High-Strength Bolting

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JUST TWENTY YEARS ago Professor Wilbur Wilson, a Professor of Structural Engineering at the University of Illinois, played a major role in the founding of the Research Council on Riveted and Bolted Structural Joints, the group largely responsible for high-strength bolting as we know it today. Since then, thousands of tests have been conducted on high-strength bolts and bolted connections, specifications for high-strength bolting have been issued by the Council, and many millions of high-strength bolts have been used in bridges and buildings.

The high-strength bolt rapidly took its place in the structural field and has now become the "workhorse" fastener for steel structures. Although this fastener has proven to be extremely effective, occasionally trouble has been encountered and questions have been raised concerning high-strength bolting. Whenever such trouble has been encountered, it has almost always been as the result of a lack of understanding or improper application of the Council's specification. To help counteract this problem, an attempt will be made herein to provide some of the "whys" and "wherefores" of high-strength bolting. Some of the questions that are raised regarding high-strength bolting will be examined, consideration will be given to some of the changes that were introduced in the September, 1966 revision of the Research Council's specifications for high-strength bolting, and finally, some of the possible future changes and new applications of high-strength bolting will be discussed.

WHY HIGH-STRENGTH BOLTING?

In view of the widespread acceptance that high-strength bolts have received, there must be important advantages to their use. Most of these advantages are obvious and will be discussed only briefly.

(a) *Greater strength*—High-strength bolts have been found to be stronger than rivets in both shear (Fig. 1) and tension. This advantage has been observed not only under static loadings but also under fatigue or repeated loadings.

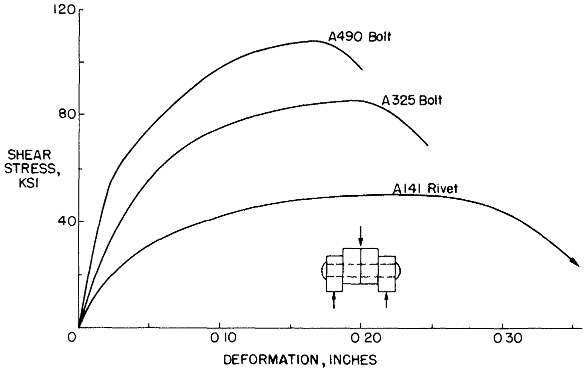

Fig. 1. Shear strength relationships for rivets and high-strength bolts (Ref. 1)

(b) *Economy*—Many applications of high-strength bolting have shown the installed cost of the bolt to be lower than that of the same size rivet. In some instances it has been estimated that the high-strength bolt has provided savings as great as 20 percent.

(c) *Friction gripping*—The forces in bolted structural connections are transmitted by friction between the connected parts rather than direct shear on the bolts. This has provided improved behavior.

(d) *Permanent fastening*—Field installations, even under extremely severe loading conditions, have shown that properly installed bolts stay tight—no lock washers or other locking devices are required to maintain this tightness. Furthermore, the bolts can be replaced easily if it becomes necessary.

(e) *Faster erection*—It is found that a two-man bolting crew can fix or install more bolts in a given time than a four-man riveting crew. This not only affects a reduction in cost for the erection of the structure but also results in a structure being erected at a greater speed.

(f) *Less noise*—Although impact wrenches are generally used for the installation of high-strength bolts, it is found that such wrenches are much quieter than the equipment used for riveting.

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(g) *Less equipment*—In the erection of a bolted structure, the steelworker finds less scaffolding necessary to install bolts than would be necessary for riveting. In addition, fewer tools and less equipment are required to properly install these high-strength fasteners.

(h) *Less training*—Only an hour or two is needed to train a bolting crew. Furthermore, the bolting crews can be made up of ordinary steelworkers and need not be trained in the same manner as riveting crews.

(i) *Reduced fire risk*—Since there are no furnaces required, and no flying hot rivets associated with bolting operations, the use of high-strength bolting is found to be safer insofar as fire hazards are concerned.

