACCORDANC WITH THE REQUIREMENTS OF SPECIFICATIO ASTM A490

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.3: Bolt Certificate for 3/4", A490 Strength Bolts

INSPECTION CERTIFICATE

SET LOT NO. _____

Specification	Size	Quantity
ASTM F1852 Type 1 -00 ASTM A563 Grade DH -00 ASTM F436 Type 1	7/8- 9 UNC X 3-1/2	5,425 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

BOLT LOT NO. 60871 Date: Aug. 08, '02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		PROOF LOAD	Hardness				C	Si	Mn	P	S	Cu	Ni	Cr	Mo	B
	Load (lbf)	Position of fracture	39250 lbf. (Length Method)	HRC	Quench	Temper	ASU 4325TC	x 100	x 100	x 100	x 1000	x 1000	x 100	x 100	x 100	x 100	x 10,000
Spec.	Min. 55450	Part of Screw	Max. +/- 0.0005 in.	25 - 34	--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average	71363	Part of Screw	ALL PASS	32.9	1580	869	7241885	32	23	79	6	8	3	4	7	2	17

06151

NUT LOT NO. _____

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %								Thread Accuracy (Bolt & Nut)
				Quench	Temper		C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100	
Spec.	24 - 38	Min. HRB 89	80850	--	Min. 850	Heat No.	20 55	--	Min. 60	Max. 40	Max. 50	--	--	--	Bolt ASME B1.1 Class 2A Nut ASME B1.1 Class 2B
Mean/3pcs.	26.9	— J910	ALL PASS	1562	1256	S52747	43	20	69	11	28	24	8	13	

WASHER LOT NO. _____

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
			C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	40.7	123110	33	18	85	14	9	-	-	-

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 40950
Mean / 5 sets.	54832
Standard Deviation	4082

REMARKS

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.4: Bolt Certificate for 7/8", F1852/A325 Strength Bolts

INSPECTION CERTIFICATE

SET LOT NO. _____

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

Specification	Size	Quantity
ASTM A490 Type 1 -00 ASTM A563 Grade DH-00 ASTM F436 Type 1	7/8- 9 UNC X 3-1/2	2,725 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

BOLT LOT NO. 62371

Date: Sep.20,'02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		PROOF LOAD	Hardness				C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
	Load (lbf)	Position of fracture	55450 lbf. (Length Method)	HRC	Quench	Temper	A490 USA										
Spec.	69300 78550	Part of Screw	Max. +/- 0.0005 in.		--	Min. 800	Heat No.	30 52	_	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average 8 pcs	75827	Part of Screw	ALL PASS	35.7	1580	1022	7440952	40	27	89	9	9	4	5	99	21	0

NUT LOT NO. 06541

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %								Thread Accuracy (Bolt & Nut)
				Quench	Temper	U DH	C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100	
Spec.	24 - 38	Min. HRB 89	80850	--	Min. 850	Heat No.	20 55	—	Min. 60	Max. 40	Max. 50	--	--	--	Bolt ASME B1.1 Class 2A Nut ASME B1.1 Class 2B
Mean/5pcs.	26.8	—	ALL PASS	1562	1049	299684	44	18	70	6	26	4	3	3	

WASHER LOT NO. J917

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
		D	C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	40.5	221344	34	18	77	12	2	-	-	-

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 51450
Mean / 5 sets.	55090
Standard Deviation	2360

REMARKS

THESE BOLTS HAVE BEEN MAGNETIC PARTICLE INSPECTION IN ACCORDANCE WITH THE REQUIREMENTS OF SPECIFICATION ASTM A490

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.5: Bolt Certificate for 7/8", A490 Strength Bolts

60971A

INSPECTION CERTIFICATE

SET LOT NO. _____

Specification	Size	Quantity
ASTM F1852 Type 1 -00 ASTM A563 Grade DH -00 ASTM F436 Type 1	1 - 8 UNC X 3-1/2	6,486 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

60971

BOLT LOT NO. _____ Date: Sep.10,'02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		PROOF LOAD 51500 lbf. (Length Method)	Hardness				C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x10,000
	Load (lbf)	Position of fracture		HRC	Quench	Temper	A325TC USA										
Spec.	Min. 72700	Part of Screw	Max. +/- 0.0005 in.	25 - 34	--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average	90507	Part of Screw	ALL PASS	30.8	1580	869	7241018	31	23	79	8	9	1	3	7	1	19

06451

NUT LOT NO. _____

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper		C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89	106000	--	Min. 850	Heat No.	20 55	--	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	26.5	—	ALL PASS	1562	1085	298334	43	18	68	5	24	7	4	5

J908

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. _____

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
			C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	41.1	401N0764	37	22	70	17	13	--	--	--

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 53550
Mean / 5 sets.	62090
Standard Deviation	3449

REMARKS

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.6: Bolt Certificate for 1", F1852/A325 Strength Bolts

INSPECTION CERTIFICATE

SET LOT NO. 66291A

Specification	Size	Quantity
ASTM A490 Type 1 -00 ASTM A563 Grade DH -00 ASTM F436 Type 1 -00	1 - 8 UNC X 3-1/2	2,005 pcs.

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

BOLT LOT NO. 66291

Date: Jan.27,'03

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		Proof Load	Hardness				C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
	Load (lbf)	Position of fracture	72700 (lbf. (Length Method)	HRC	Quench	Temper	A490 USA										
Spec.	90,900 103,000	Part of Screw	Max. +/- 0.0005 in.		--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average 8 pcs	99703	Part of Screw	ALL PASS	35.5	1580	1049	236620	41	24	89	9	11	8	5	103	22	2

NUT LOT NO. 08851

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper		C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89	106000	--	Min. 850	Heat No.	20 55	—	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	27.2	—	ALL PASS	1562	1256	855540	43	21	70	12	26	23	9	18

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. J924

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
			C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	39.9	40208230	34	19	65	10	2	-	-	-

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 67200
Mean / 5 sets.	76130
Standard Deviation	2240

REMARKS

THESE BOLTS HAVE BEEN MAGNETIC PARTICLE INSPECTION IN ACCORDANCE WITH THE REQUIREMENTS OF SPECIFICATION ASTM A490

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.7: Bolt Certificate for 1", A490 Strength Bolts

INSPECTION CERTIFICATE

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

SET LOT NO. 52201A

Specification	Size	Quantity
ASTM F1852 Type 1 - 00 ASTM A563 Grade DH - 00 ASTM F436 Type 1 - 00	1-1/8" - 7 X 5-1/2"	3,250

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

COPY

BOLT LOT NO. 52201 Date: 03-27-02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		Proof Load	Hardness													
	Load (lbf)	Position of fracture	56450 lbf. (Length Method)	HRC	Quench	Temper	USA A325TC	C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
Spec.	Min. 80100	Part of Screw	Max. +/- 0.0005 in.	25 - 34	--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average	102560	Part of Screw	ALL PASS	27.2	1580	923	7224455	31	25	81	10	12	2	2	7	1	-

NUT LOT NO. 01951

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper	DH	C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89		--	Min. 850	Heat No.	20 55	--	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	28.9	—	ALL PASS	1562	1112	298007	43	18	74	23	24	10	4	2

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. 3756

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
		P	C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	40.9	A82240	52	17	70	11	3	-	-	-

Fastener Tension

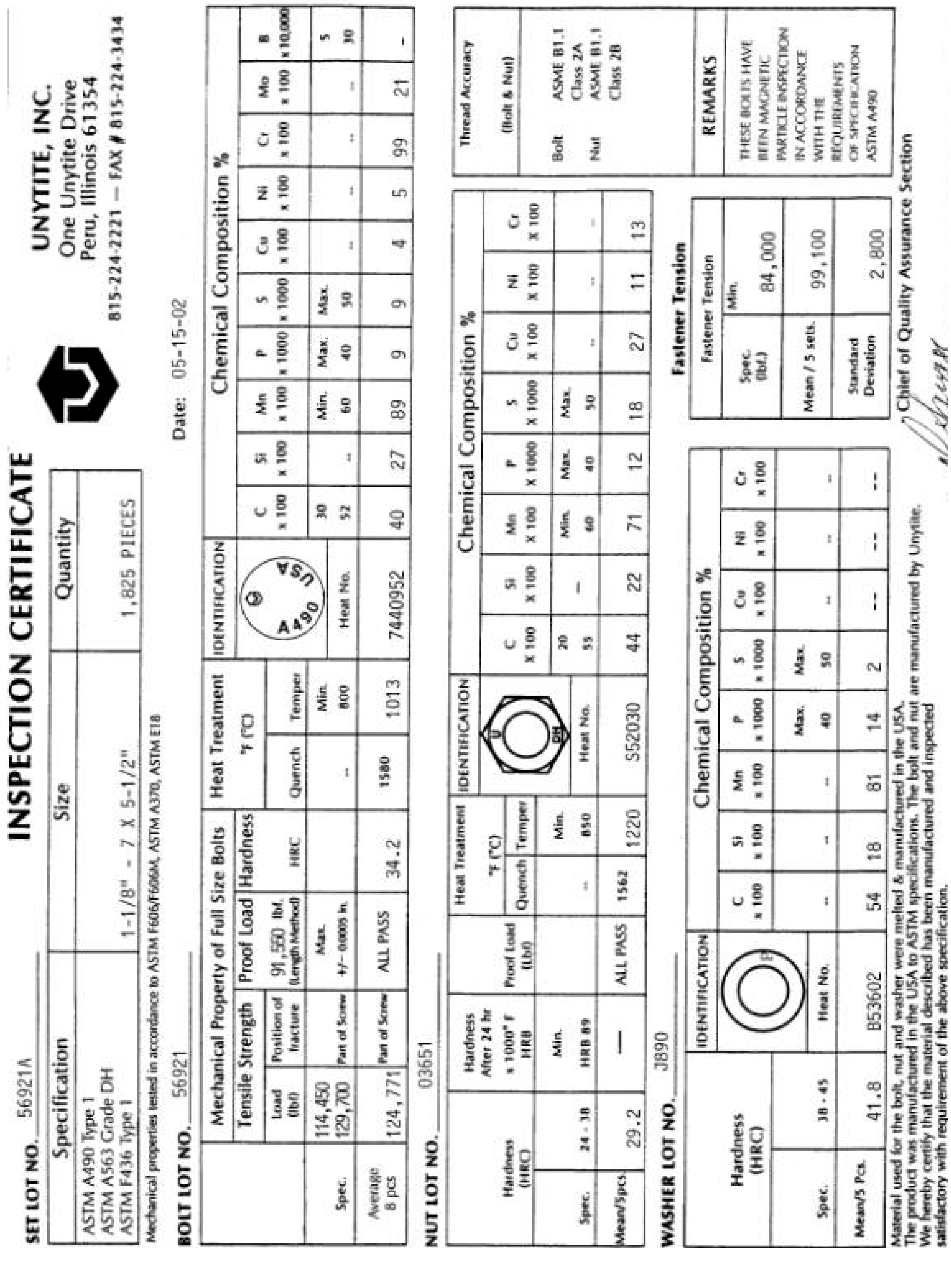
Fastener Tension	
Spec. (lbf.)	Min. 58,800
Mean / 5 sets.	80,300
Standard Deviation	2,200

REMARKS

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected

Chief of Quality Assurance Section

Figure A.8: Bolt Certificate for 1-1/8", F1852/A325 Strength Bolts



INSPECTION CERTIFICATE

SET LOT NO. 56921A

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX # 815-224-3434

Specification	Size	Quantity
ASTM A490 Type 1 ASTM A563 Grade DH ASTM F436 Type 1	1-1/8" - 7 X 5-1/2"	1,825 PIECES

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

BOLT LOT NO. 56921

Date: 05-15-02

	Mechanical Property of Full Size Bolts				Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %									
	Tensile Strength		Proof Load	Hardness			A490 USA										
	Load (lbf)	Position of fracture	91,550 lbf. (Length Method)	HRC	Quench	Temper		C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100	Mo x 100	B x 10,000
Spec.	114,450 129,700	Part of Screw	Max. +/- 0.0005 in.		--	Min. 800	Heat No.	30 52	--	Min. 60	Max. 40	Max. 50	--	--	--	--	5 30
Average 8 pcs	124,771	Part of Screw	ALL PASS	34.2	1580	1013	7440952	40	27	89	9	9	4	5	99	21	-

NUT LOT NO. 03651

Hardness (HRC)		Hardness After 24 hr x 1000° F HRB	Proof Load (Lbf)	Heat Treatment °F (°C)		IDENTIFICATION	Chemical Composition %							
				Quench	Temper		C X 100	Si X 100	Mn X 100	P X 1000	S X 1000	Cu X 100	Ni X 100	Cr X 100
Spec.	24 - 38	Min. HRB 89		--	Min. 850	Heat No.	20 55	—	Min. 60	Max. 40	Max. 50	--	--	--
Mean/5pcs.	29.2	—	ALL PASS	1562	1220	S52030	44	22	71	12	18	27	11	13

Thread Accuracy (Bolt & Nut)	
Bolt	ASME B1.1 Class 2A
Nut	ASME B1.1 Class 2B

WASHER LOT NO. J890

Hardness (HRC)		IDENTIFICATION	Chemical Composition %							
			C x 100	Si x 100	Mn x 100	P x 1000	S x 1000	Cu x 100	Ni x 100	Cr x 100
Spec.	38 - 45	Heat No.	--	--	--	Max. 40	Max. 50	--	--	--
Mean/5 Pcs.	41.8	B53602	54	18	81	14	2	--	--	--

Fastener Tension

Fastener Tension	
Spec. (lbf.)	Min. 84,000
Mean / 5 sets.	99,100
Standard Deviation	2,800

REMARKS

THESE BOLTS HAVE BEEN MAGNETIC PARTICLE INSPECTION IN ACCORDANCE WITH THE REQUIREMENTS OF SPECIFICATION ASTM A490

Material used for the bolt, nut and washer were melted & manufactured in the USA.
The product was manufactured in the USA to ASTM specifications. The bolt and nut are manufactured by Unytite.
We hereby certify that the material described has been manufactured and inspected satisfactory with requirement of the above specification.

Chief of Quality Assurance Section

Figure A.9: Bolt Certificate for 1-1/8", A490 Strength Bolts

APPENDIX B

GRAPHICS OF BOLT AND PLATE LAYOUTS

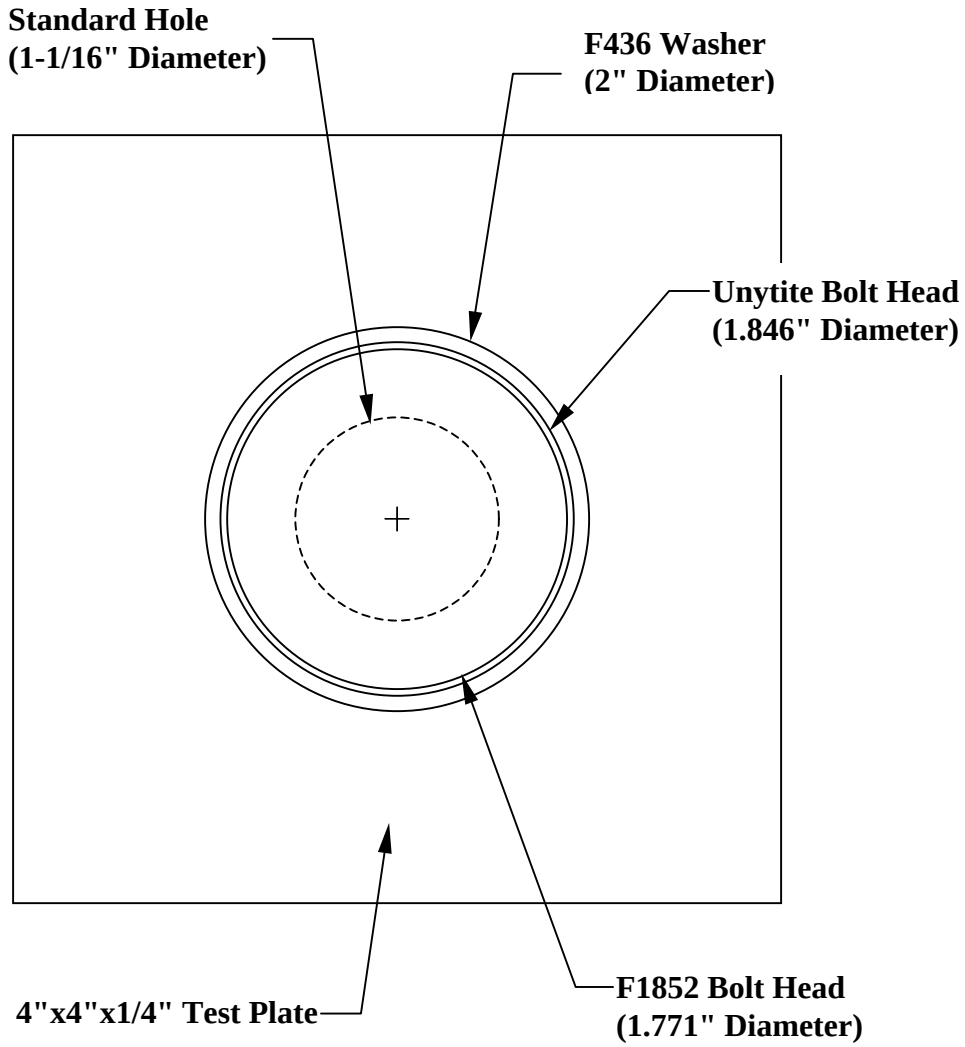


Figure B.1: Bolt and Plate Layout for 1" Bolt in Standard Hole
(Drawn 1:1)

