Reuse of A325 and A490 High-Strength Bolts

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INTRODUCTION

The reuse of high-strength structural bolts often refers to the removal and subsequent reinstallation of bolts when a structural connection is reassembled. Although bolt reuse is not commonplace, it may be feasible for certain types of structures, such as temporary structures used in construction, reusable military structures, and rehabilitation projects of existing structures. Moreover, a moderate cost savings may be possible if the structural bolts are reused when the structure is reassembled.

The primary purpose of this study was to provide information on the effect of reuse on the behavior of various high-strength structural bolts. The performance of bolts which either were loaded in direct tension or were continuously torqued to failure was also examined so that comparisons could be made with bolts that were repetitively tightened and loosened. The influence of lubrication applied to the threads was also studied.

Background Information

The reuse of high-strength bolts is discussed in the specification requirements issued by the Research Council on Structural Connections.[10] These requirements indicate that galvanized A325 bolts and A490 bolts may not be reused. The reuse of A325 black bolts, however, is permitted if approved by the engineer responsible for the project.

Only limited information is available to assist the engineer in evaluating the adequacy of high strength bolts that are to be reused. One general method, however, that is easy to implement is described in the AISC Quality Criteria and Inspection Standard.[11] In these requirements the acceptability of A325 black bolts for reuse is based on whether the nuts can be placed on the threads and run down the full length of the thread by hand. Significant plastic deformation from prior use of the bolt could prevent the nut from being able to travel along the full length of the threads. Thread damage, which usually occurs as a result of improper site storage or handling, may also prevent the nut from running down the full length of the bolt.

Relatively few experimental data have been obtained to examine the behavior of high-strength bolts which have been repetitively tightened. The results of a few tests[1,9] that utilized ⅞-in. diameter A325 bolts indicated that it was possible to reuse the bolts once or twice without seriously compromising the clamping force or the reserve strength.

A more comprehensive study on the reuse of A354 and A490 alloy steel bolts was conducted by Christopher et al.[4] It was found that A490 bolts could be repetitively tightened five times and still develop the proof load when the threads were lubricated prior to tightening. The A490 bolts in the as-received condition, however, were observed to reach the proof load once only. Moreover, the as-received A490 bolts failed after four cycles of tightening on the average, whereas similar bolts with lubricated threads averaged eight cycles prior to failure.

EXPERIMENTAL PROGRAM

An experimental study was conducted in this investigation to examine the load-deformation behavior of ASTM A325[6] and A490[5] structural bolts. Eight lots of bolts were included in the study: two lots each of A325 and A490 bolts; and two lots each of mechanically and hot-dipped galvanized A325 bolts. All bolt specimens were ⅞-in. diameter, heavy semi-finished hexagon head bolts. Nuts with semi-finished heads were used with all bolts tested; hardened washers were used under the nuts of the A490 bolts only.

A description of the bolt type and the general dimensions for the bolt test specimens are given in Table 1. The surface coating, bolt head type, nut type, thread type, length under the bolt head (L), grip length (g), and thread length under the nut (t) are described in the table. Each lot of bolts is identified by a series of letters and numbers that identifies the bolt coating, type, and length.

A total of 125 high-strength bolts were tested in the study. Of this total, 12 bolts were tested in direct tension, 49 bolts in continuous torque, and 64 bolts tested in repetitive torque. Direct tension refers to the application of a direct tensile load, while continuous torque refers to the continuous rotation of the nut until failure occurs. Repetitive torque refers to repeated tightening-and-loosening cycles, in which the bolt is tightened by the turn-of-the-nut method, until failure occurs.

The testing program was developed to study the influence of lubrication applied to the threads. Three conditions were examined: "as-received," "waxed," and "greased." All black bolts were received in a light machine oil normally present

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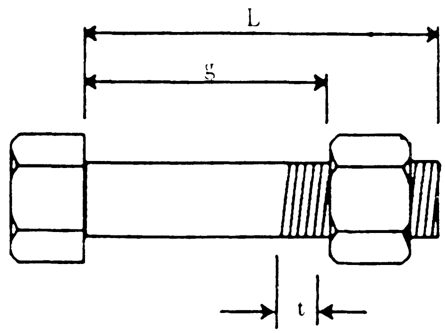
Table 1.
Description of ⅞-in. Diameter Test Bolt Specimens

Bolt Lot	ASTM Mark	Surface Coating*	Thread Type	Nut Type	*L* in.	*g* in.	*t* in.
R3-2.5	A325	—	Rolled	A563 Gr C	2½	1.375	0.375
R3-5.5	A325	—	Rolled	A563 Gr C	5½	4.375	0.375
R4-2.5	A490	—	Cut	A194 2H	2½	1.375	0.375
R4-5.5	A490	—	Cut	A194 2H	5½	4.375	0.375
HD3-2.5	A325	HD	Rolled	A194 2H	2½	1.375	0.375
HD3-5.5	A325	HD	Rolled	A563 Gr C	5½	4.375	0.375
MG3-2.5	A325	MG	Rolled	A194 2H	2½	1.375	0.375
MG3-5.5	A325	MG	Rolled	A194 2H	5½	4.375	0.375

* HD hot-dipped galvanized
MG mechanically galvanized



in the packaging process, whereas the galvanized A325 bolts appeared to be dry. These two conditions were considered the "as-received" state. A commercial wax (Johnson's #140 Stik-wax) applied to the bolt and nut threads was considered the "waxed" condition. The "greased" condition consisted of applying a heavy multi-purpose grease (Molykotte G-n) to the bolt and nut threads.