(*j*) *Less inspection*—Because of the more consistent nature of high-strength bolting and the better control possible over the installation procedure, less and improved inspection is required during the erection operations.

With so many advantages it is quite obvious why this fastener has become so important to the structural steel industry.

Table 1 Approximate Properties of High-Strength Bolts

Bolt Type	Yield Strength (psi)	Tensile Strength (psi)
A325	85,000	120,000
A490	120,000	150,000

HIGH-STRENGTH BOLTS AND SPECIFICATIONS

At the present time two general structural fasteners are available for high-strength bolting—ASTM A325 and A490 bolts (Table 1). The A325 bolt is the basic fastener introduced by the Research Council twenty years ago for structural purposes. The material in this fastener provides a yield strength of approximately 85,000 psi, an ultimate tensile strength of approximately 120,000 psi, and has proven to be a most efficient and effective fastening device. However, with the introduction of many new high-strength structural steels, it was assumed that further advantages in high-strength bolting might be achieved through the introduction of a bolt having still greater strength—the A490 bolt.

The A490 bolt is produced from material having a yield strength of approximately 120,000 psi and an ultimate tensile strength of approximately 150,000 psi. Thus, an increase of approximately 50 percent has been achieved in the yield strength of this "higher" high-strength bolt. More detailed descriptions of these bolts and their properties will be found in the appropriate ASTM specifications.

The identification markings of A325 bolts as well as the nuts which are employed with these bolts are shown in Fig. 2. With these markings it is a simple matter to verify in the field that the proper bolts have been used.

The Research Council's Specification for Structural Joints Using ASTM A325 or A490 Bolts[2] provides for the design and assembly of joints using these two types of bolts, or equivalent fasteners, tightened to a specified tension. The joints covered by this specification are designated as either "friction-type" or "bearing-type". Initially it might appear that the connections designated by these terms are significantly different. However, the two types of connections are essentially the same. The principal difference lies in the allowable stress employed in the design of the connections. A somewhat higher allowable stress is permitted for the so-called "bearing-type" connections wherein slip would not be harmful. In the "friction-type" connections slippage is undesirable and consequently a lower allowable shear stress must be employed. Under normal working conditions it is most likely that neither type of connection will undergo slippage and consequently they will behave generally in a similar fashion.

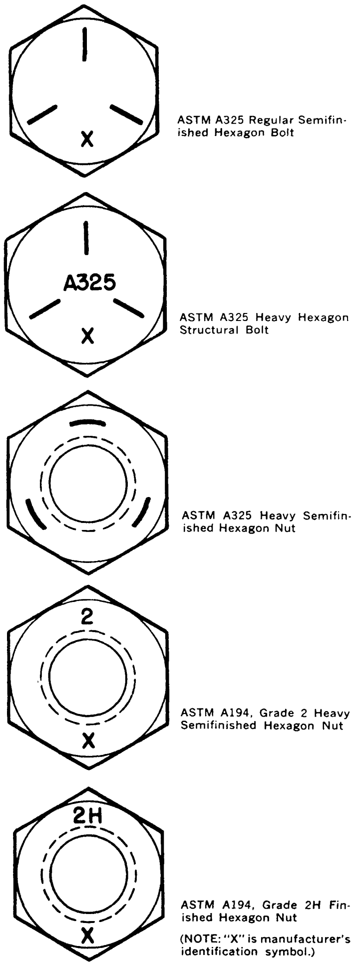

Fig. 2. Markings for high-strength bolts and nuts

BOLTS, NUTS AND WASHERS FOR HIGH-STRENGTH BOLTING

High-strength bolting is generally accomplished with ASTM A325 or A490 heavy hex-head bolts. Other fasteners which meet the chemical composition and mechanical property requirements of the ASTM specifications may be used as alternate fasteners (Fig. 3). However, the adequacy of these alternate fasteners must be verified.