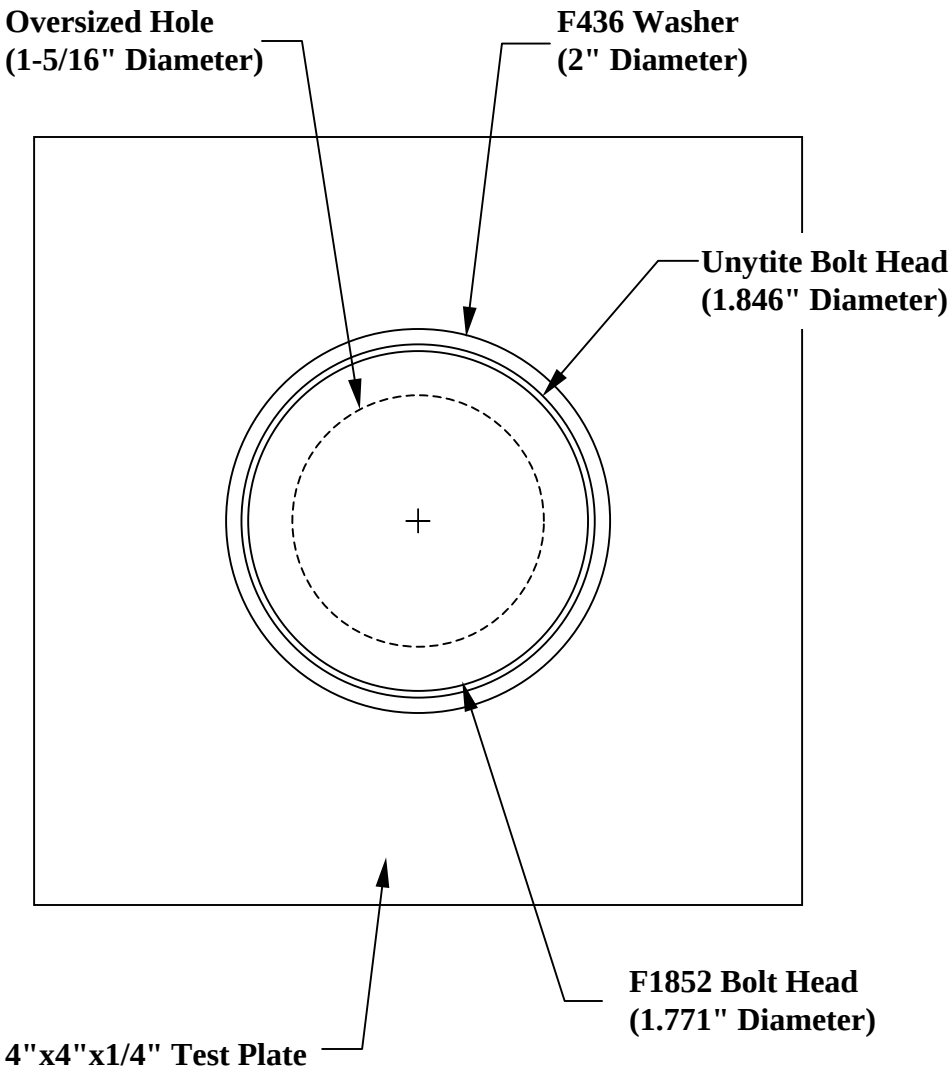


Figure B.2: Bolt and Plate Layout for 1" Bolt in Oversized Hole
(Drawn 1:1)

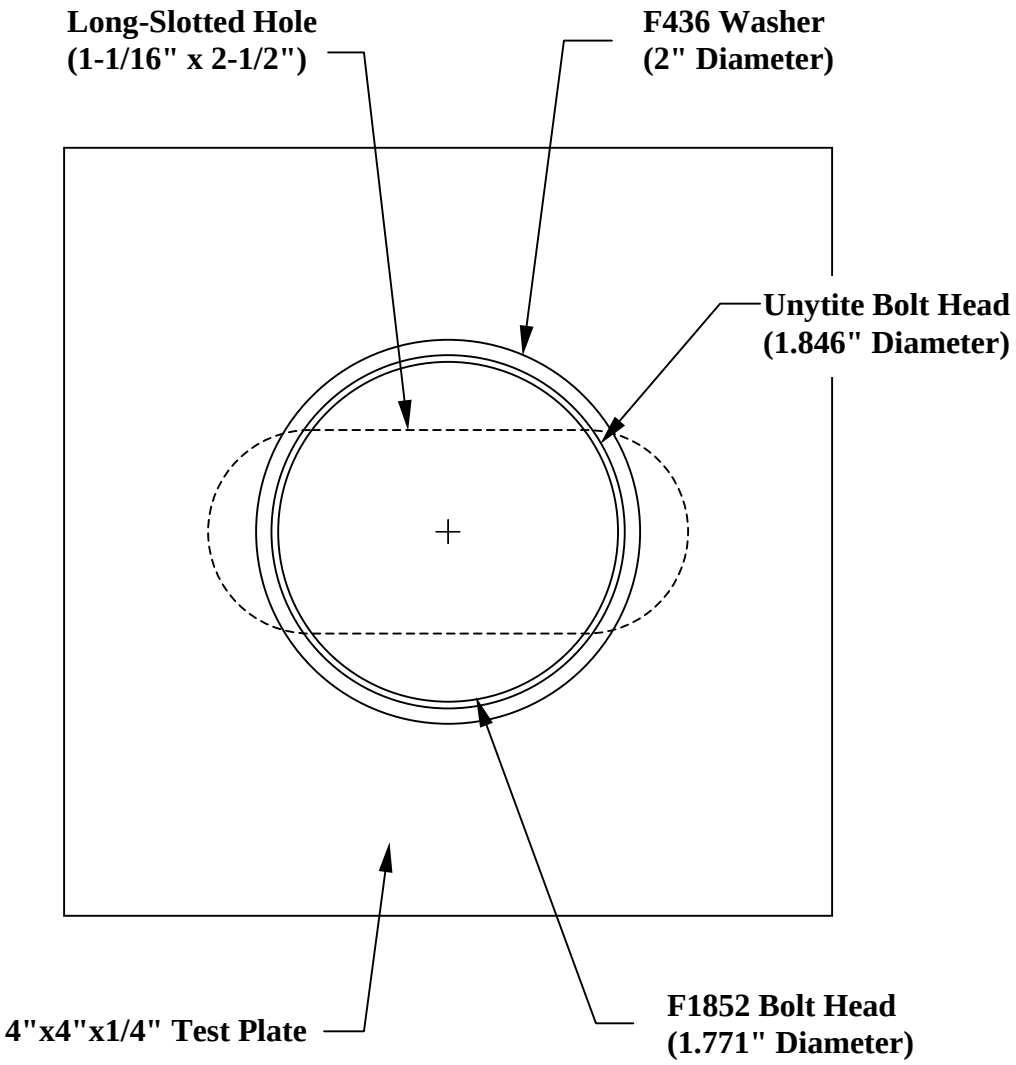


Figure B.3: Bolt and Plate Layout for 1" Bolt in Long-Slotted Hole
(Drawn 1:1)

APPENDIX C

TEST RESULTS FOR F1852/A325 STRENGTH BOLTS

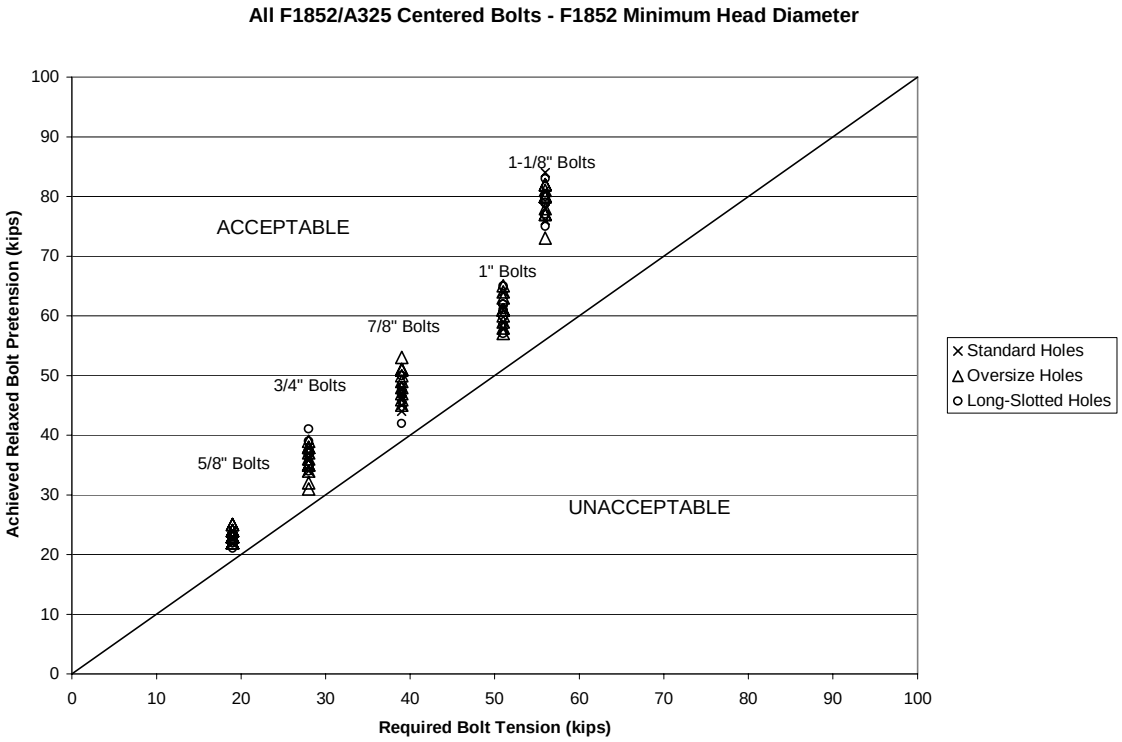


Figure C.1: All F1852/A325 Strength, Centered Bolts, Minimum Head

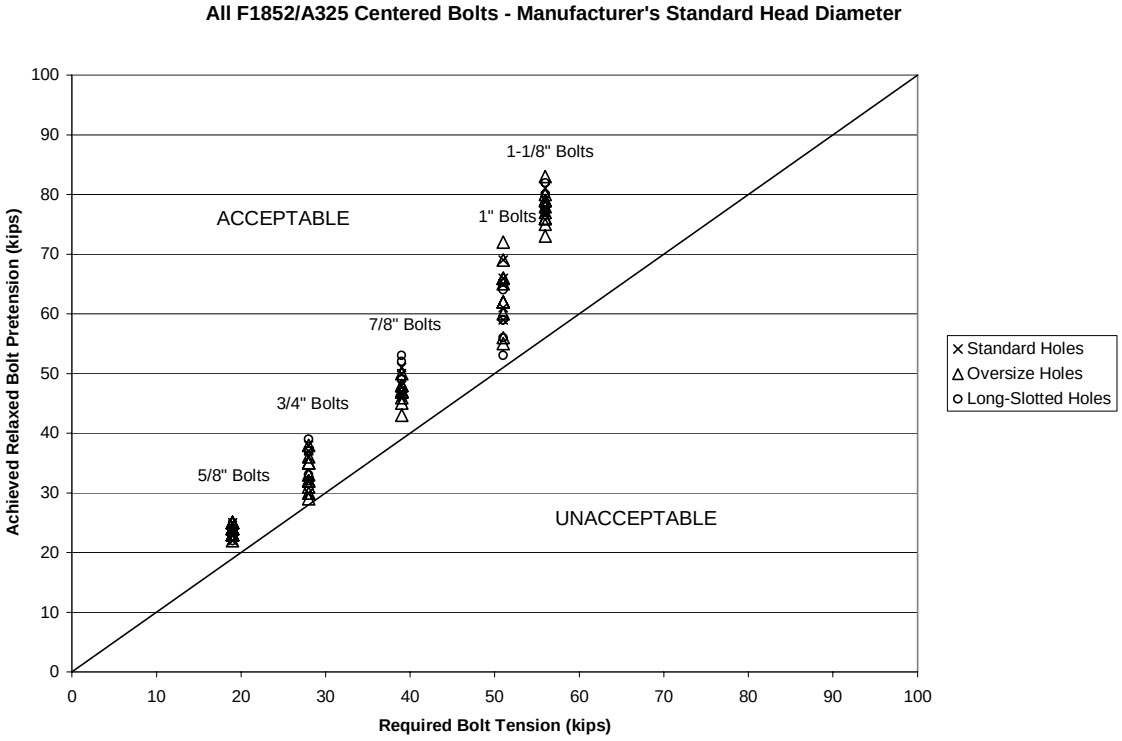


Figure C.2: All F1852/A325 Strength, Centered Bolts, Standard Head

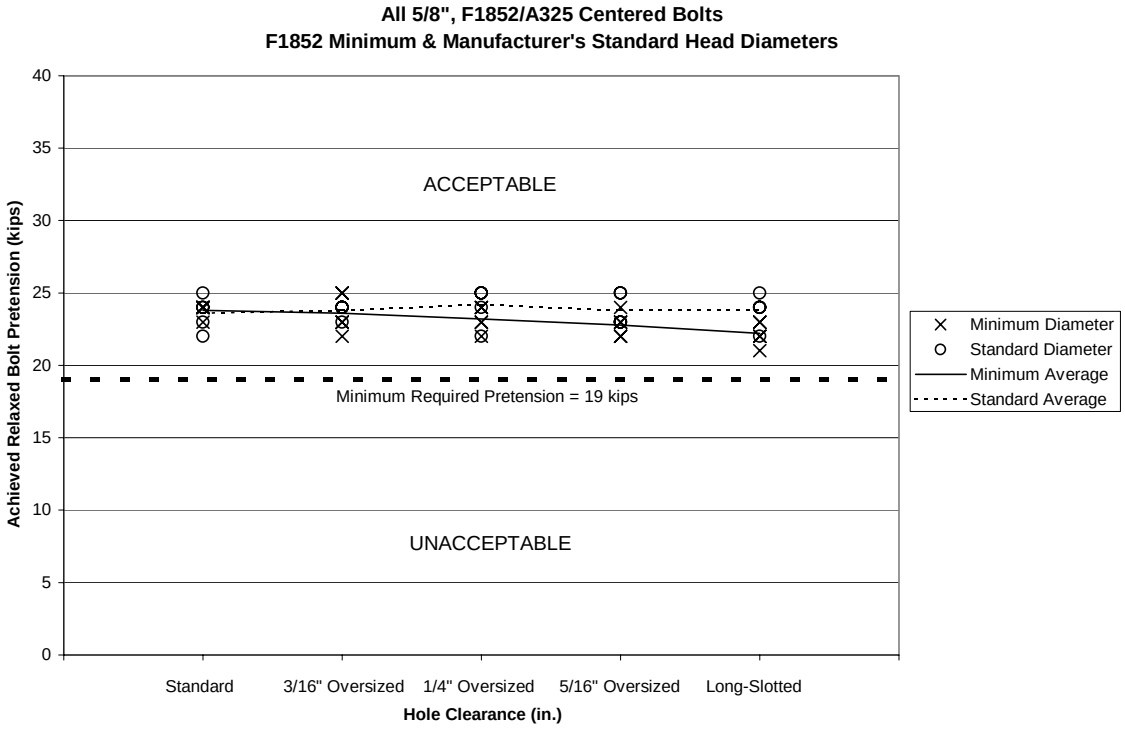


Figure C.3: Results for 5/8" F1852/A325 Strength, Centered Bolts, Minimum & Standard Heads