Direct Tension Tests

In the direct tension phase of the study, a 220,000-lb. capacity MTS servohydraulic testing machine, equipped with special tension grips to hold the nut and the head of the bolt, was used to apply an axial tension force to the bolt. Bolts only in the "as-received" condition were tested in direct tension. Moreover, only the 5½-in. long bolts could be tested in direct tension due to the necessary thickness of the grip plates.

A 1-in. Schaevitz DC-LVDT was attached to the bolt head and nut so that bolt elongation measurements could be taken throughout the test. Testing was conducted in a stroke control mode at a rate of approximately 0.005 inches of elongation per minute. Load and elongation values were recorded at 10 second intervals until bolt failure occurred.

Torqued Tension Test

In the torqued tension tests the tension force was developed in the bolt by turning the nut. Two types of torqued-tension tests were conducted: repetitive torque and continuous torque. The repetitive torque tests were performed to examine the effect of bolt reuse on bolts tightened by the turn-of-the-nut method, while the continuous torque tests were conducted to obtain the load-deformation response of bolts tightened continuously to failure.

In the repetitive torque tests the bolt was first tightened with a hand wrench to a "snug" load of approximately 8 kips. The nut was then turned with a pneumatic impact wrench in 30 or 45 degree increments until the specified nut rotation[10] of the bolt was achieved.* The rotation of the nut was then reversed in 30 or 45 degree increments until all load was removed. Load and elongation readings were recorded at each increment. This procedure was repeated as many times as necessary until bolt failure occurred. The final load, elongation, and number of cycles to failure were recorded for each specimen.

In order to investigate a bolt torqued continuously to failure, the same initial procedure was used. However, instead of reversing the direction of rotation, the nut rotation was continued in 30 or 45 degree increments until bolt failure occurred.

The tension loads induced in the bolts as a result of nut rotation were measured using a commercial bolt force sensor (Lebow Model 3711-875 bolt load cell). The short length of the load cell unit, 0.56-in. for the bolt force sensor and two accompanying hardened washers, allowed it to be used for both the 2½-in. and 5½-in. bolt lengths.

Bolt elongations in the torqued tension tests were measured

* The 2½-in. long bolts were tested by turning the nut at 30 degree increments to the specified ⅓ turn from snug. Likewise, the 5½-in. long bolts were tested by turning the nut at 45 degree increments to the specified ½ turn snug.

Table 2. Direct Tension Test Results								
Bolt Lot	No. Spec.	ASTM Tensile Strength (kips)	Ultimate Load		Mean Elongation at Ultimate Load (in.)	Mean Rupture Load (kips)	Mean Elongation at Rupture Load (in.)
			Mean (kips)	% ASTM Min. Tensile Load			
R3-5.5	3	55.45	66.5	120	0.123	64.5	0.164
R4-5.5	3	69.30	74.7	108	0.074	70.9	0.102
HD3-5.5	3	55.45	67.7	122	0.118	66.2	0.130
MG3-5.5	3	55.45	67.0	121	0.112	66.1	0.123

by using a C-frame extensometer consisting of a rigid steel frame fitted with a Schaevitz DC-LVDT. A counterweight attached to the upper arm of the frame balanced the instrument in a vertical measuring position when mounted to the test bolt. The C-frame extensometer was made so that it could easily be removed and then accurately repositioned between nut rotations. Additional details of the C-frame and the testing procedures are provided elsewhere.[2]

When performing a torque tension test, a pneumatic impact wrench (1200 ft-lb capacity) was used initially on all bolts. However, for some of the tests the bolts would "lock-up" as a result of the friction developed between the bolt and nut threads; this behavior was especially true for the A490 bolts and the A325 galvanized bolts. When the impact wrench was no longer able to rotate the nut during a test, an alternate method was used to apply a greater torque. Early in the study, a "come-along" winch attached to a large torque wrench was the secondary means of nut rotation and was used to complete the stalled test. Later in the study, however, a hydraulic jack system was found to be much more effective than the winch and was adopted as the secondary means of nut rotation for all stalled bolts.

BOLT TEST RESULTS

Direct Tension Test Results

Three specimens from four different lots of ⅞-in. diameter bolts were tested in direct tension. As mentioned previously, only the 5½-in. long bolts were tested in direct tension due to the thickness necessary for the grip plates of the tension test fixture. All of the bolts tested failed by tensile rupture in the threaded portion of the bolt shank between the face of the nut and the thread runout.

Table 2 indicates the mean values of the ultimate load, the rupture load, and the bolt elongation associated with the ultimate and the rupture loads obtained by the three direct tension tests for each bolt lot. All bolt types tested in direct tension met the corresponding ASTM minimum tensile load requirements.[5,6] The average ultimate tensile strength of the three lots of A325 bolts varied from 120 to 122% of the ASTM minimum tensile strength value. The average tensile strength of the A490 bolts was 108% of the ASTM minimum tensile strength. Although there is no tensile strength limit for A325 bolts, the ASTM specification requires that the tensile strength for A490 bolts does not exceed 170 ksi. The A490 tensile strength test results are about midway between the minimum and maximum ASTM limits.