Two alternate fasteners that have been examined in some detail are the interference-body bolts and the Huck-bolt fasteners. Such fasteners, manufactured of the appropriate materials, have been found to be suitable alternates for high-strength bolting. In foreign countries, still other alternates have been devised and accepted for high-strength bolting. Although some of the alternate fasteners have provided certain advantages, the cost of such proprietary items is generally greater than that of the usual quenched and tempered high-strength hex-head bolt.

When alternate fasteners are employed, their installation procedure may differ from that used for the A325 high-strength bolts. If so, supplemental specifications must be provided with adequate control to insure that the alternate fastener is acceptable and provides the desired clamping force.

On occasion, studies have been made on various types of nuts that might be used with high-strength bolts. Several of these nuts are shown in Fig. 4. Although all of these nuts have proven to be suitable for use with high-strength bolts, the most effective and probably cheapest has been the heavy hex nut. It is this heavy semifinished hex nut which is provided as a standard for the A325 high-strength bolt.

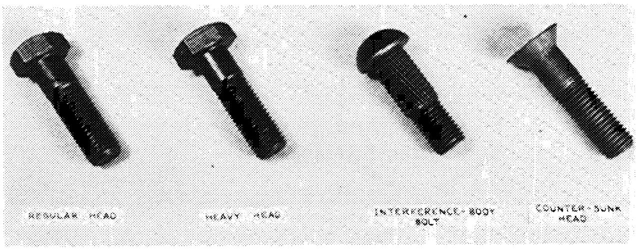

Fig. 3. Various high-strength bolts for structural joints

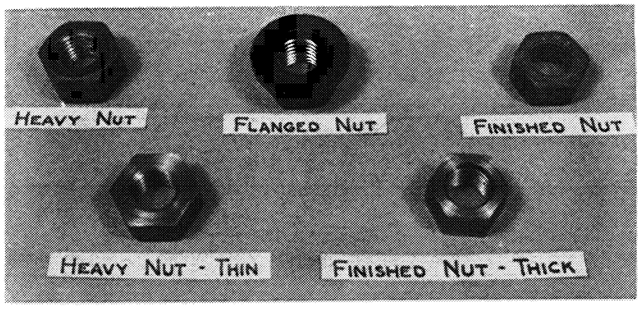

Fig. 4. Various types of nut studies in laboratory tests

BOLTED PARTS

In the Research Council's specification it is required that the surfaces of bolted parts in contact with the bolt head and nut shall not have surfaces with slopes that exceed 1:20 with respect to a plane normal to the bolt axis. The bolts are ductile and will deform to the 1:20 slope. However, a greater slope would be undesirable and produce too great a loss in bolt strength and ductility. When greater slopes exist, beveled washers must be employed to compensate for this condition.

The Research Council's specification further requires that all joint surfaces, including those adjacent to the bolt heads, nuts or washers, shall be free of scale, except tight mill scale, and shall also be free of burrs, dirt and other foreign material that would prevent solid seating of the parts. This provision is essential if the connections are of the "friction-type" and must carry the applied load or forces by virtue of the friction between the connected parts. However, "bearing-type" connections can be and often are assembled with painted contact surfaces since such connections are permitted to slip into bearing.

ALLOWABLE WORKING STRESSES FOR HIGH-STRENGTH BOLTING

The Research Council, on the basis of laboratory studies and field experience (see Table 2), has provided allowable working stresses for both the A325 and A490 bolts. Changes in some of the allowable working stresses for the A490 bolts have been made in the September, 1966 revision of the specification.

Tension—The laboratory tests conducted during the past several years indicate that the proof load of the A490 bolt cannot *always* be achieved, even if the turn-of-nut method is used for installation purposes. As a result, the allowable tensile working stresses have been reduced somewhat. The allowable tension, based on the nominal cross-sectional area of the bolt, is now 48,000 psi for use in bridges and 54,000 psi for use in buildings; the values in the 1964 Specifications were 54,000 and 60,000 psi, respectively. These stresses are for static loading only. When dynamic or repeated loadings are applied to the fasteners, the allowable stresses should be the same as those provided for the A325 bolts.