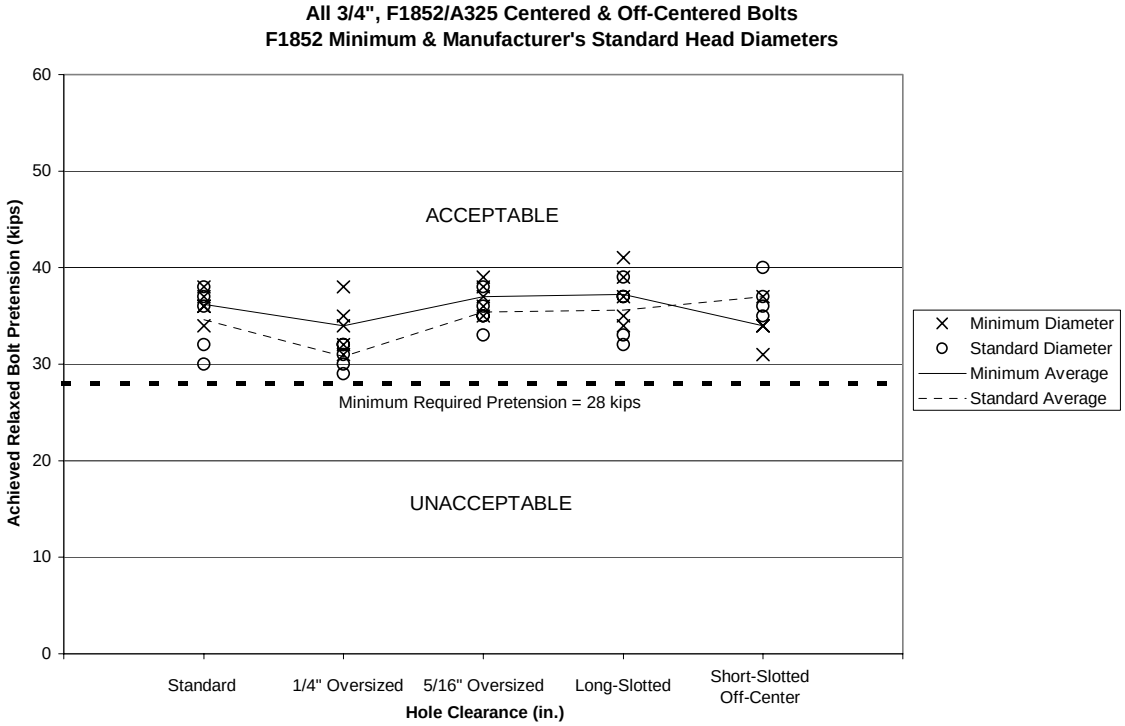


Figure C.4: Results for 3/4" F1852/A325 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

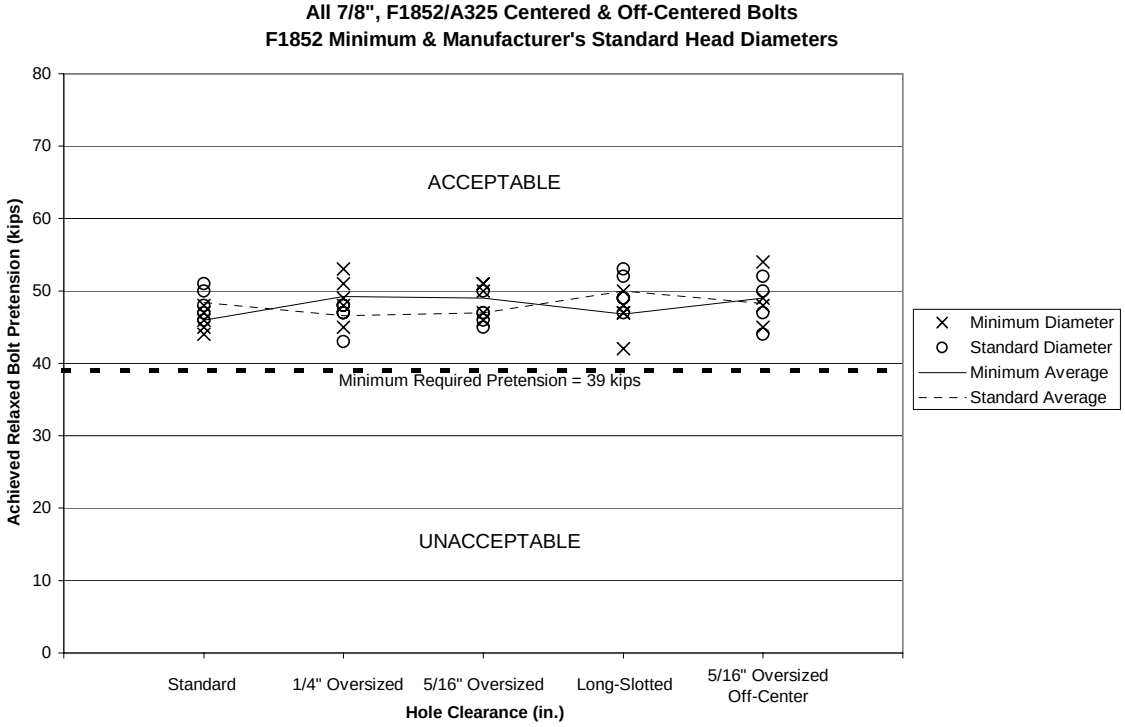


Figure C.5: Results for 7/8" F1852/A325 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

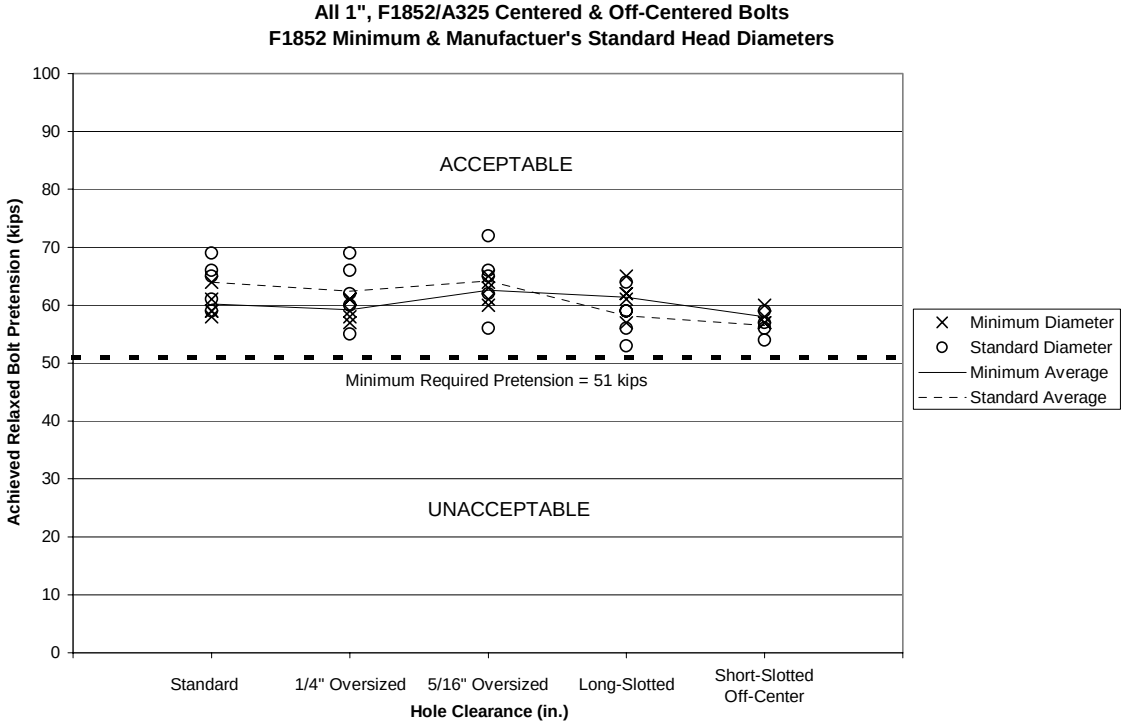


Figure C.6: Results for 1" F1852/A325 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

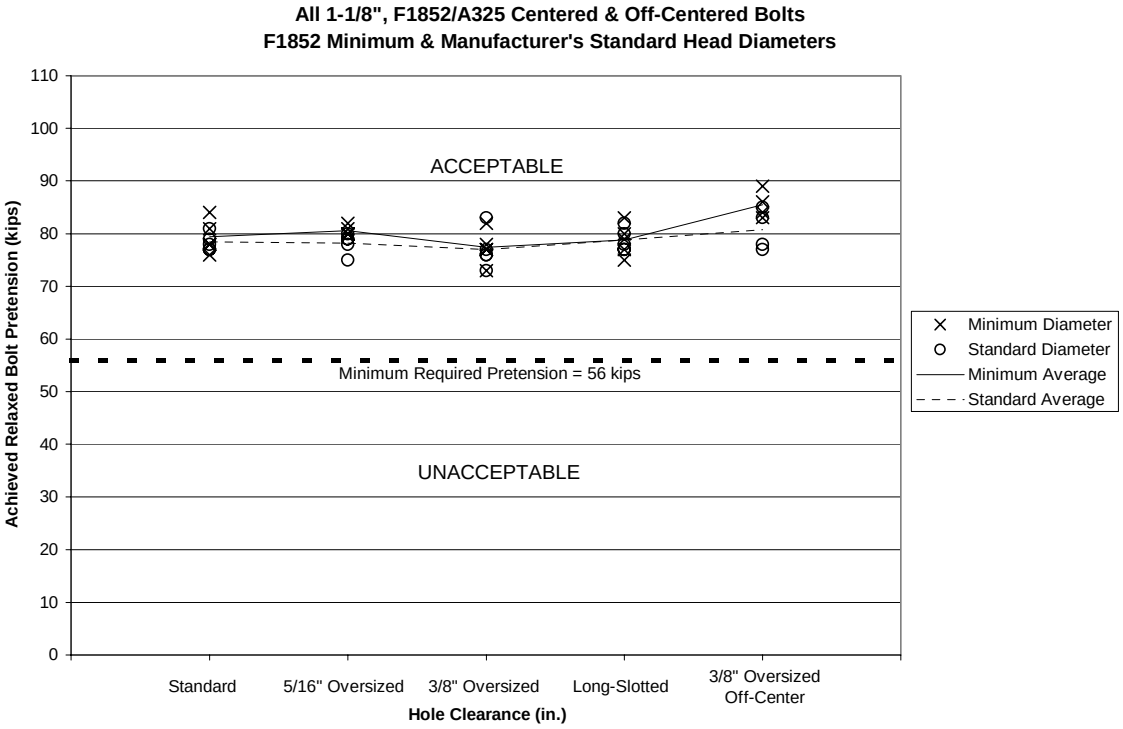


Figure C.7: Results for 1-1/8" F1852/A325 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

Table C.1: Pretension Force in Kips for 5/8" Bolts (F1852/A325 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	**Reading**	**11/16"**	**13/16"**	**7/8"**	**15/16"**	**11/16" x 1-9/16"**
1	**Initial**	24	24	24	25	23
	Relaxed	24	23	24	24	22
2	**Initial**	24	25	23	23	22
	Relaxed	23	25	23	22	21
3	**Initial**	24	25	24	22	23
	Relaxed	24	25	24	22	22
4	**Initial**	24	23	22	24	23
	Relaxed	24	23	22	23	23
5	**Initial**	25	23	23	23	24
	Relaxed	24	22	23	23	23
	Avg Initial	24.2	24.0	23.2	23.4	23.0
	Avg Relaxed	23.8	23.6	23.2	22.8	22.2

Required Bolt Pretension = 19 kips

Table C.2: Pretension Force in Kips for 5/8" Bolts (F1852/A325 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	**Reading**	**11/16"**	**13/16"**	**7/8"**	**15/16"**	**11/16" x 1-9/16"**
1	**Initial**	25	24	25	23	25
	Relaxed	25	24	25	23	25
2	**Initial**	23	24	24	25	24
	Relaxed	23	24	24	25	24
3	**Initial**	22	24	25	25	24
	Relaxed	22	24	25	25	24
4	**Initial**	24	24	22	23	24
	Relaxed	24	24	22	23	24
5	**Initial**	24	23	25	23	22
	Relaxed	24	23	25	23	22
	Avg Initial	23.6	23.8	24.2	23.8	23.8
	Avg Relaxed	23.6	23.8	24.2	23.8	23.8

Required Bolt Pretension = 19 kips

Table C.3: Pretension Force in Kips for 3/4" Bolts (F1852/A325 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	**Reading**	**13/16"**	**1"**	**1-1/16"**	**13/16" x 1-7/8"**	**1-1/16" x 1-5/16" OC**
1	**Initial**	37	32	39	35	31
	Relaxed	36	31	38	34	31
2	**Initial**	34	32	36	36	35
	Relaxed	34	32	35	35	34
3	**Initial**	36	35	37	38	34
	Relaxed	36	34	37	37	34
4	**Initial**	38	38	36	39	37
	Relaxed	37	38	36	39	37
5	**Initial**	38	35	39	42	
	Relaxed	38	35	39	41	
	Avg Initial	36.6	34.4	37.4	38.0	34.3
	Avg Relaxed	36.2	34.0	37.0	37.2	34.0

Required Bolt Pretension = 28 kips

Table C.4: Pretension Force in Kips for 3/4" Bolts (F1852/A325 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	**Reading**	**13/16"**	**1"**	**1-1/16"**	**13/16" x 1-7/8"**	**1-1/16" x 1-5/16" OC**
1	**Initial**	36	31	34	33	36
	Relaxed	36	30	33	32	36
2	**Initial**	38	32	37	39	40
	Relaxed	37	32	36	39	40
3	**Initial**	38	32	39	37	35
	Relaxed	38	31	38	37	35
4	**Initial**	32	30	35	38	38
	Relaxed	32	29	35	37	37
5	**Initial**	31	33	36	33	
	Relaxed	30	32	35	33	
	Avg Initial	35.0	31.6	36.2	36.0	37.3
	Avg Relaxed	34.6	30.8	35.4	35.6	37.0

Required Bolt Pretension = 28 kips

Table C.5: Pretension Force in Kips for 7/8" Bolts (F1852/A325 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	15/16"	1-1/8"	1-3/16"	15/16" x 2-3/16"	1-3/16" OC
1	Initial	49	49	48	43	49
	Relaxed	48	49	47	42	48
2	Initial	48	49	51	48	50
	Relaxed	47	48	51	47	49
3	Initial	45	46	51	48	46
	Relaxed	44	45	50	47	45
4	Initial	47	52	52	50	55
	Relaxed	46	51	51	50	54
5	Initial	45	54	47	49	
	Relaxed	45	53	46	48	
	Avg Initial	46.8	50.0	49.8	47.6	50.0
	Avg Relaxed	46.0	49.2	49.0	46.8	49.0

Required Bolt Pretension = 39 kips

Table C.6: Pretension Force in Kips for 7/8" Bolts (F1852/A325 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	15/16"	1-1/8"	1-3/16"	15/16" x 2-3/16"	1-3/16" OC
1	Initial	46	48	47	52	48
	Relaxed	46	47	47	52	47
2	Initial	47	44	47	48	45
	Relaxed	47	43	46	47	44
3	Initial	51	49	48	49	53
	Relaxed	50	48	47	49	52
4	Initial	49	48	51	50	50
	Relaxed	48	47	50	49	50
5	Initial	52	48	46	54	
	Relaxed	51	48	45	53	
	Avg Initial	49.0	47.4	47.8	50.6	49.0
	Avg Relaxed	48.4	46.6	47.0	50.0	48.3

Required Bolt Pretension = 39 kips

Table C.7: Pretension Force in Kips for 1" Bolts (F1852/A325 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-1/16"	1-1/4"	1-5/16"	1-1/16" x 2-1/2"	1-3/16" x 1-9/16" OC
1	Initial	60	60	65	58	58
	Relaxed	59	59	64	57	57
2	Initial	66	62	64	63	59
	Relaxed	64	61	63	62	58
3	Initial	59	58	62	62	58
	Relaxed	58	57	61	61	57
4	Initial	62	62	61	66	61
	Relaxed	61	61	60	65	60
5	Initial	60	59	66	63	
	Relaxed	59	58	65	62	
	Avg Initial	61.4	60.2	63.6	62.4	59.0
	Avg Relaxed	60.2	59.2	62.6	61.4	58.0

Required Bolt Pretension = 51 kips

Table C.8: Pretension Force in Kips for 1" Bolts (F1852/A325 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-1/16"	1-1/4"	1-5/16"	1-1/16" x 2-1/2"	1-3/16" x 1-9/16" OC
1	Initial	60	70	63	54	57
	Relaxed	59	69	62	53	56
2	Initial	71	63	66	60	60
	Relaxed	69	62	65	59	59
3	Initial	62	67	74	65	55
	Relaxed	61	66	72	64	54
4	Initial	67	61	67	60	58
	Relaxed	66	60	66	59	57
5	Initial	66	56	57	57	
	Relaxed	65	55	56	56	
	Avg Initial	65.2	63.4	65.4	59.2	57.5
	Avg Relaxed	64.0	62.4	64.2	58.2	56.5