The test results obtained for the galvanized and black A325 bolts indicate a very close agreement in the direct tension strength. The galvanized bolts, however, failed at an elongation slightly less than that recorded for the black A325 fasteners. The A490 bolts exhibited a greater ultimate load and a reduced elongation at rupture than the black or galvanized A325 bolts.

Hardness tests, which can be correlated to tensile strength, were conducted for all bolt lots and bolt lengths in the study. The Rockwell C hardness values measured for all bolts were within the limits prescribed by the ASTM bolt specifications. The hardness test results and test procedures are reported elsewhere.[2]

Results of Continuously Torqued Bolts

The results of the continuously torqued bolt tests are summarized in Table 3. Values of the ultimate and rupture load and the total elongation and nut rotation at failure are indicated in the table. The values reported in the table are average values based upon three or more tests. Moreover, for most of the bolt lots examined two sets of torqued tension tests were performed. These bolt tests were the same in all respects, other than the application of a lubricant to the bolt threads. One set of tests was conducted in the "as-received" condition. In the second set of tests, the threads were lubricated with a commercial wax, denoted by the "waxed" condition, to study the effect of thread lubrication on the torqued tension strength.

Two types of failure were encountered when continuously torquing the bolts to failure: tension-shear rupture and nut stripping. In the tension-shear rupture mode, failure occurs in the threaded portion of the bolt shank due to a combination of torsional shear stress and direct tension stress. In the nut stripping mode, however, failure occurs when the bolt and nut threads disengage as a result of shearing of the bolt or nut threads. The mode of failure observed during the tests is indicated in Table 3 as "shank" for tension-shear rupture

Table 3. Continuously Torqued Tension Test Results										
Bolt Lot	Lub. Type*	Method of Instl.**	No. Bolt Spec.	Ultimate Load Mean (kips)	Ultimate Load % Dir. Ten. Ult.	Mean Elongation at Ultimate Load (in.)	Mean Rupture Load (kips)	Mean Elongation at Rupture Load (in.)	Mean Nut Rotation to Failure (deg)	Type of Failure
R3-2.5	AR	IW	3	56.6	85	0.071	45.2	0.237	870	Shank
	SW	IW	3	66.1	99	0.069	54.5	0.144	750	Thread
R4-2.5	AR	IW	3	62.6	84	0.043	53.1	0.121	410	Shank
	SW	IW	3	63.5	85	0.051	56.7	0.120	410	Shank
HD3-2.5	AR	IW,CA	3	67.1	99	0.076	58.3	0.258	810	Shank
	SW	IW	3	64.9	96	0.072	52.8	0.258	830	Shank
MG3-2.5	AR	IW,CA	4	55.2	82	0.018	46.8	0.078	260	Shank
	SW	IW	3	67.2	100	0.072	54.3	0.225	760	Shank
R3-5.5	AR	IW	3	57.1	86	0.095	52.5	0.119	615	Thread
	SW	—	—	—	—	—	—	—	—	—
R4-5.5	AR	IW,CA	3	58.8	79	0.059	53.2	0.101	310	Shank
	SW	—	—	—	—	—	—	—	—	—
HD3-5.5	AR	IW,CA	3	49.0	72	0.033	42.1	0.071	270	Shank
	SW	IW	3	65.6	97	0.085	59.9	0.126	570	Thread
MG3-5.5	AR	IW,CA	3	40.0	60	0.043	39.9	0.053	200	Shank
	SW	IW	3	64.7	97	0.102	61.8	0.150	550	Shank

* AR as-received, SW waxed
** IW impact wrench, CA "come-along" winch

and "thread" for thread stripping. Nearly all of the continuously torqued bolts were observed to fail in the tension-shear rupture mode. However, stripping failures did occur in some cases when wax was applied to the threads. This behavior agrees with the failure modes observed by other investigators.[4,7,8]

Figure 1 illustrates the load-elongation curves for 5½-in. long A325 bolts with the load induced by either direct tension or continuous torque. In the elastic range, no appreciable difference between the two curves was found for the two loading methods. Beyond the proof load, however, both the ultimate load and the elongation at rupture were greater for bolts tested in direct tension than for the continuously torqued bolts. The ultimate load observed for the four lots of as-received continuously torqued bolts were reduced by 14% to 40% of their respective values in pure tension. The elongation at rupture for the continuously torqued bolts was found to be 2% to 57% less than the rupture elongations recorded during the direct tension test. It is important to note that the tension test results utilized in this comparison are based upon the tests for 5½-in. long bolts only, since the tensile strength of the short bolts could not be obtained directly. Overall, however, the observed bolt behavior is in agreement with the results observed by other investigators.[4,9]

The effect of grip length on the tension-elongation behavior of A325 and A490 black bolts tested in continuous torque is illustrated in Fig. 2. The thickness of the gripped material varied from 1⅜ in. to 4⅜ in. for the 2½-in. and 5½-in. long bolts, respectively, and both types had the same thread length of ⅜ in. under the nut. The curves shown in Fig. 2 demonstrate that a notable difference exists among the load-elongation relationships of the black bolts for different grip conditions. The most apparent effect of grip length is on the elongation at rupture. The rupture elongation of the 5½-in. long bolts is 50% less than that of the 2½-in. long A325 bolts, and 20% less for the A490 bolts. The average ultimate load, however, was not considerably affected by grip length. The difference in ultimate load for each bolt type was 1%