When high-strength bolts are employed to resist tensile loadings, the design load for the bolts should be taken as the sum of the external load and any tension that might result from prying action produced by the deformation of the connected parts. The effect of this prying action on the efficiency of the bolts has been clearly observed in tests wherein tee-section flanges are bolted together with tension bolts and then subjected to tensile

Table 2 Allowable Working Stresses for Fasteners[a] *

Specification Paragraph	Loading Conditions	ASTM A325 Bolts		ASTM A490 Bolts	
		Bridges	Buildings	Bridges	Buildings
4(b)	Applied tension, psi	36,000	40,000	48,000[b]	54,000[b]
4(c)	Shear, psi				
	1. Friction-type connection	13,500	15,000	18,000	20,000
	2. Bearing-type connection, shear plane through threads	13,500	15,000	20,000	22,500
	3. Bearing-type connection, threads excluded	20,000	22,000	29,000	32,000
4(d)	Bearing, psi[c]	$1.22 F_y$	$1.35 F_y$	$1.22 F_y$	$1.35 F_y$

[a] The tabulated stresses, except for bearing stress, apply to bolts used in any grade of steel.

[b] Static loading only.

[c] F_y = Specified minimum yield point of the lowest strength connected part. The bearing stress shall not be more than the specified minimum tensile strength of the lowest strength connected material.

load (Fig. 5). It is found that the fasteners may lose a large part of their efficiency as a result of the prying action, depending upon the flange thickness and also on the number of lines of bolts. With two lines of fasteners full efficiency can only be achieved with very thick flanges; with four lines of fasteners it is virtually impossible to achieve full efficiency of the bolts. Thus, it is essential that the effects of prying be examined carefully in the design of tension connections, not only for bolted but also for riveted connections.

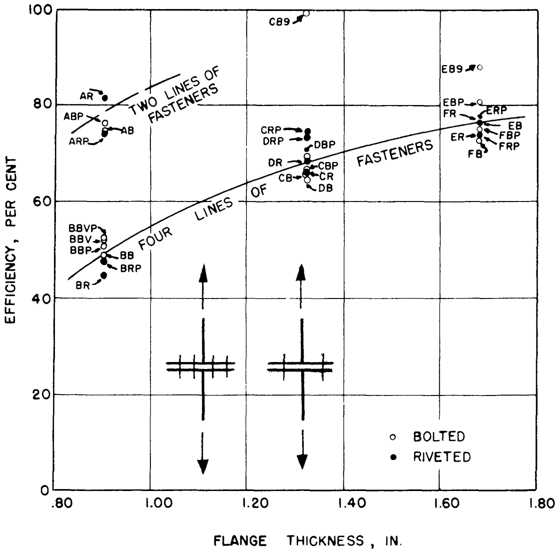

Fig. 5. Efficiency of high-strength bolts in tension when subjected to prying (Ref. 3)

Shear—Modifications have been made also in the allowable working stresses for shear on A490 bolts. Because of the possible reduction in initial clamping force and, since the allowable shearing stress is a direct function of the clamping force, these modifications apply only to the "friction-type" connections. The allowable shearing stresses for "friction-type" connections for bridges and buildings have been reduced to 18,000 and 20,000 psi, respectively (reduced from 20,000 and 22,500 psi).