Required Bolt Pretension = 51 kips

Table C.9: Pretension Force in Kips for 1-1/8" Bolts (F1852/A325 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-3/16"	1-7/16"	1-1/2"	1-3/16" x 2-13/16"	1-1/2" OC
1	Initial	85	84	78	81	87
	Relaxed	84	82	77	80	86
2	Initial	82	83	74	85	85
	Relaxed	81	81	73	83	84
3	Initial	79	81	84	77	84
	Relaxed	78	80	82	75	83
4	Initial	79	82	79	78	90
	Relaxed	78	80	78	77	89
5	Initial	77	82	79	81	
	Relaxed	76	80	77	79	
	Avg Initial	80.4	82.4	78.8	80.4	86.5
	Avg Relaxed	79.4	80.6	77.4	78.8	85.5

Required Bolt Pretension = 56 kips

Table C.10: Pretension Force in Kips for 1-1/8" Bolts (F1852/A325 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-3/16"	1-7/16"	1-1/2"	1-3/16" x 2-13/16"	1-1/2" OC
1	Initial	79	80	77	79	78
	Relaxed	78	79	76	78	77
2	Initial	80	81	85	78	84
	Relaxed	79	79	83	77	83
3	Initial	82	76	77	81	79
	Relaxed	81	75	76	80	78
4	Initial	78	81	75	83	86
	Relaxed	77	80	73	82	85
5	Initial	78	79	78	79	
	Relaxed	77	78	77	77	
	Avg Initial	79.4	79.4	78.4	80.0	81.8
	Avg Relaxed	78.4	78.2	77.0	78.8	80.8

Required Bolt Pretension = 56 kips

APPENDIX D

TEST RESULTS FOR A490 STRENGTH BOLTS

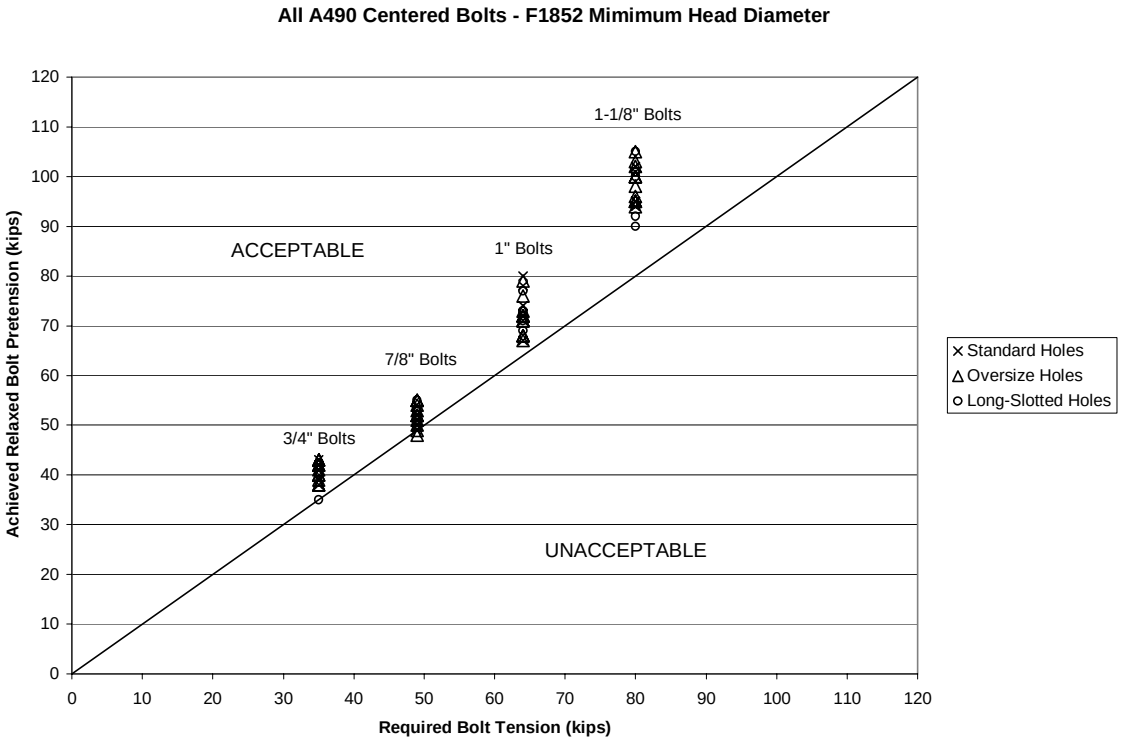


Figure D.1: All A490 Strength, Centered Bolts, Minimum Head

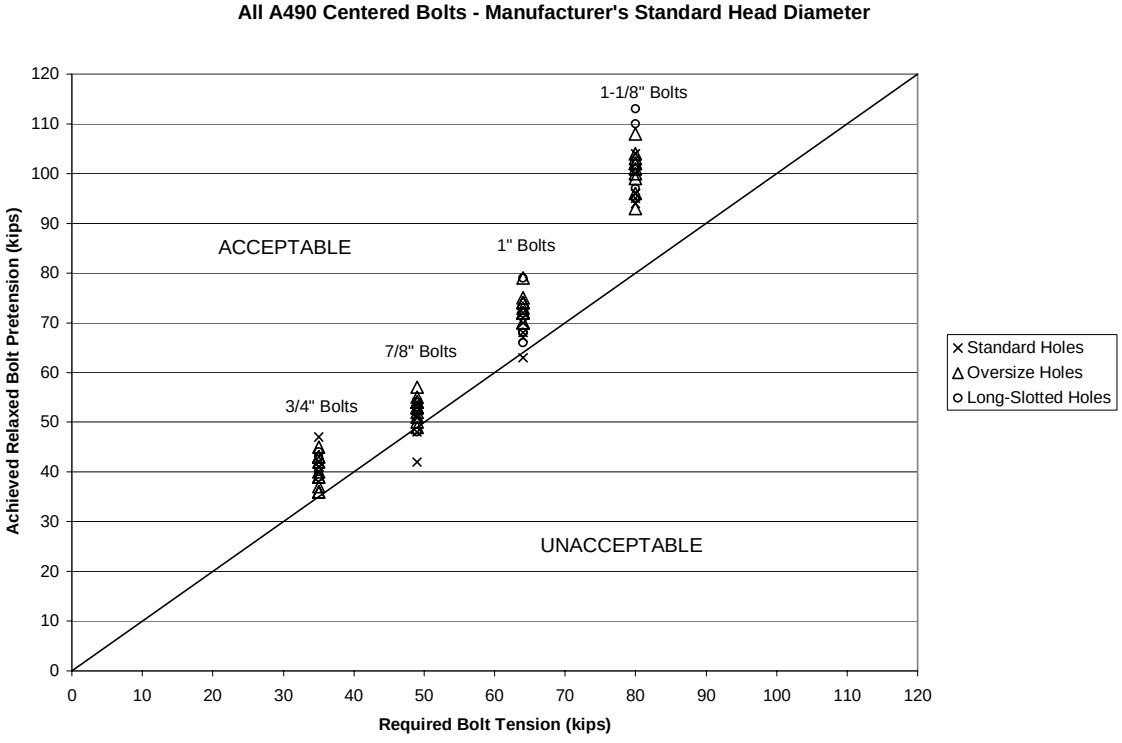


Figure D.2: All A490 Strength, Centered Bolts, Standard Head

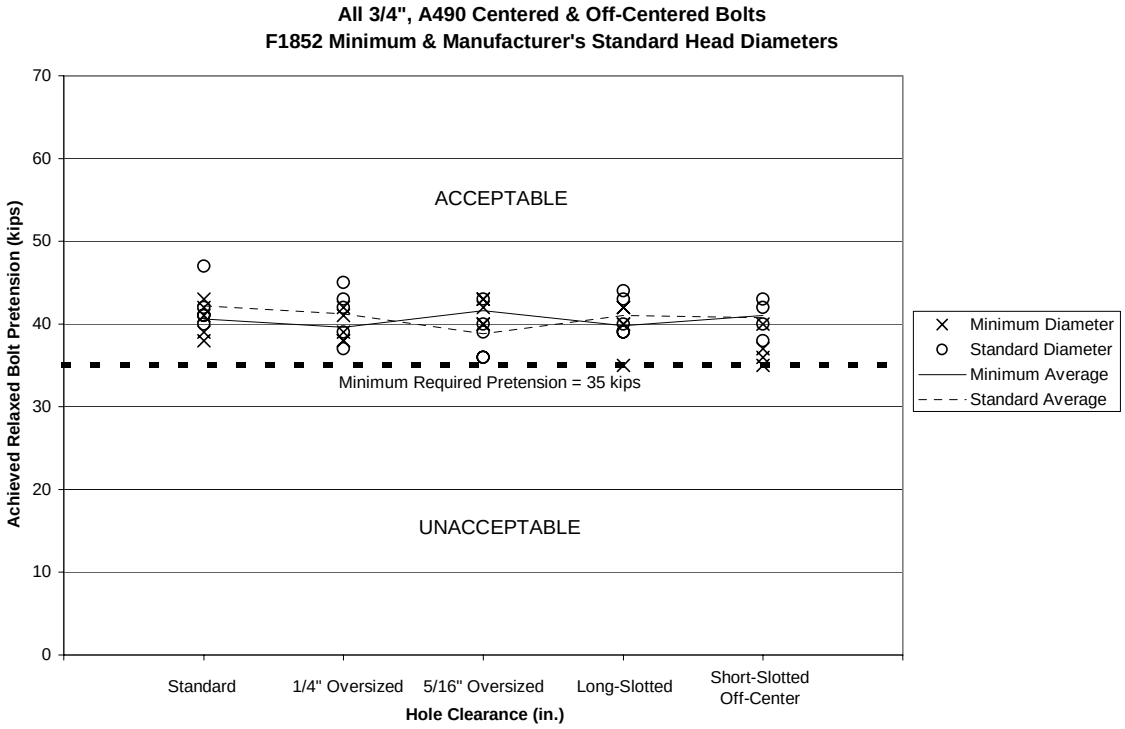


Figure D.3: Results for 3/4" A490 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads,

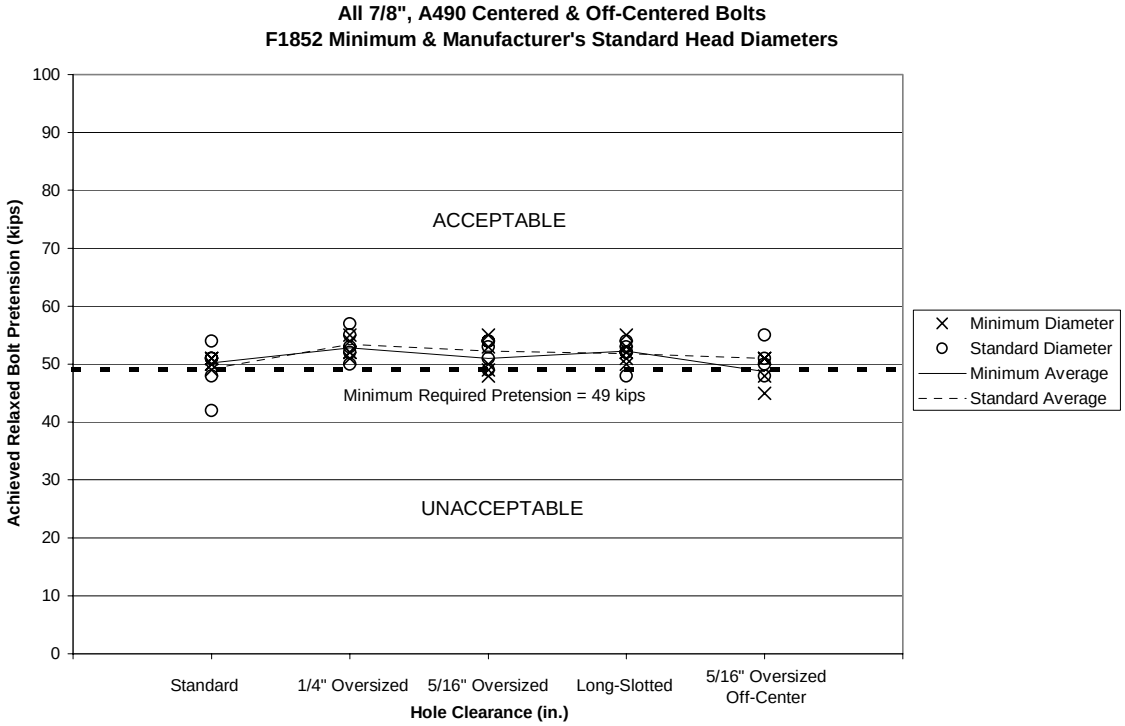


Figure D.4: Results for 7/8" A490 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

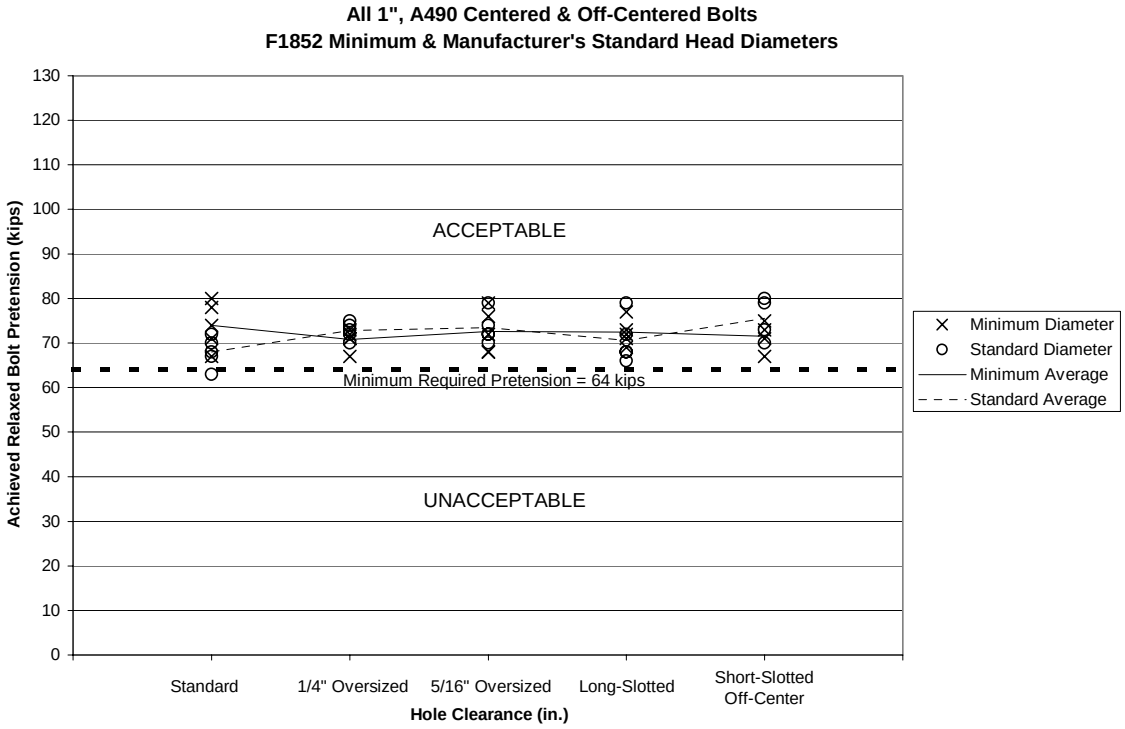


Figure D.5: Results for 1" A490 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

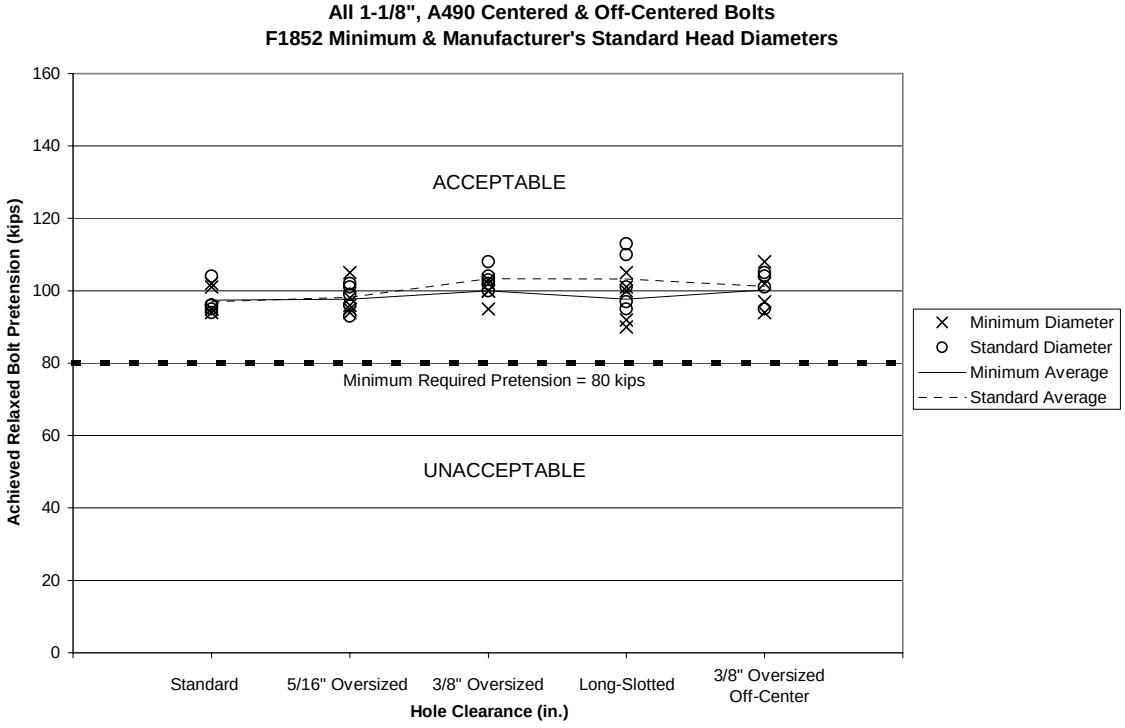


Figure D.6: Results for 1-1/8" A490 Strength, Centered & Off-Centered Bolts, Minimum & Standard Heads