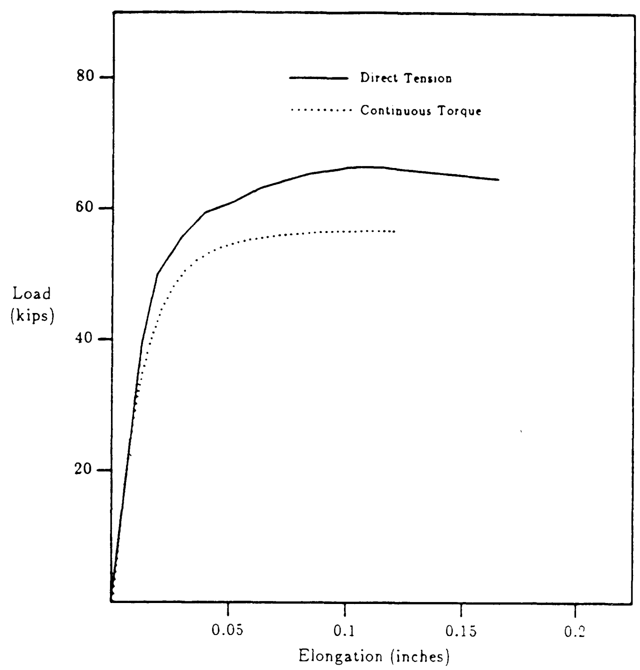


Fig. 1. Comparison between direct tension and continuous torque for 5½-in. long A325 high-strength bolts.

for the A325 bolts and 6% for the A490 bolts. The shorter bolts also had a steeper elastic slope than the longer bolts.

Continuous torque tests performed on hot-dipped and mechanically galvanized A325 bolts also indicated that the load-elongation behavior is significantly affected by varying the grip length. Figure 3 shows that the ultimate load and the elongation at rupture are greater for the 2½-in. long bolts. The reduction in the ultimate load was 27% for both of the 5½-in. long hot-dipped galvanized and the mechanically galvanized bolts. The elongation at rupture was found to be 72% less for the hot-dipped bolts and 32% less for the mechanically galvanized bolts. Again, the 2½-in. long bolts exhibited a steeper slope in the elastic region than the longer bolts.

Significant differences in the load-elongation behavior were observed when the commercial wax was applied to the threads. For example, the ultimate load induced by continuously torquing the bolts to failure was found to range between 60% and 99% of the direct tension ultimate load for all of the bolt types tested in the "as-received" condition (see Table 3). The average reduction in the ultimate load due to continuous torquing, however, was found to be 19% for all bolt tests in the "as-received" condition. The "waxed" elements produced bolt tension values between 85% and 100% of the direct tension ultimate, with an average reduction in ultimate load of only 4% for all tests in the waxed condition. In addition to larger bolt tension forces, the rotation capacity of the nut was observed usually to be greater when wax was applied to the threads.

The effect of thread lubrication on the mechanically galvanized A325 bolts is shown in Fig. 4. These figures indicate significant differences between the "waxed" and the "as-received" thread conditions. The test results indicate that in most cases the "as-received" galvanized bolts did not perform to the full potential of an A325 bolt; in some instances below acceptable levels.

Galvanized bolts from the same lot when waxed, however, demonstrated considerably improved characteristics. As a whole, thread lubrication resulted in improvements in the ultimate load, ductility, and the rotational capacity of the galvanized fasteners. It appears that wax applied to the threads is reasonably effective in reducing the frictional resistance at the bolt-nut interface caused by the galvanized coating.

REPETITIVELY TORQUED BOLTS

Test Results

The results of the repetitively torqued bolt tests are summarized in Table 4. The quantities indicated in the table for load, elongation, and number of tightening cycles to failure are average values based upon three or more tests. As in the continuously torqued tests, additional tests were conducted for each bolt lot to examine the influence of thread lubrication.

The load-deformation envelope was used to evaluate the behavior of the repetitively torqued bolts. For example, Fig. 5 presents all of the load-elongation curves for one of the ⅞-in. diameter by 2½-in. long, hot-dipped galvanized A325 bolts tested in repetitive torque. The dotted line is the actual load-elongation behavior exhibited by the test bolt during each

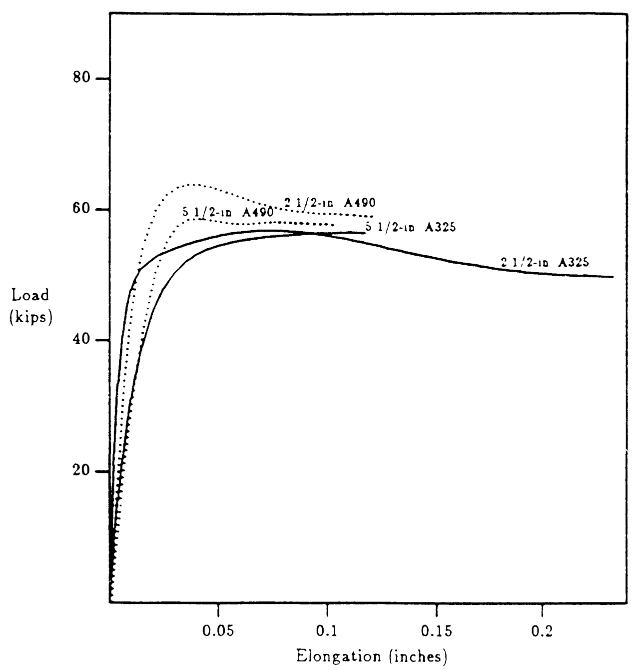


Fig. 2. Effect of grip length on A490 and A325 high-strength bolts in continuous torque.