Another factor that has an effect on the allowable shear stress is the length of the threads (Fig. 6). Numerous load (shear) versus deformation plots have been obtained for high-strength bolts wherein either the full shank of the bolt or threaded portions of the bolts are placed in the shear planes. As one might expect, the greatest shear strength is obtained when the full shank of the bolt is available to resist the applied shear loads. When the threads project beyond the shear planes the shear capacity of the bolts may be reduced to as little

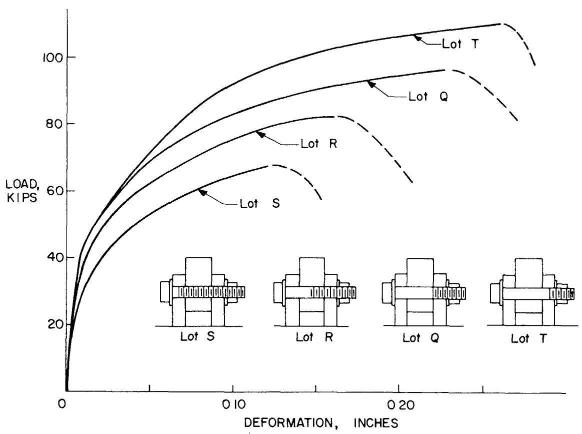

Fig. 6. Shear-deformation curves for various thread lengths (Ref. 7)

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* *Specification for Structural Joints Using ASTM A325 or A490 Bolts*

as 70 percent of the full shank strength. It is for this reason that the allowable shear stresses for "bearing-type" connections are reduced when the shear plane or planes pass through the fastener threads.

Although not presently included, another factor which may soon be considered in the specification is the effect of joint length (Fig. 7). Laboratory tests have indicated that the average shear strength of fasteners in a long joint may be reduced considerably below that of a single fastener. As a result, it may be desirable to modify the allowable working stresses to permit an increase in the allowable shear stress for "bearing-type" connections when the joints are relatively short; or conversely, to require a reduction in the allowable shear stress when the connections are long. Such a modification could be made to provide for a more uniform factor of safety in the connections of high-strength bolted structures.

Combined Tension and Shear—On occasion, it is necessary to use bolts that are subjected to a combination of tensile and shear loadings. Although laboratory tests (Fig. 8) have provided extensive data for high-strength bolts subjected to this type of loading, the specifications of the Research Council on Riveted and Bolted Structural Joints do not provide allowable stresses for this condition. However, the AISC Specification[6] does cover this case with the following relationship:

$$F_t = 50{,}000 - 1.6 f_v \leq 40{,}000$$

where F_t is the allowable tensile stress under the oblique loading, and f_v is the shear stress produced by the same force but shall not exceed the allowable value of working stress for shear.

End Distance—One further factor which should be called to the designer's attention is the need for an increase in the end distance of small bolted connections. Because of the shear strength of the high-strength bolt it has been found that previous specifications did not provide sufficient end distance for small joints. Provisions now require that the distance between the center of the nearest bolt and the end of the connected members toward which the pressure from the bolt is directed shall be not less than the following:

$$\text{End distance} = AC/t$$

where A is the nominal shear area of the bolt, C is the ratio of specified minimum tensile strength of the fastener to the specified minimum tensile strength of the connected part, and t is the thickness of the connected part. This provision protects against the tearing out of the plate at the end of a structural connection.

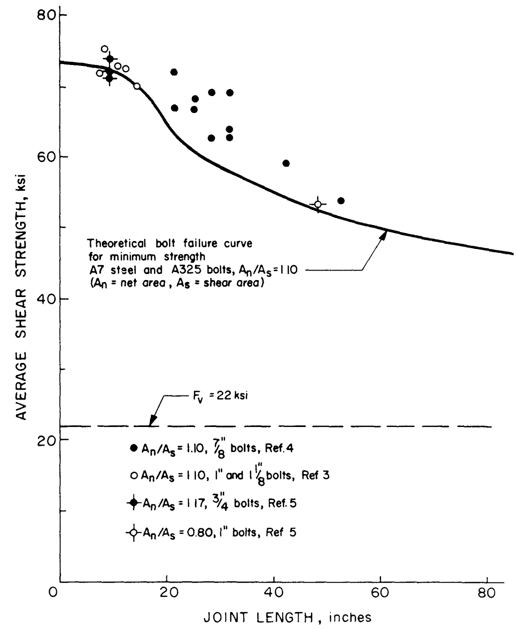

Fig. 7. Effect of joint length on bolt shear strength (Ref. 4)