Table D.1: Pretension Force in Kips for 3/4" Bolts (A490 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	13/16"	1"	1-1/16"	13/16" x 1-7/8"	1-1/16" x 1-5/16" OC
1	Initial	39	39	40	35	44
	Relaxed	39	38	40	35	44
2	Initial	42	38	44	42	40
	Relaxed	42	38	43	42	39
3	Initial	44	42	41	41	42
	Relaxed	43	42	40	40	42
4	Initial	39	41	42	42	40
	Relaxed	38	41	42	42	39
5	Initial	42	39	44	41	
	Relaxed	41	39	43	40	
	Avg Initial	41.2	39.8	42.2	40.2	41.5
	Avg Relaxed	40.6	39.6	41.6	39.8	41.0

Required Bolt Pretension = 35 kips

Table D.2: Pretension Force in Kips for 3/4" Bolts (A490 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	13/16"	1"	1-1/16"	13/16" x 1-7/8"	1-1/16" x 1-5/16" OC
1	Initial	47	39	41	44	42
	Relaxed	47	39	40	43	42
2	Initial	40	42	44	45	41
	Relaxed	40	42	43	44	40
3	Initial	42	38	36	41	39
	Relaxed	42	37	36	40	38
4	Initial	42	44	36	40	43
	Relaxed	41	43	36	39	43
5	Initial	41	46	40	39	
	Relaxed	41	45	39	39	
	Avg Initial	42.4	41.8	39.4	41.8	41.3
	Avg Relaxed	42.2	41.2	38.8	41.0	40.8

Required Bolt Pretension = 35 kips

Table D.3: Pretension Force in Kips for 7/8" Bolts (A490 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	15/16"	1-1/8"	1-3/16"	15/16" x 2-3/16"	1-3/16" OC
1	Initial	52	53	50	55	46
	Relaxed	51	52	49	55	45
2	Initial	50	52	54	52	52
	Relaxed	49	52	53	51	51
3	Initial	52	52	50	51	49
	Relaxed	51	51	50	50	48
4	Initial	51	55	49	54	51
	Relaxed	50	54	48	53	51
5	Initial	51	56	56	53	
	Relaxed	50	55	55	52	
	Avg Initial	51.2	53.6	51.8	53.0	49.5
	Avg Relaxed	50.2	52.8	51.0	52.2	48.8

Required Bolt Pretension = 49 kips

Table D.4: Pretension Force in Kips for 7/8" Bolts (A490 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	15/16"	1-1/8"	1-3/16"	15/16" x 2-3/16"	1-3/16" OC
1	Initial	55	53	50	53	51
	Relaxed	54	52	49	52	51
2	Initial	42	56	55	54	51
	Relaxed	42	55	54	53	50
3	Initial	52	58	53	55	48
	Relaxed	51	57	53	54	48
4	Initial	51	54	51	49	56
	Relaxed	51	53	51	48	55
5	Initial	49	51	54	53	
	Relaxed	48	50	54	52	
	Avg Initial	49.8	54.4	52.6	52.8	51.5
	Avg Relaxed	49.2	53.4	52.2	51.8	51.0

Required Bolt Pretension = 49 kips

Table D.5: Pretension Force in Kips for 1" Bolts (A490 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-1/16"	1-1/4"	1-5/16"	1-1/16" x 2-1/2"	1-3/16" x 1-9/16" OC
1	Initial	81	72	69	74	74
	Relaxed	80	71	68	73	73
2	Initial	72	72	69	73	72
	Relaxed	71	71	68	72	71
3	Initial	79	74	80	78	76
	Relaxed	78	73	79	77	75
4	Initial	75	68	77	72	68
	Relaxed	74	67	76	71	67
5	Initial	68	73	73	70	
	Relaxed	67	72	72	69	
	Avg Initial	75.0	71.8	73.6	73.4	72.5
	Avg Relaxed	74.0	70.8	72.6	72.4	71.5

Required Bolt Pretension = 64 kips

Table D.6: Pretension Force in Kips for 1" Bolts (A490 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-1/16"	1-1/4"	1-5/16"	1-1/16" x 2-1/2"	1-3/16" x 1-9/16" OC
1	Initial	73	73	75	73	74
	Relaxed	72	72	74	72	73
2	Initial	64	74	80	80	81
	Relaxed	63	73	79	79	80
3	Initial	68	76	73	69	80
	Relaxed	67	75	72	68	79
4	Initial	69	75	73	67	71
	Relaxed	68	74	72	66	70
5	Initial	71	71	71	69	
	Relaxed	70	70	70	68	
	Avg Initial	69.0	73.8	74.4	71.6	76.5
	Avg Relaxed	68.0	72.8	73.4	70.6	75.5

Required Bolt Pretension = 64 kips

Table D.7: Pretension Force in Kips for 1-1/8" Bolts (A490 Strength, F1852 Minimum Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-3/16"	1-7/16"	1-1/2"	1-3/16" x 2-13/16"	1-1/2" OC
1	Initial	103	98	105	102	96
	Relaxed	101	96	103	100	94
2	Initial	96	96	102	107	104
	Relaxed	95	94	100	105	102
3	Initial	96	97	104	103	110
	Relaxed	94	95	102	101	108
4	Initial	103	107	102	92	99
	Relaxed	102	105	100	90	97
5	Initial	96	100	97	94	
	Relaxed	95	98	95	92	
	Avg Initial	98.8	99.6	102.0	99.6	102.3
	Avg Relaxed	97.4	97.6	100.0	97.6	100.3

Required Bolt Pretension = 80 kips

Table D.8: Pretension Force in Kips for 1-1/8" Bolts (A490 Strength, Manufacturer's Standard Head Diameter)

		Hole Size in Plate				
Test #	Reading	1-3/16"	1-7/16"	1-1/2"	1-3/16" x 2-13/16"	1-1/2" OC
1	Initial	98	98	105	103	106
	Relaxed	96	96	104	101	105
2	Initial	97	104	104	97	102
	Relaxed	96	102	102	95	101
3	Initial	96	103	110	115	96
	Relaxed	95	101	108	113	95
4	Initial	96	100	104	112	105
	Relaxed	94	99	103	110	104
5	Initial	106	95	102	99	
	Relaxed	104	93	100	97	
	Avg Initial	98.6	100.0	105.0	105.2	102.3
	Avg Relaxed	97.0	98.2	103.4	103.2	101.3

Required Bolt Pretension = 80 kips

APPENDIX E

STATISTICAL PLOTS AND TABLES

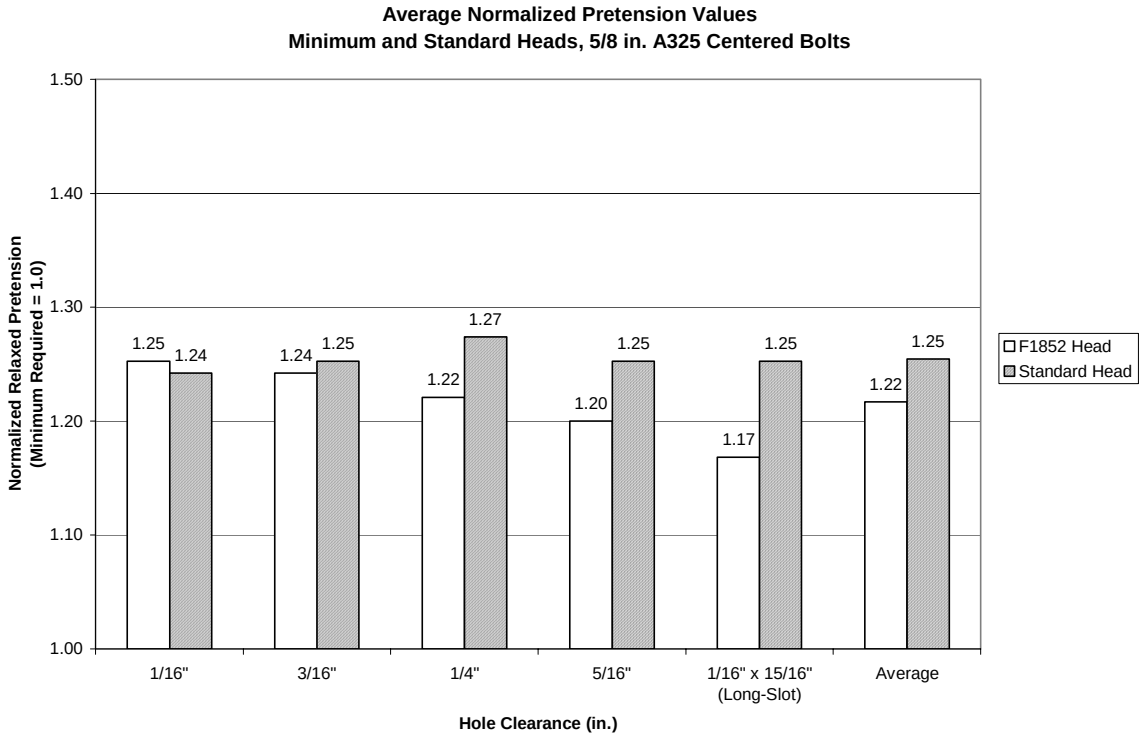


Figure E.1: Normalized Relaxed Pretension for 5/8", F1852/A325 Strength Centered Bolts

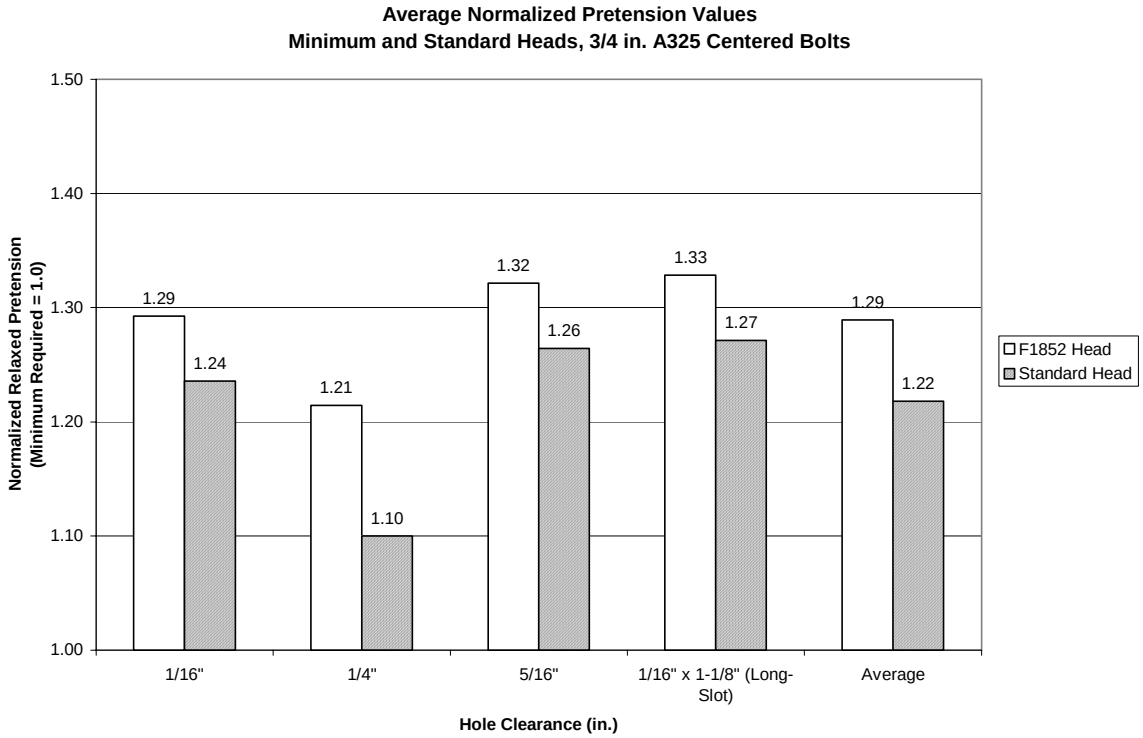


Figure E.2: Normalized Relaxed Pretension for 3/4", F1852/A325 Strength Centered Bolts

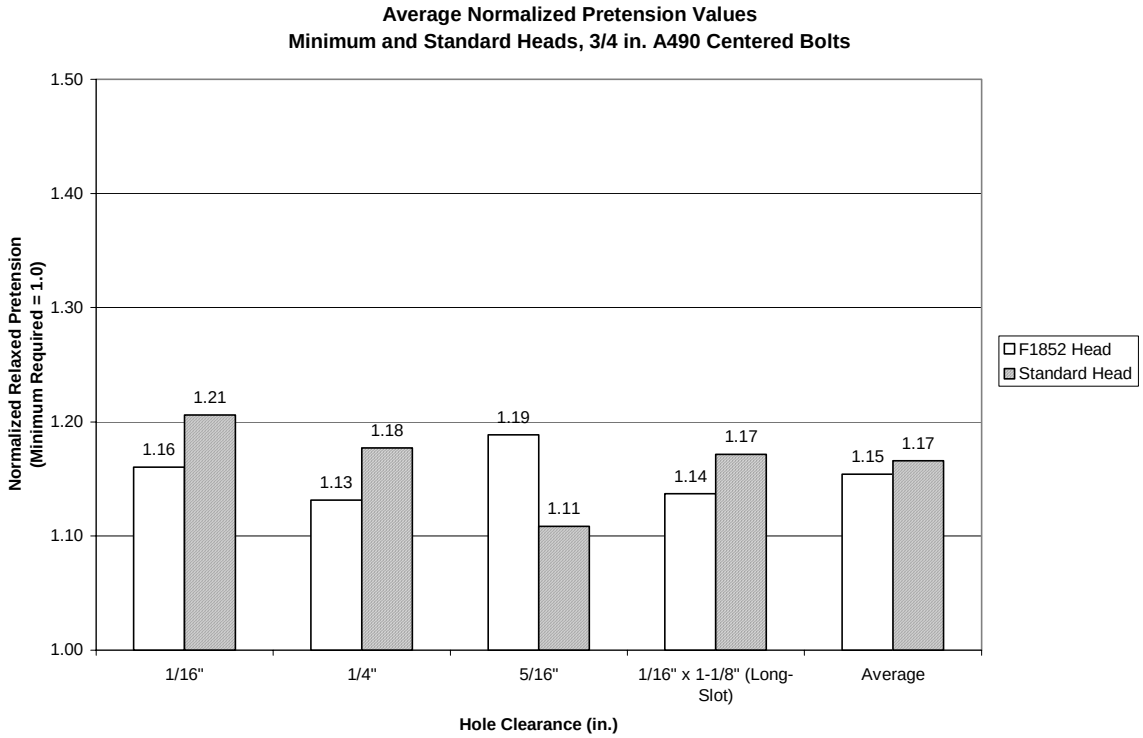


Figure E.3: Normalized Relaxed Pretension for 3/4", A490 Strength Centered Bolts

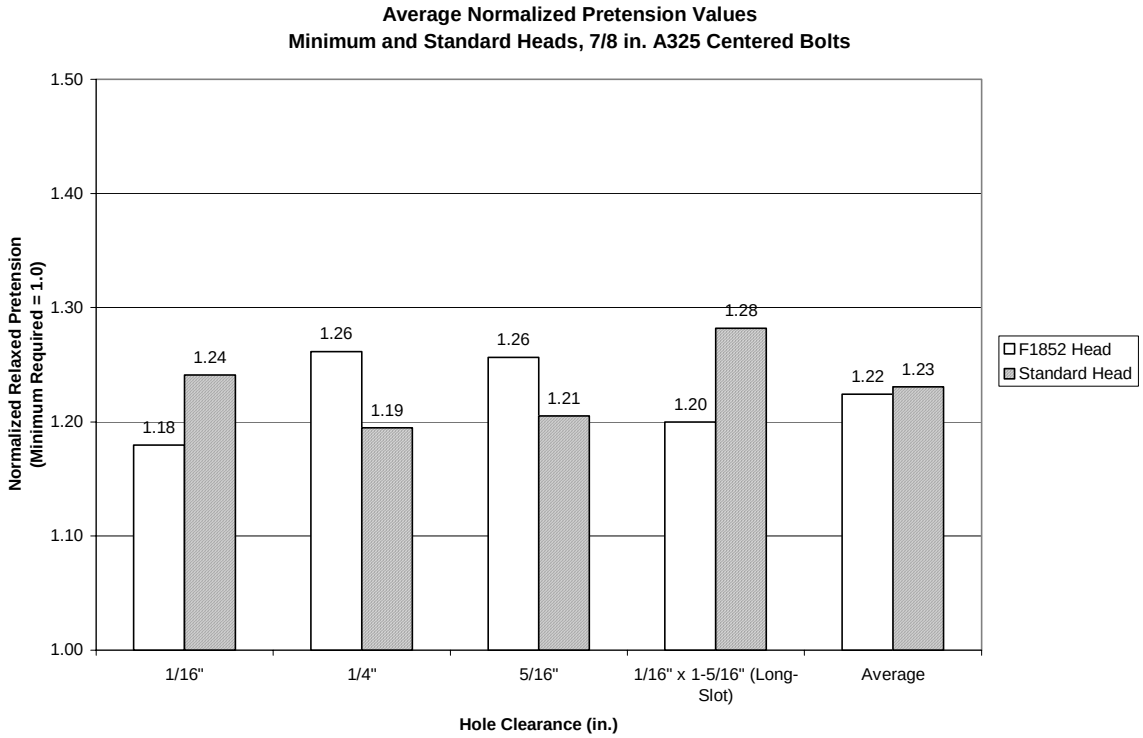


Figure E.4: Normalized Relaxed Pretension for 7/8", F1852/A325 Strength Centered Bolts