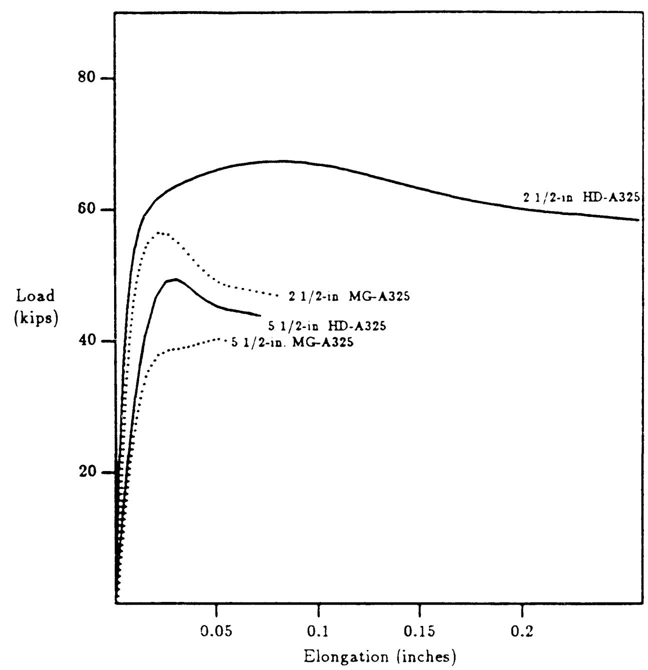


Fig. 3. Effect of grip length on galvanized A325 high-strength bolts in continuous torque.

Table 4.
Repetitively Torqued Tension Test Results

Bolt Lot	Lub. Type*	Method of Instl.**	No. Bolt Spec.	Ultimate Load Mean (kips)	Ultimate Load % Cont. Torq. Ult.	Mean Elongation at Ultimate Load (in.)	Mean Rupture Load (kips)	Mean Elongation at Rupture Load (in.)	Mean No. Cycles to Failure	Type of Failure
R3-2.5	AR	IW	3	57.6	102	0.083	48.3	0.123	10.3	Thread
	W	IW	3	63.3	96	0.059	48.7	0.110	8.7	Thread
R4-2.5	AR	IW,HJ	3	63.7	102	0.049	51.0	0.128	7.0	Shank
	W	IW	3	70.2	111	0.047	41.2	0.144	9.0	Shank
HD3-2.5	AR	IW	3	56.5	84	0.067	40.7	0.248	11.3	Shank
	W	IW	3	62.3	96	0.081	45.0	0.247	12.0	Shank
	G	IW	3	64.2	–	0.072	53.2	0.241	11.0	Shank
MG3-2.5	AR	IW	3	68.3	124	0.036	47.2	0.157	8.0	Shank
	W	IW	3	64.7	96	0.066	53.8	0.137	9.7	Thread
	G	IW	3	69.5	–	0.063	50.5	0.187	9.7	Shank
R3-5.5	AR	IW	3	58.7	103	0.067	55.1	0.087	5.0	Thread
	W	IW	3	62.6	–	0.092	59.0	0.124	6.3	Thread
R4-5.5	AR	IW,HJ	3	63.5	108	0.061	58.2	0.120	3.3	Shank
	W	IW	3	66.5	–	0.063	63.3	0.103	3.0	Shank
HD3-5.5	AR	IW,HJ	5	59.8	122	0.076	44.1	0.121	3.8	Shank
	W	IW	3	64.5	98	0.099	55.0	0.168	6.3	Shank
	G	IW	3	64.3	–	0.113	57.9	0.171	5.7	Shank
MG3-5.5	AR	IW,HJ	5	49.4	123	0.048	39.3	0.078	1.8	Shank
	W	IW	3	63.1	97	0.108	56.4	0.166	5.0	Shank
	G	IW	3	63.2	–	0.116	60.1	0.177	5.0	Shank

* AR as-received, W waxed, G greased
** IW impact wrench, HJ hydralic jack

cycle of bolt tightening and subsequent loosening. The solid line is the repetitively torqued tension envelope obtained by connecting the peak load values at the end of each successive tightening cycle. As the plot shows, each load-unload cycle diminishes the available ductility remaining in the bolt.