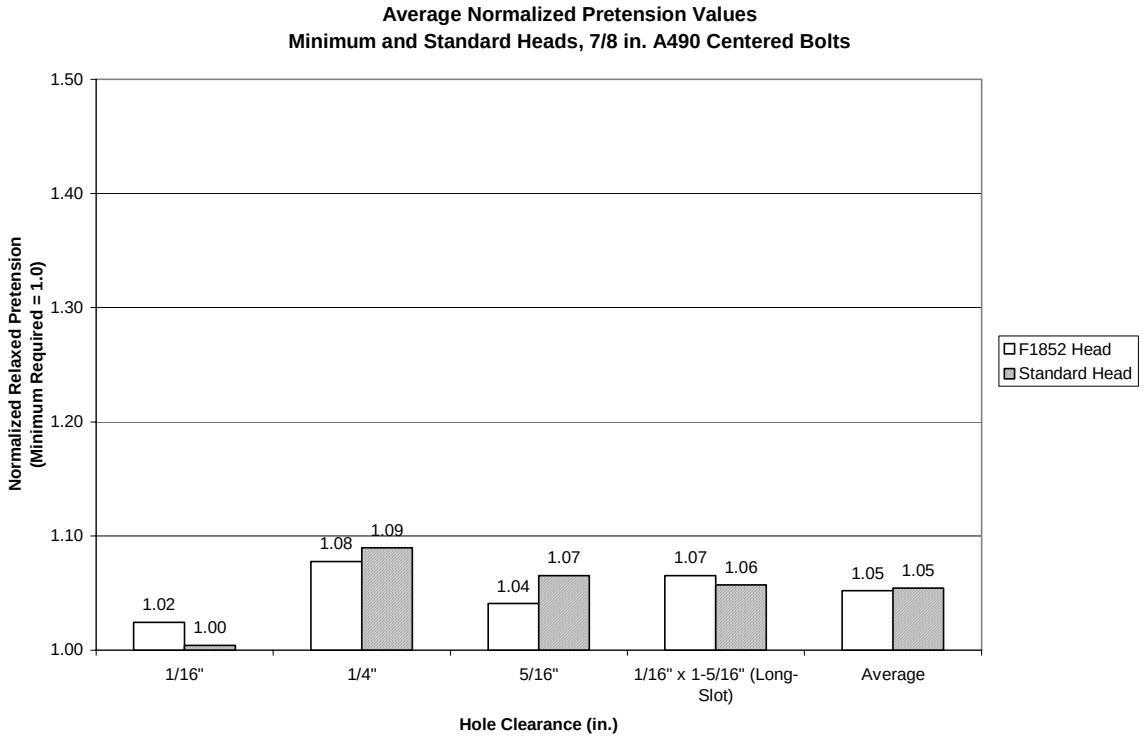


Figure E.5: Normalized Relaxed Pretension for 7/8", A490 Strength Centered Bolts

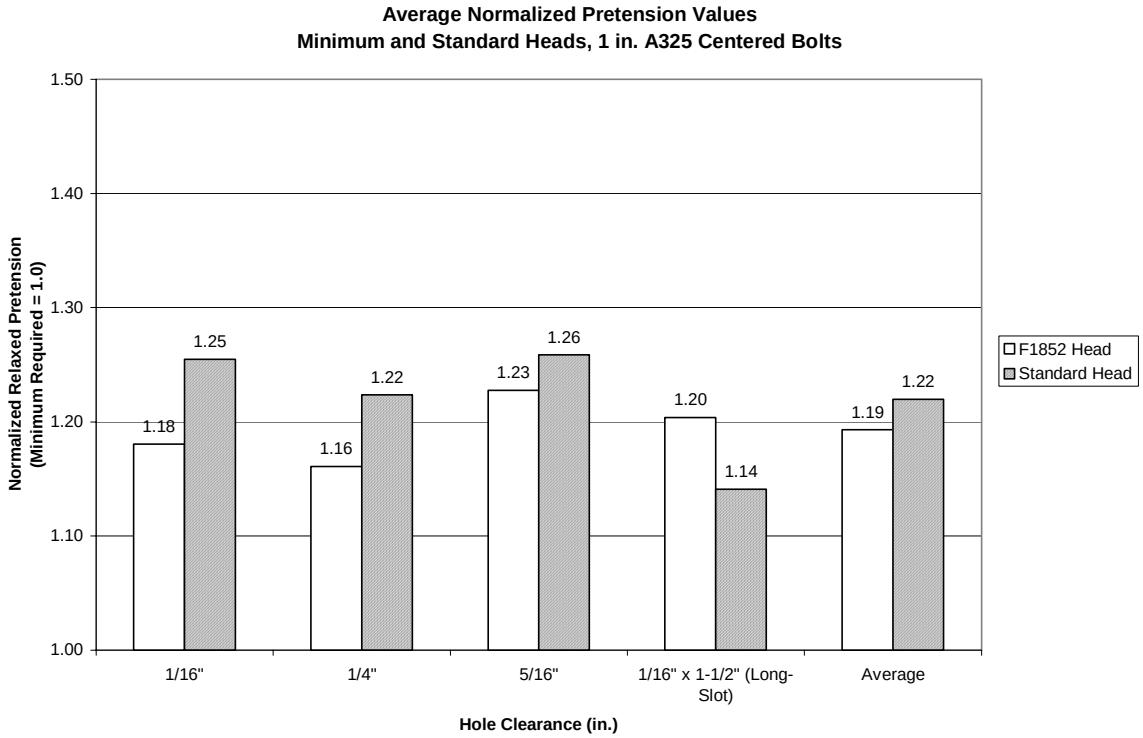


Figure E.6: Normalized Relaxed Pretension for 1", F1852/A325 Strength Centered Bolts

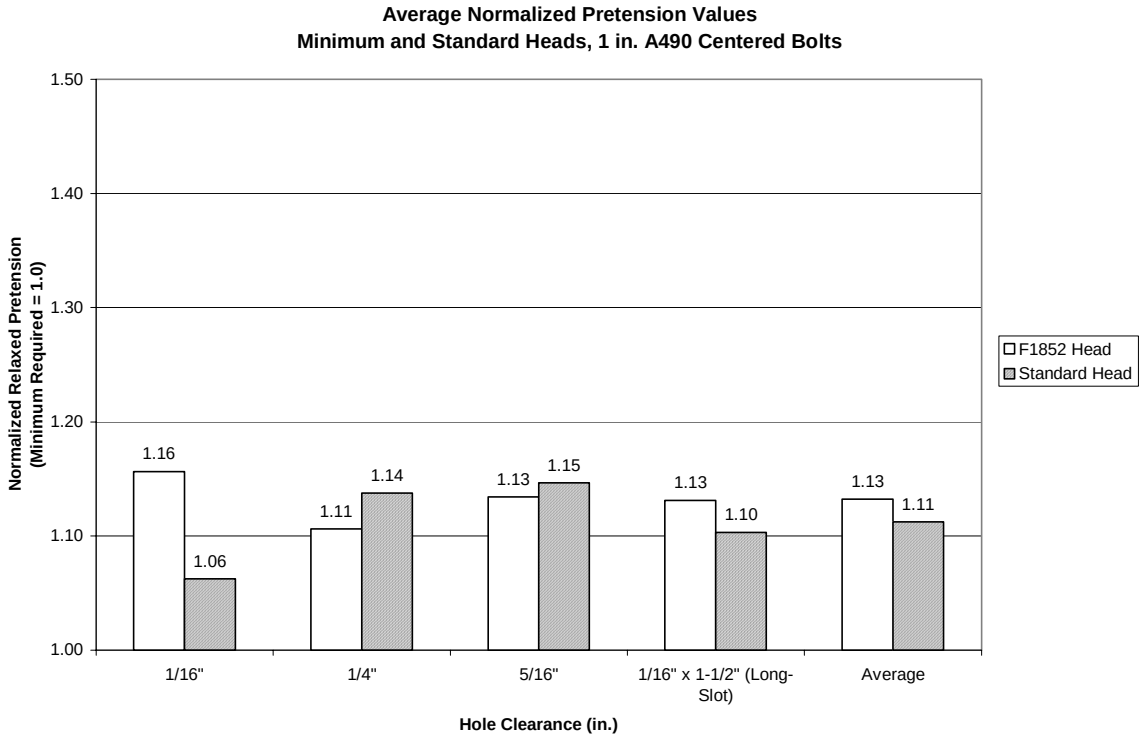


Figure E.7: Normalized Relaxed Pretension for 1", A490 Strength Centered Bolts

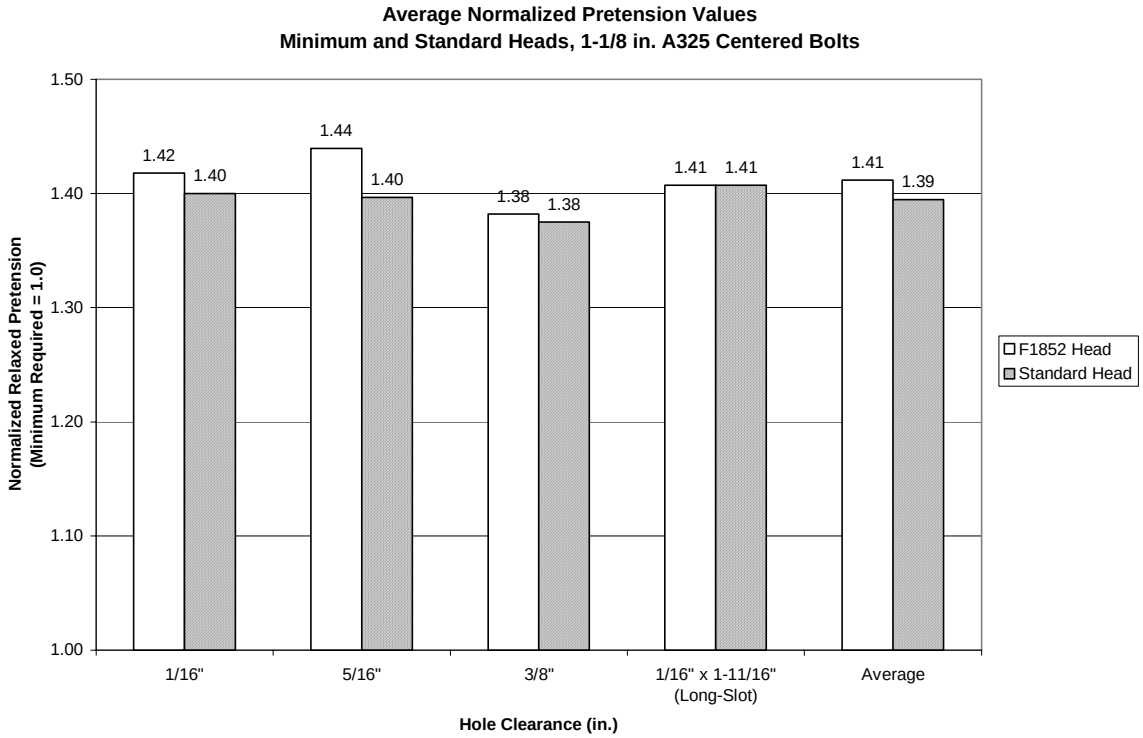


Figure E.8: Normalized Relaxed Pretension for 1-1/8", F1852/A325 Strength Centered Bolts

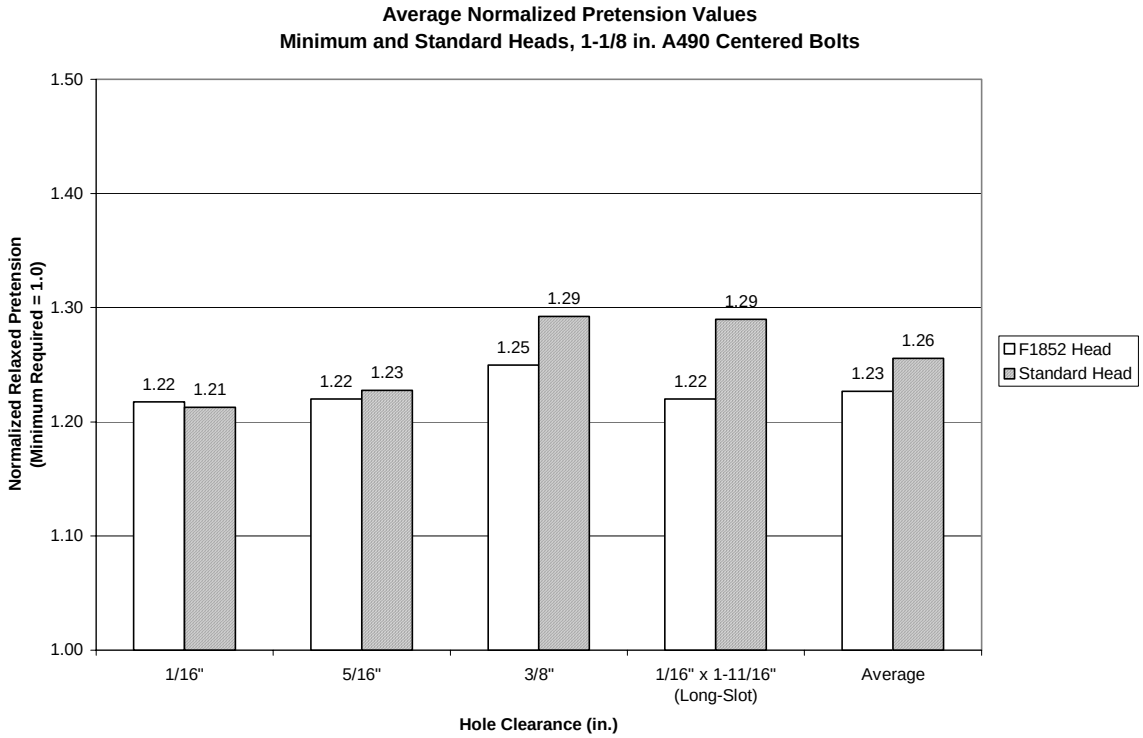


Figure E.9: Normalized Relaxed Pretension for 1-1/8", A490 Strength Centered Bolts