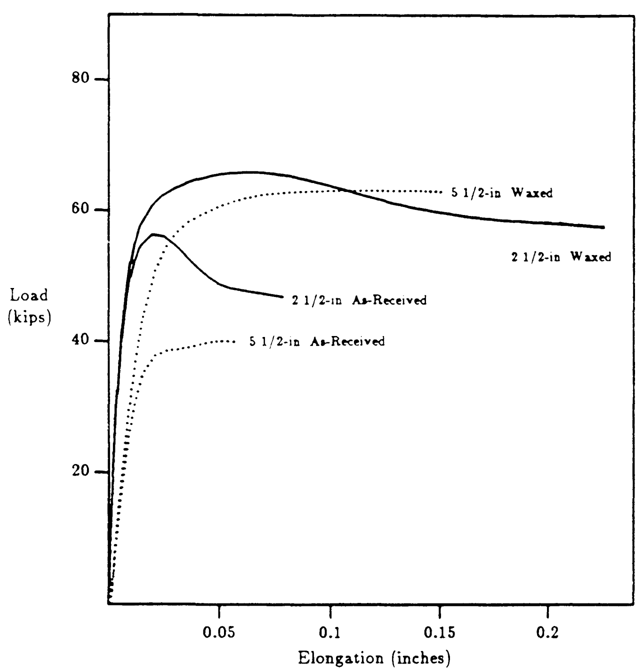


Fig. 4. Effect of thread lubrication on mechanically galvanized A325 high-strength bolts in continous torque.

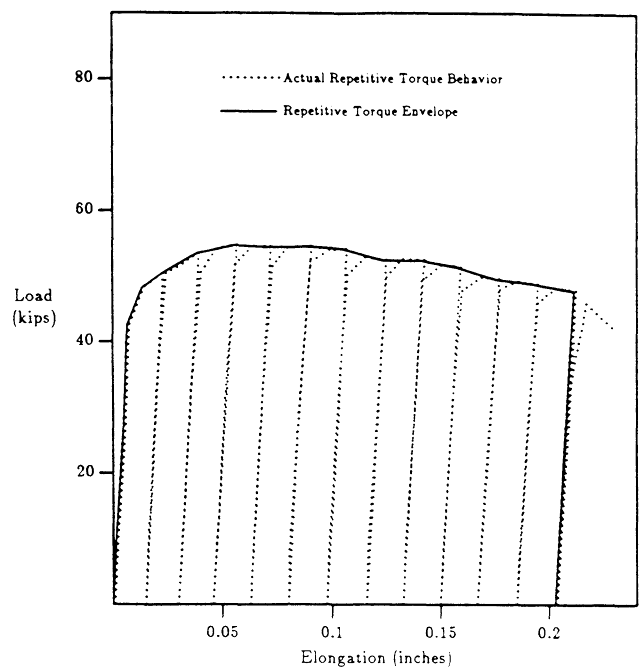


Fig. 5. Typical load-elongation behavior in repetitive torque for 2½-in. long hot-dipped galvanized A325 high-strength bolts.

The plot also indicates that the minimum bolt tension required by the RCSC Specification[10]—39,000 lbs. in this case—was developed for all tightening cycles prior to failure. This behavior is representative of the other repetitive torque tests, with the minimum bolt pretension developed for all tightening cycles prior to failure.

The envelope curves for three 2½-in. long hot-dipped galvanized bolts tested in repetitive torque are shown in Fig. 6. Envelopes are shown, rather than the actual repetitive test data, for the sake of clarity when comparing more than one bolt test. The individual bolt test envelopes are plotted as dotted lines, whereas the average envelope for the three tests is shown as a solid line. The number shown next to each individual bolt test envelope indicates the number of complete load-unload cycles sustained prior to failure. The dispersion of the repetitive bolt test data can be evaluated by comparing the load-deformation envelopes. In most cases, the load-deformation behavior was relatively uniform and the average envelope is a reasonable representation for a given bolt lot.

Continuous Torque Comparison

For most bolt types it was observed that the load-elongation behavior was similar for bolts tightened in continuous and repetitive torque. For example, the average load-elongation curve for continuous torque and the envelope curve for repetitive torque of the 2½-in. long A490 test bolts are shown in Fig. 7.

Generally, the tightening cycles from the turn-of-the-nut method cause plastic deformations that tend to follow the load-deformation curve for the continuously torqued bolt. Differences between the load-deformation curves and the repetitive torque envelopes, however, were noted for the "as-received" galvanized A325 bolts. It is believed that the differences observed in the average curves were due to variations of the zinc coating that resulted in scatter in the torque needed to fully tighten the bolt. The differences observed for the curves were less pronounced when lubrication was placed on the threads of the galvanized bolts prior to tightening.

Grip Length

Figure 8 illustrates the effect of grip length on the repetitive torque behavior of the hot-dipped galvanized bolts in the "as-received" condition. Although this is only one comparison, it is representative of the results observed and demonstrates that the 2½-in. long bolts performed much better overall than the 5½-in. long bolts. The shorter bolts sustained an average of 3 to 7 more tightenings to failure than the longer bolts.

It is believed that one factor responsible for the differences observed for the two bolt lengths is a variation in the stress and strain that develops when the bolt is tensioned by turning the nut. According to the turn-of-the-nut method given in the RCSC Specification,[10] the specified nut rotation for the shorter bolts is less than that specified for the long bolts. For a ⅞-in. diameter by 2½-in. long bolt, a nut rotation of ⅓ turn from the snug-tight condition is required to achieve the minimum required bolt pretension. For a ⅞-in. diameter by 5½-in. long bolt, the required nut rotation is ½ turn from snug. Since the same thread length under the nut was used