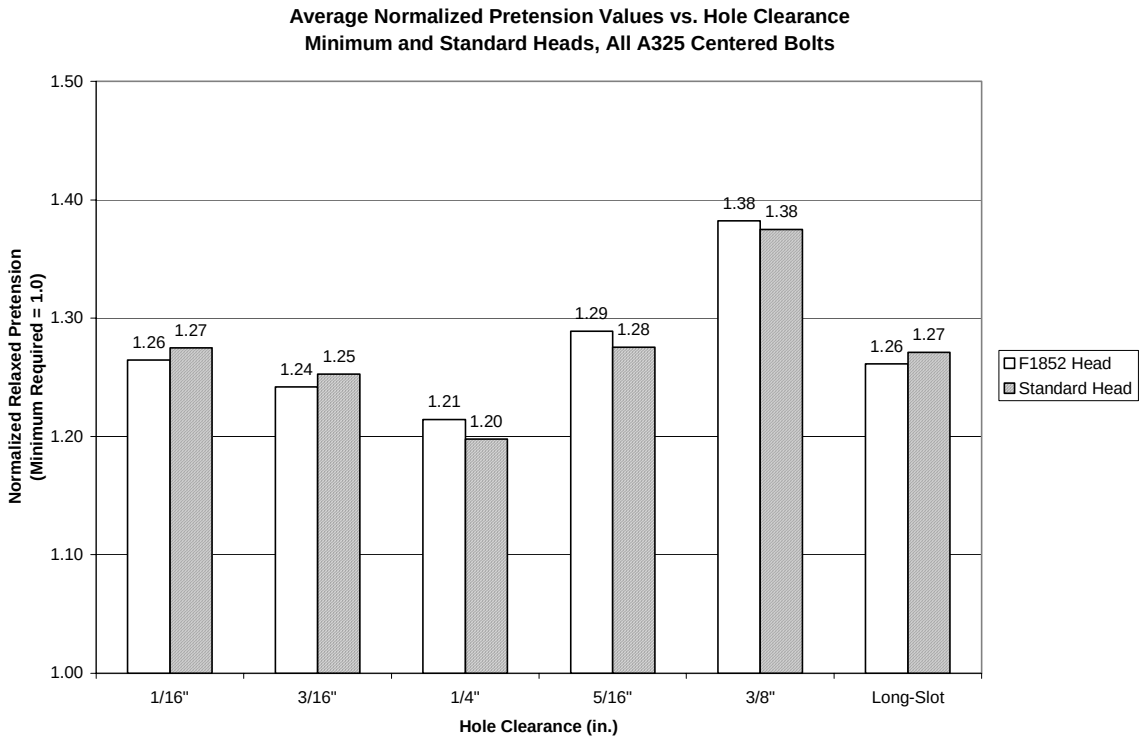


Figure E.10: Normalized Relaxed Pretension for F1852/A325 Strength Centered Bolts

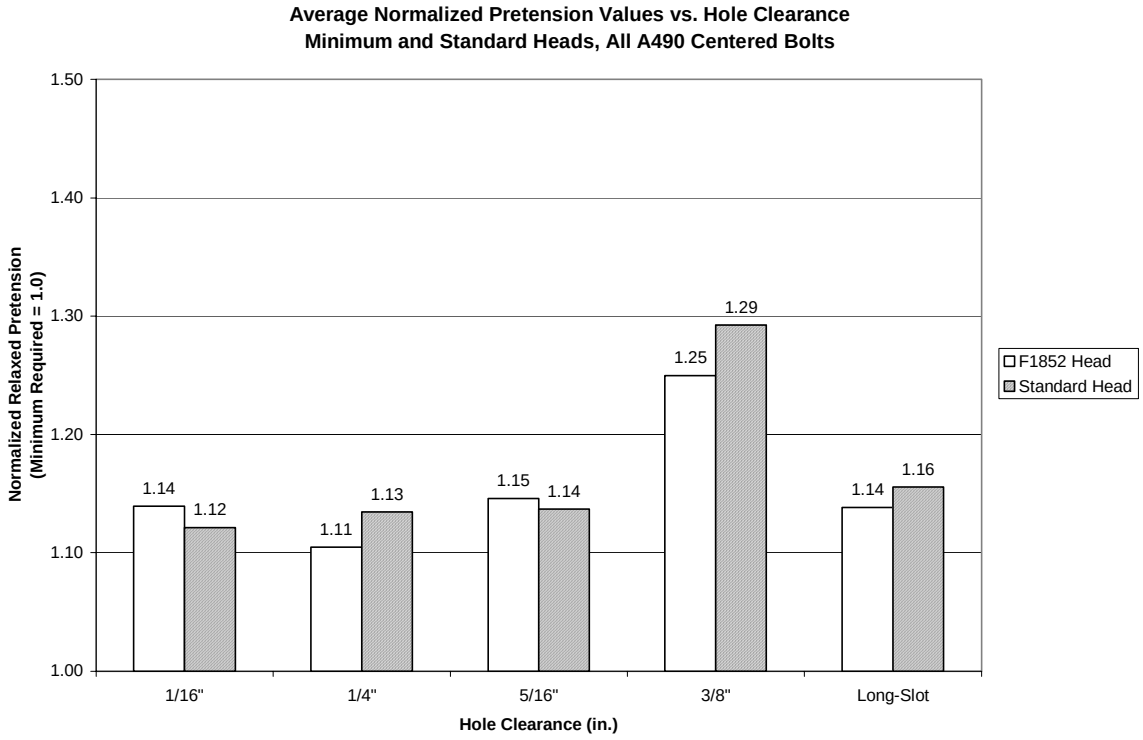


Figure E.11: Normalized Relaxed Pretension for A490 Strength Centered Bolts

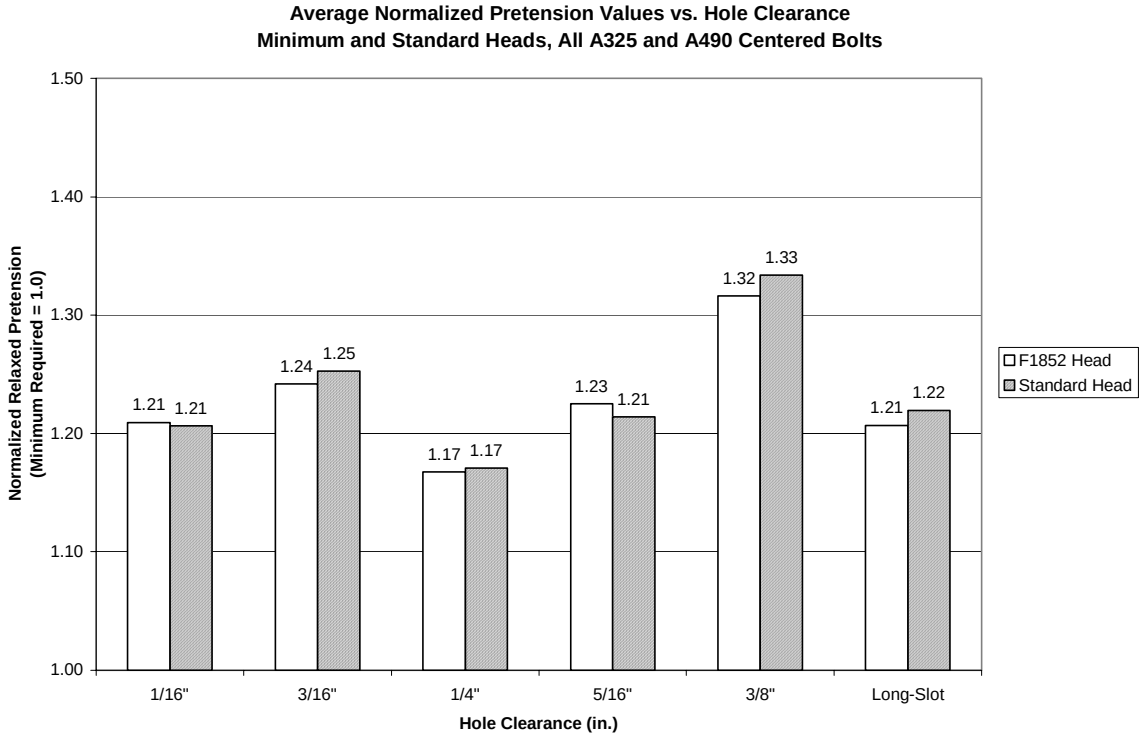


Figure E.12: Normalized Relaxed Pretension for F1852/A325 & A490 Strength Centered Bolts

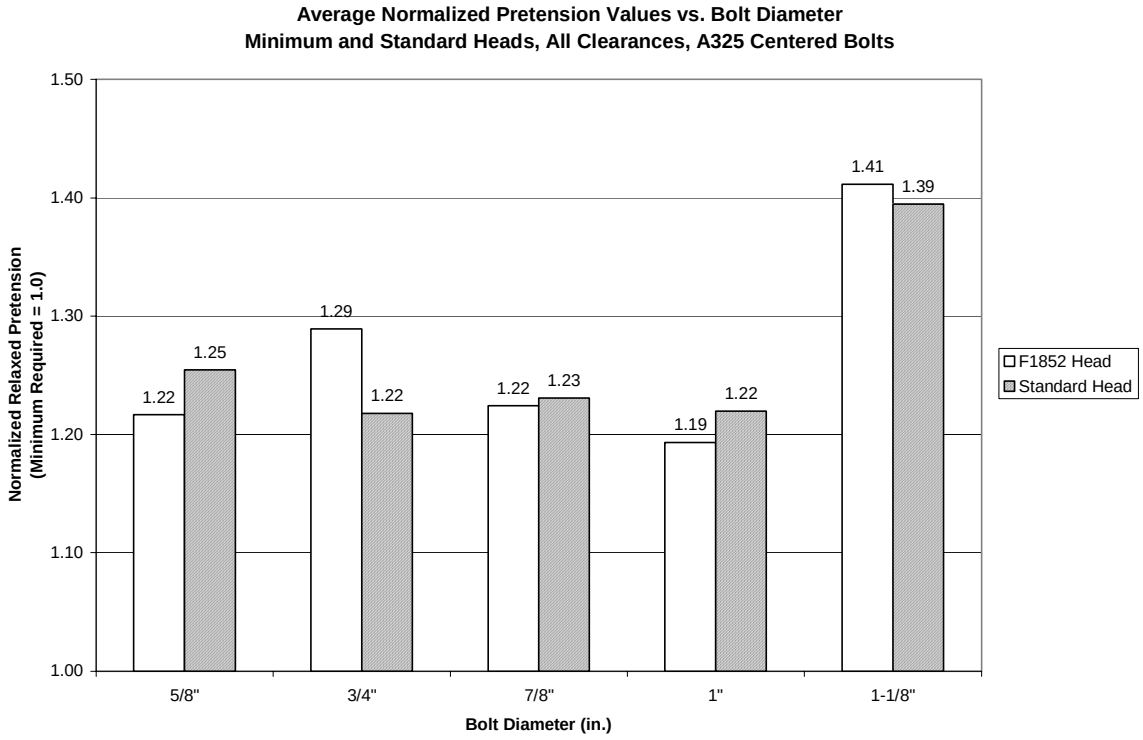


Figure E.13: Normalized Relaxed Pretension for each F1852/A325 Strength Centered Bolt Diameter

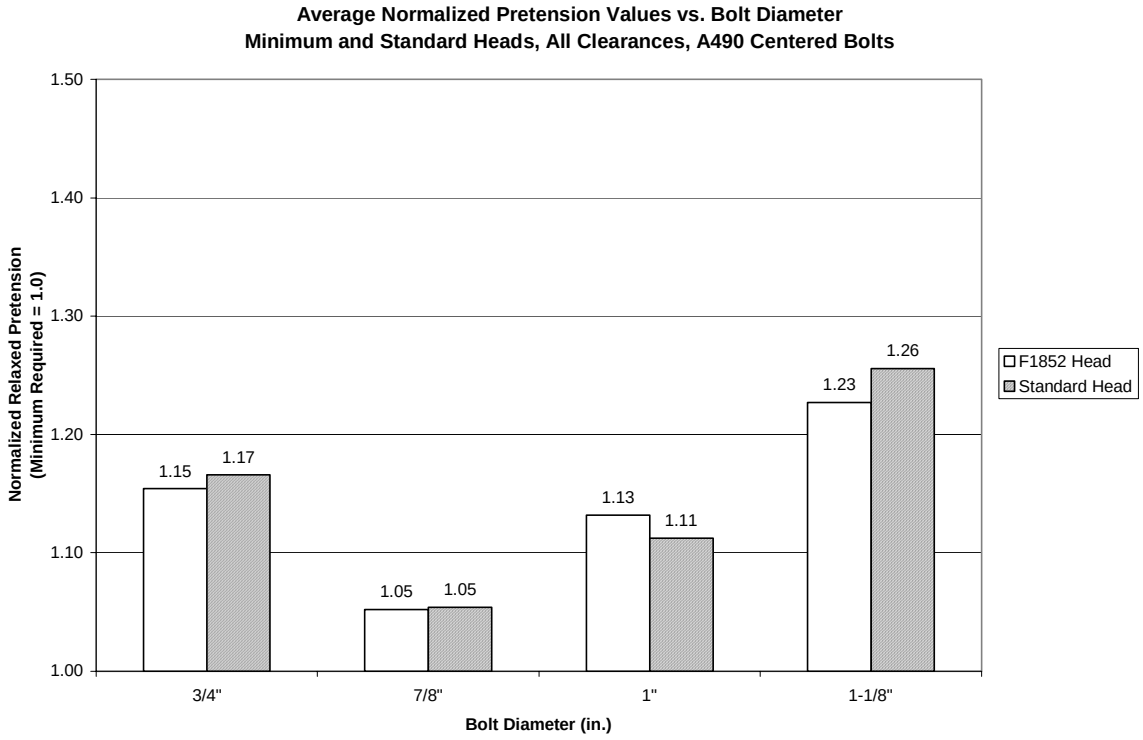


Figure E.14: Normalized Relaxed Pretension for each A490 Strength Centered Bolt Diameter

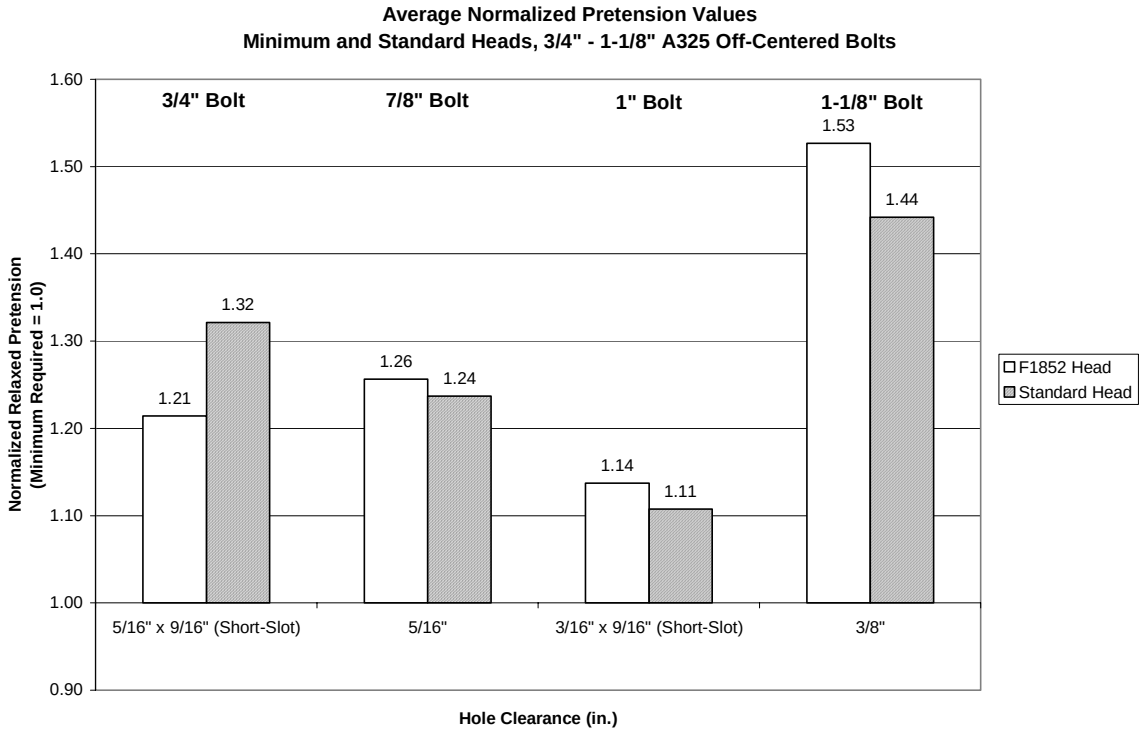


Figure E.15: Normalized Relaxed Pretension for each F1852/A325 Strength Off-Centered Bolt Diameter

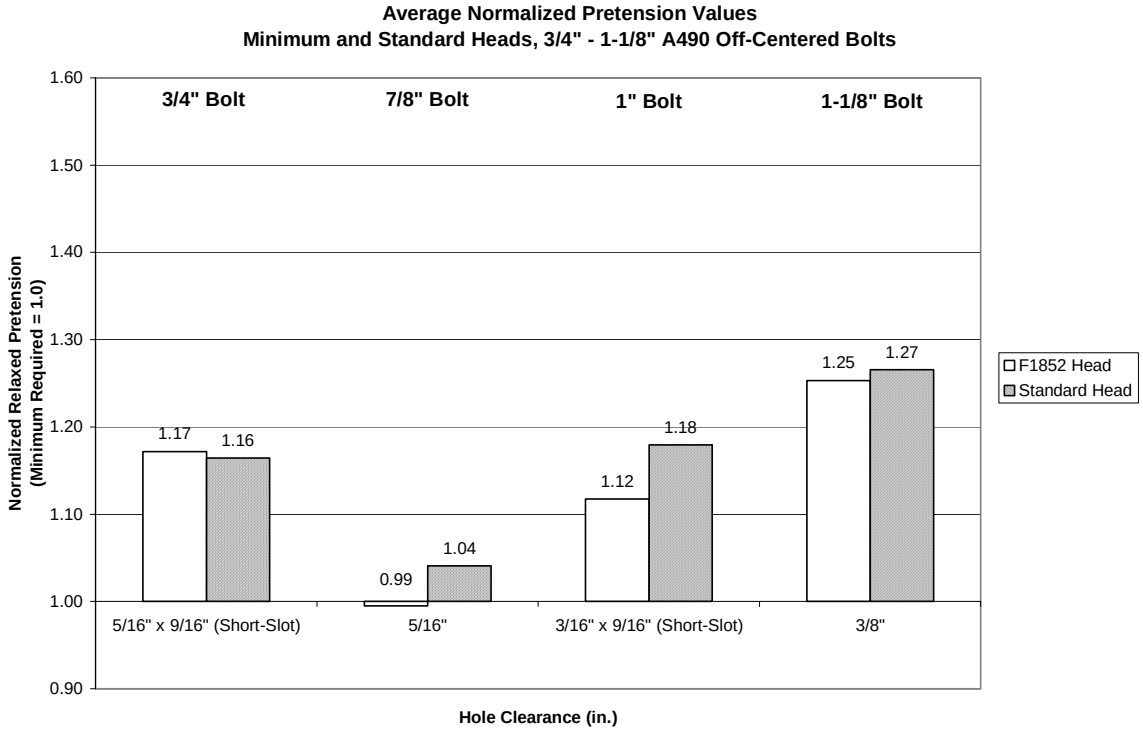


Figure E.16: Normalized Relaxed Pretension for each A490 Strength Off-Centered Bolt Diameter

Table E.1: Statistical Results for 5/8", F1852/A325 Strength Centered Bolts

5/8", A325 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 15/16"	
Average Relaxed Pretension (kips)	23.80	23.60	23.20	22.80	N/A	22.20	23.12
Normalized Value	1.253	1.242	1.221	1.200	N/A	1.168	1.217
Standard Deviation (kips)	0.447	1.342	0.837	0.837	N/A	0.837	1.013

5/8", A325 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 15/16"	
Average Relaxed Pretension (kips)	23.60	23.80	24.20	23.80	N/A	23.80	23.84
Normalized Value	1.242	1.253	1.274	1.253	N/A	1.253	1.255
Standard Deviation (kips)	1.140	0.447	1.304	1.095	N/A	1.095	0.987

Note: A490 strength, 5/8 in. diameter bolts are not available for testing.

Table E.2: Statistical Results for 3/4", F1852/A325 & A490 Strength Centered Bolts

3/4", A325 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/8"	
Average Relaxed Pretension (kips)	36.20	N/A	34.00	37.00	N/A	37.20	36.10
Normalized Value	1.293	N/A	1.214	1.321	N/A	1.329	1.289
Standard Deviation (kips)	1.483	N/A	2.739	1.581	N/A	2.864	2.447

3/4", A325 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/8"	
Average Relaxed Pretension (kips)	34.60	N/A	30.80	35.40	N/A	35.60	34.10
Normalized Value	1.236	N/A	1.100	1.264	N/A	1.271	1.218
Standard Deviation (kips)	3.435	N/A	1.304	1.817	N/A	2.966	3.059

3/4", A490 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/8"	
Average Relaxed Pretension (kips)	40.60	N/A	39.60	41.60	N/A	39.80	40.40
Normalized Value	1.160	N/A	1.131	1.189	N/A	1.137	1.154
Standard Deviation (kips)	2.074	N/A	1.817	1.517	N/A	2.864	2.113

3/4", A490 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/8"	
Average Relaxed Pretension (kips)	42.20	N/A	41.20	38.80	N/A	41.00	40.80
Normalized Value	1.206	N/A	1.177	1.109	N/A	1.171	1.166
Standard Deviation (kips)	2.775	N/A	3.194	2.950	N/A	2.345	2.895

Table E.3: Statistical Results for 7/8", F1852/A325 & A490 Strength Centered Bolts

7/8", A325 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-5/16"	
Average Relaxed Pretension (kips)	46.00	N/A	49.20	49.00	N/A	46.80	47.75
Normalized Value	1.179	N/A	1.262	1.256	N/A	1.200	1.224
Standard Deviation (kips)	1.581	N/A	3.033	2.345	N/A	2.950	2.731

7/8", A325 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-5/16"	
Average Relaxed Pretension (kips)	48.40	N/A	46.60	47.00	N/A	50.00	48.00
Normalized Value	1.241	N/A	1.195	1.205	N/A	1.282	1.231
Standard Deviation (kips)	2.074	N/A	2.074	1.871	N/A	2.449	2.384

7/8", A490 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-5/16"	
Average Relaxed Pretension (kips)	50.20	N/A	52.80	51.00	N/A	52.20	51.55
Normalized Value	1.024	N/A	1.078	1.041	N/A	1.065	1.052
Standard Deviation (kips)	0.837	N/A	1.643	2.915	N/A	1.924	2.089

7/8", A490 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-5/16"	
Average Relaxed Pretension (kips)	49.20	N/A	53.40	52.20	N/A	51.80	51.65
Normalized Value	1.004	N/A	1.090	1.065	N/A	1.057	1.054
Standard Deviation (kips)	4.550	N/A	2.702	2.168	N/A	2.280	3.233

Table E.4: Statistical Results for 1", F1852/A325 & A490 Strength Centered Bolts

1", A325 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/2"	
Average Relaxed Pretension (kips)	60.20	N/A	59.20	62.60	N/A	61.40	60.85
Normalized Value	1.180	N/A	1.161	1.227	N/A	1.204	1.193
Standard Deviation (kips)	2.387	N/A	1.789	2.074	N/A	2.881	2.498

1", A325 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/2"	
Average Relaxed Pretension (kips)	64.00	N/A	62.40	64.20	N/A	58.20	62.20
Normalized Value	1.255	N/A	1.224	1.259	N/A	1.141	1.220
Standard Deviation (kips)	4.000	N/A	5.413	5.848	N/A	4.087	5.136

1", A490 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/2"	
Average Relaxed Pretension (kips)	74.00	N/A	70.80	72.60	N/A	72.40	72.45
Normalized Value	1.156	N/A	1.106	1.134	N/A	1.131	1.132
Standard Deviation (kips)	5.244	N/A	2.280	4.879	N/A	2.966	3.886

1", A490 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-1/2"	
Average Relaxed Pretension (kips)	68.00	N/A	72.80	73.40	N/A	70.60	71.20
Normalized Value	1.063	N/A	1.138	1.147	N/A	1.103	1.113
Standard Deviation (kips)	3.391	N/A	1.924	3.435	N/A	5.177	4.008

Table E.5: Statistical Results for 1-1/8", F1852/A325 & A490 Strength Centered Bolts

1-1/8", A325 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-11/16"	
Average Relaxed Pretension (kips)	79.40	N/A	N/A	80.60	77.40	78.80	79.05
Normalized Value	1.418	N/A	N/A	1.439	1.382	1.407	1.412
Standard Deviation (kips)	3.130	N/A	N/A	0.894	3.209	3.033	2.781

1-1/8", A325 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-11/16"	
Average Relaxed Pretension (kips)	78.40	N/A	N/A	78.20	77.00	78.80	78.10
Normalized Value	1.400	N/A	N/A	1.396	1.375	1.407	1.395
Standard Deviation (kips)	1.673	N/A	N/A	1.924	3.674	2.168	2.382

1-1/8", A490 BOLTS MINIMUM HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-11/16"	
Average Relaxed Pretension (kips)	97.40	N/A	N/A	97.60	100.00	97.60	98.15
Normalized Value	1.218	N/A	N/A	1.220	1.250	1.220	1.227
Standard Deviation (kips)	3.782	N/A	N/A	4.393	3.082	6.348	4.332

1-1/8", A490 BOLTS STANDARD HEAD	Hole Clearance						Overall Average
	1/16"	3/16"	1/4"	5/16"	3/8"	1/16" x 1-11/16"	
Average Relaxed Pretension (kips)	97.00	N/A	N/A	98.20	103.40	103.20	100.45
Normalized Value	1.213	N/A	N/A	1.228	1.293	1.290	1.256
Standard Deviation (kips)	4.000	N/A	N/A	3.701	2.966	7.950	5.491

Table E.6: Overall Statistical Averages for Bolts in Centered Holes

ALL BOLTS	Hole Clearance						
	1/16"	3/16"	1/4"	5/16"	3/8"	Long-Slot	Average
Average Normalized Relaxed Pretension, Minimum Head	1.209	1.242	1.168	1.225	1.316	1.207	1.211
Average Normalized Relaxed Pretension, Standard Head	1.207	1.253	1.171	1.214	1.334	1.220	1.213
Average Standard Deviation, Minimum Head (kips)	2.329	1.342	2.020	2.382	3.146	2.963	2.610
Average Standard Deviation, Standard Head (kips)	3.004	0.447	2.559	2.756	3.320	3.391	3.224

A325 STRENGTH BOLTS	Hole Clearance						
	1/16"	3/16"	1/4"	5/16"	3/8"	Long-Slot	Average
Average Normalized Relaxed Pretension, Minimum Head	1.265	1.242	1.214	1.289	1.382	1.262	1.265
Average Normalized Relaxed Pretension, Standard Head	1.275	1.253	1.198	1.275	1.375	1.271	1.263
Average Standard Deviation, Minimum Head (kips)	1.806	1.342	2.099	1.546	3.209	2.513	1.757
Average Standard Deviation, Standard Head (kips)	2.464	0.447	2.524	2.511	3.674	2.553	2.704

A490 STRENGTH BOLTS	Hole Clearance						
	1/16"	3/16"	1/4"	5/16"	3/8"	Long-Slot	Average
Average Normalized Relaxed Pretension, Minimum Head	1.140	NA	1.105	1.146	1.250	1.138	1.141
Average Normalized Relaxed Pretension, Standard Head	1.121	NA	1.135	1.137	1.293	1.155	1.147
Average Standard Deviation, Minimum Head (kips)	2.984	NA	1.913	3.426	3.082	3.525	3.105
Average Standard Deviation, Standard Head (kips)	3.679	NA	2.606	3.063	2.966	4.438	1.692

Table E.7: Statistical Results for Bolts in Off-Centered Holes

A325 BOLTS, MINIMUM HEAD	**Bolt Diameter**			
	3/4"	**7/8"**	**1"**	**1-1/8"**
Hole Clearance	**5/16" x 9/16" (Short-Slot)**	**5/16"**	**3/16" x 9/16" (Short-Slot)**	**3/8"**
Average Relaxed Pretension (kips)	34.00	49.00	58.00	85.50
Normalized Value	1.214	1.256	1.137	1.527
Standard Deviation (kips)	2.449	3.742	1.414	2.646

A325 BOLTS, STANDARD HEAD	**Bolt Diameter**			
	3/4"	**7/8"**	**1"**	**1-1/8"**
Hole Clearance	**5/16" x 9/16" (Short-Slot)**	**5/16"**	**3/16" x 9/16" (Short-Slot)**	**3/8"**
Average Relaxed Pretension (kips)	37.00	48.25	56.50	80.75
Normalized Value	1.321	1.237	1.108	1.442
Standard Deviation (kips)	2.160	3.500	2.082	3.862

A490 BOLTS, MINIMUM HEAD	**Bolt Diameter**			
	3/4"	**7/8"**	**1"**	**1-1/8"**
Hole Clearance	**5/16" x 9/16" (Short-Slot)**	**5/16"**	**3/16" x 9/16" (Short-Slot)**	**3/8"**
Average Relaxed Pretension (kips)	41.00	48.75	71.50	100.25
Normalized Value	1.171	0.995	1.117	1.253
Standard Deviation (kips)	2.449	2.872	3.416	6.131

A490 BOLTS, STANDARD HEAD	**Bolt Diameter**			
	3/4"	**7/8"**	**1"**	**1-1/8"**
Hole Clearance	**5/16" x 9/16" (Short-Slot)**	**5/16"**	**3/16" x 9/16" (Short-Slot)**	**3/8"**
Average Relaxed Pretension (kips)	40.75	51.00	75.50	101.25
Normalized Value	1.164	1.041	1.180	1.266
Standard Deviation (kips)	2.217	2.944	4.796	4.500

APPENDIX F

PHOTOGRAPHS TAKEN DURING TESTING

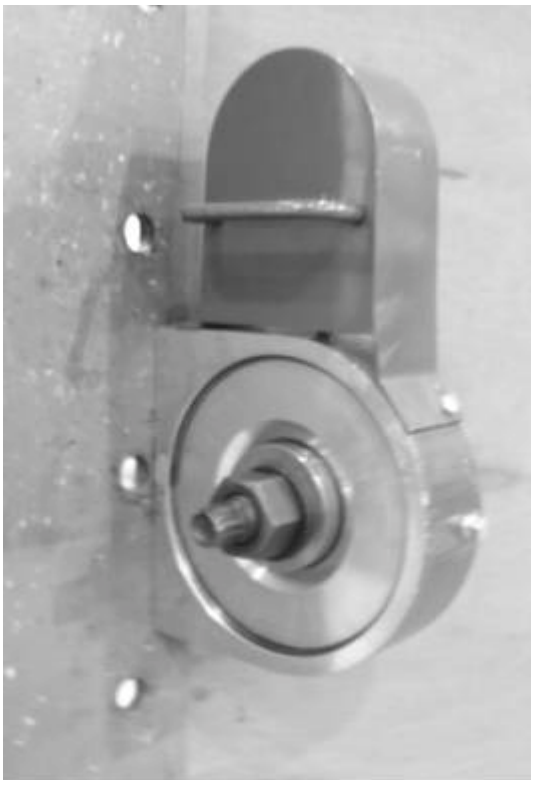


Figure F.1: Rear View of Typical Skidmore Setup

Figure F.2: Manufacturer's Standard and F1852 Minimum Bolt Heads

Figure F.3: Tone Wrenches Used for Tightening

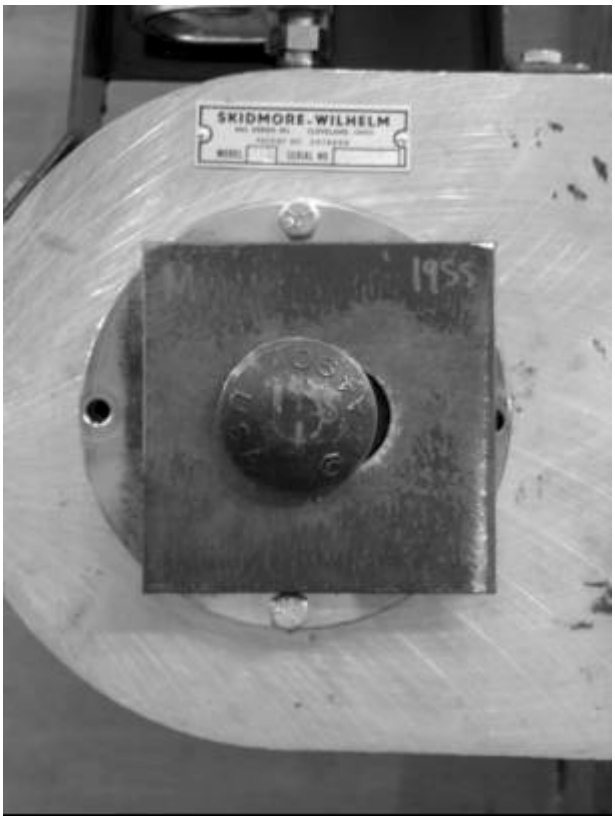


Figure F.4: Setup for 1" Bolt, A490 Strength, Off-Centered Test

VITA

Keith Otto Schnupp was born on May 23, 1979 in Fairfax, Virginia to Alfred and Sandee Schnupp. He is the youngest of five, having three older brothers and a sister. Keith was raised in Fairfax and graduated from Robinson High School in June of 1997. Keith chose to attend Virginia Tech to obtain his degree in Civil Engineering. He received his Bachelor of Science Degree in December of 2001. From there Keith began his graduate work at Virginia Tech hoping to obtain a Master of Science Degree in Civil Engineering. Upon completion of his degree, Keith will be starting his career at an engineering firm in Sterling, Virginia.

Keith Otto Schnupp

GO HOKIES!