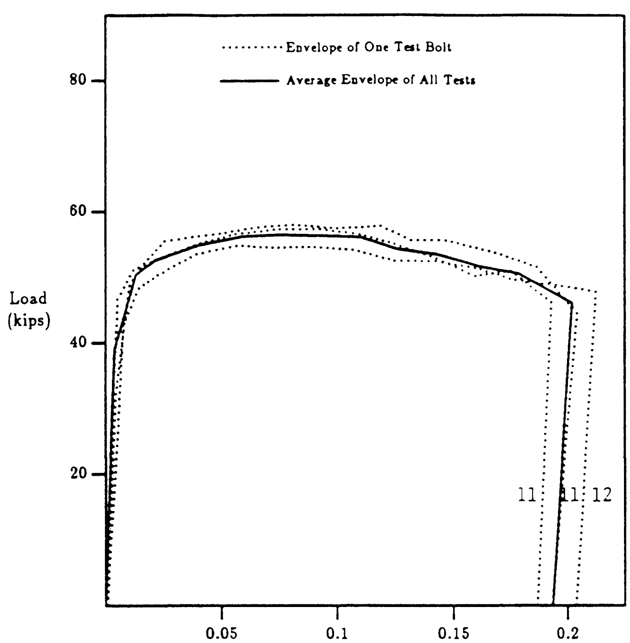


Fig. 6. Repetitive torque envelope for the "as-received" 2½-in. long hot-dipped galvanized A325 high-strength bolts.

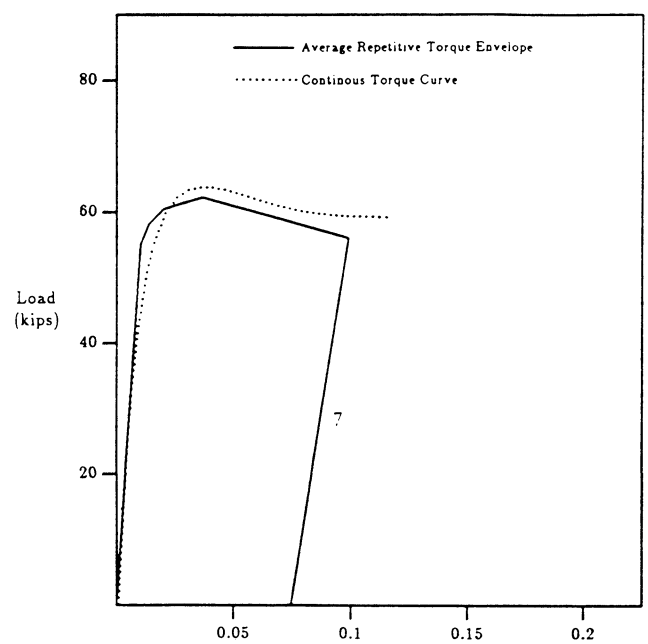


Fig. 7. Comparison between continuous torque and repetitive torque for "as-received" 2½-in. long A490 high-strength bolts.

for both bolt lengths, the shorter bolts experienced less deformation in the threaded portion of the bolt shank in the grip region than the longer bolts as a result of the lower specified nut rotation from snug. Consequently, it is logical to expect a larger number of tightenings prior to failure for the shorter bolts.

An additional factor that may have influenced the differences observed in the bolt behavior is the variation in available ductility for the bolt types. The continuous torque bolt test results indicate that the ductility was usually greater, and sometimes appreciably greater, for the shorter bolts than for the longer bolts (see Figs. 2 and 3). Therefore, the significant increase in the number of tightenings to failure for the shorter bolts may also be partly due to the greater available ductility in these bolts.

Thread Lubrication

The influence of thread lubrication on the load-deformation behavior of high-strength bolts that are repetitively tightened by the turn-of-the-nut procedure was also studied. The lubricants used included a commercial wax ("waxed" condition) for all bolt lots and a heavy multi-purpose grease ("greased" condition) for the galvanized bolt lots. In the "as-received" condition the threads for the galvanized bolts appeared to be dry, while the threads for the black bolts were covered with a light machine oil, which was present during shipping.

Thread lubrication was found to have some influence on certain bolt types that were repetitively torqued. One notable difference that can be observed in Table 4 is the number of complete tightening-loosening cycles required to cause failure. In almost all cases, the number of complete cycles to failure was higher for bolts in the "waxed" or "greased" condition than that achieved by bolts in the "as-received" condition. An increase of one to three cycles of the average number of cycles to failure was found, depending upon bolt type.

Another factor related to thread lubrication is that the average ultimate load and the elongation at rupture were greater in most cases for the lubricated bolts than for the "as-received" bolts. For example, the load-elongation envelope curves for the 5½-in. long hot-dipped galvanized bolt tests are shown in Fig. 9. In this case, the waxed and greased conditions were both found to be equally effective in increasing the ultimate load, the elongation at rupture, and the number of tightening cycles prior to failure.

The average ultimate loads for the "waxed" elements of all bolt lots were found to be between 96% and 111% of the continuously torqued ultimate load values. For the "as-received" black bolts, the average ultimate loads were between 102% and 108% of the continuously torqued ultimate loads. However, the average ultimate loads for the "as-received" galvanized bolts were between 84% and 124% of the continuously torqued ultimate load value. The variations noted in the ultimate load of the galvanized bolts are consistent with the findings of other investigators who observed that "as-received" galvanized bolts produce variable results when lubrication is not applied to the threads.[3,7,8]

As in the continuously torqued bolt tests, two types of fractures were encountered during the repetitive torque bolt tests. Again, tension-shear rupture in the threaded portion of the

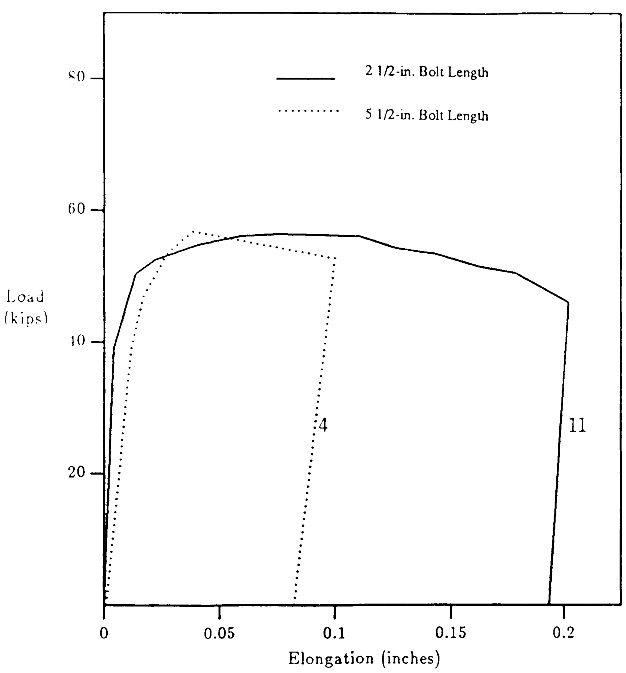


Fig. 8. Effect of grip length on hot-dipped galvanized A325 high-strength bolts in repetitive torque.

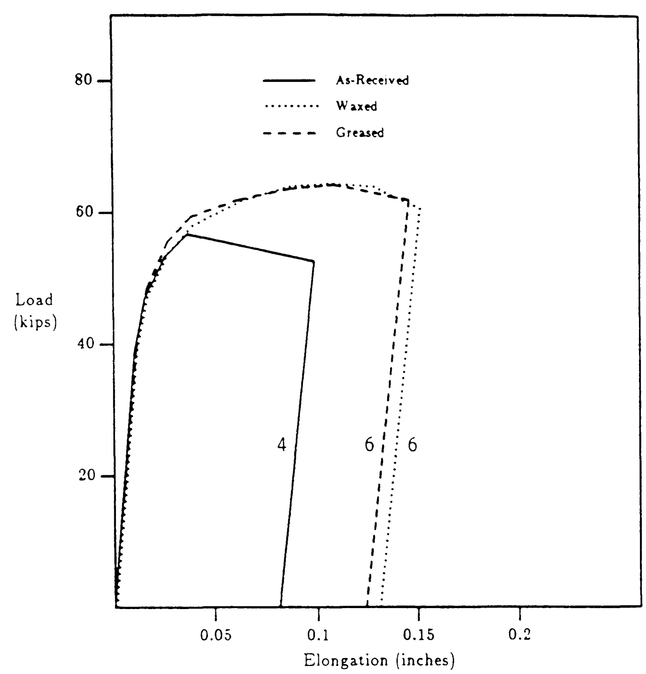


Fig. 9. Effect of thread lubrication for 5½-in. long hot-dipped galvanized A325 high-strength bolts in repetitive torque.

bolt shank was the most frequent mode of failure. Stripping failure, however, was encountered frequently when the threads were waxed.

One notable case of thread stripping involved the 2½-in. long A325 black bolts. In these tests the thread lubrication appears to have caused a reduction in the number of tightening cycles and the ultimate elongation. The primary cause of the premature failure, however, is believed to be the result of stripping of the soft A563 Gr C nuts used with these bolts.

Finally, the repetitive bolt test results indicate that a greater improvement in the number of cycles to failure was found for the lubricated 5½-in. long bolts than for the lubricated 2½-in. long bolts. It is believed that this difference is related to a more significant reduction in the torque needed to tighten the longer bolts when the threads are lubricated. The nuts for the 5½-in. long bolts must be turned more than those for the 2½-in. long bolts to achieve the minimum bolt pretension. The additional rotation requires the application of a greater torque, some of which can be reduced if a lubricant is applied to the bolt threads.

CONCLUSIONS

On the basis of the limited number of tests conducted in this study using ⅞-in. diameter A325, A490, and galvanized A325 bolts, the following conclusions regarding bolt behavior can be stated:

1. Bolts lubricated with either wax or grease perform much better, or at worst only equal to, that of similar bolts in the "as-received" condition. Thread lubrication resulted in improvements in the ultimate load, elongation, and rotational capacity of the structural fasteners tested, especially for the galvanized bolts.
2. The load-elongation characteristics of the bolts loaded in repetitive torque do not differ significantly from that of similar bolts in continuous torque. For most bolt types observed, there was a similar pattern of torque-tension behavior between the two loading methods.
3. The performance of 2½-in. long bolts was found to be superior to that of 5½-in. long bolts when the bolts were repetitively tightened until the bolts failed. The shorter bolts sustained an average of nine complete cycles prior to failure for all bolt types tested, whereas the longer bolts averaged four complete cycles prior to failure. A difference of one or two tightenings was observed between the black A325 and the galvanized A325 high-strength bolts.
4. Thread lubrication was observed to increase the number of cycles to failure of the repetitively tightened test bolts by one to three cycles. Moreover, thread lubrication was found to be more effective in improving the repetitive torque behavior of the galvanized bolts than of the black bolts.

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