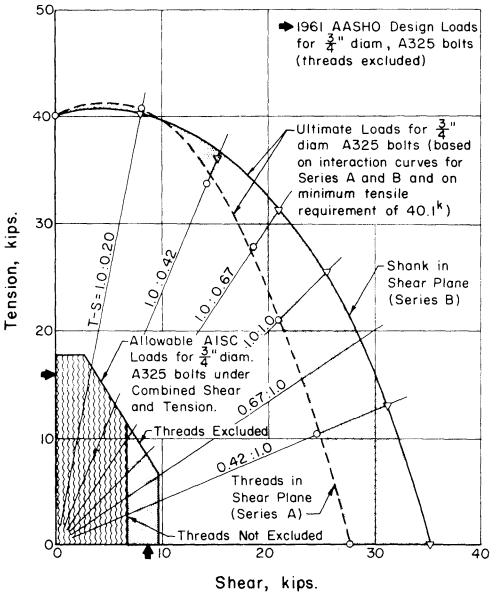

Fig. 8. Behavior of A325 high-strength bolts under combined tension and shear (Ref. 5)

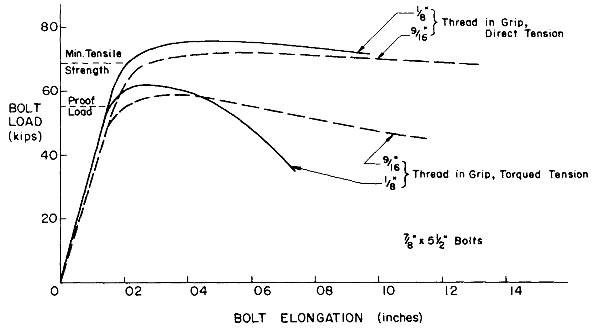

Fig. 9. Reduction of bolt strength with method of loading (Ref. 7)

Table 3 Fastener Tension *

Bolt Size, in Inches	Minimum Fastener Tension[a] in Thousands of Pounds (kips)	
	A325 Bolts	A490 Bolts
½	12	15
⅝	19	24
¾	28	35
⅞	39	49
1	51	64
1⅛	56	80
1¼	71	102
1⅜	85	121
1½	103	148
Over 1½		0.7 × T.S.

[a] Equal to 70 percent of specified minimum tensile strengths of bolts, rounded off to the nearest kip.

INSTALLATION AND RE-INSTALLATION OF HIGH-STRENGTH BOLTS

How does one best install high-strength bolts? This question has received much attention and several aspects of the problem will be discussed.

Bolt Tension—In order for high-strength bolts and bolted structures to function properly, the installation procedures must be capable of producing the required minimum bolt tensions (Table 3). In the 1964 edition of the Research Council's specifications, minimum bolt tensions equal to the proof load were specified for both A325 and A490 fasteners. However, as noted previously, laboratory data have indicated that on occasion the proof load may not be achieved with a minimum strength A490 bolt. This results from the fact that the bolt material has a proof load requirement which is 80 percent of the tensile strength of the bolt; and, when an A490 bolt is torqued to failure it is found that the torqued tensile strength is only 80 to 90 percent of the direct tensile strength of the fastener, the exact magnitude depending upon the frictional resistance on the threads of the fastener (Fig. 9). Using the usual bolt installation procedures, a bolt load somewhat below the torqued tensile strength (probably about 10 percent) is obtained. As a result, a guaranteed clamping force in the fastener of 70 percent of the tensile strength is all that can be assured (Fig. 10). The clamping, therefore, may be below the proof load for A490 bolts.

Another important observation concerning high-strength bolts concerns the ultimate tensile strength of these fasteners after they have been torqued to a high initial tension. Although the bolts are generally installed at or possibly a little above proof load, the fasteners still retain their full tensile capacity (Fig. 11). This is why it has often been stated that a bolt that does not fail on installation is a good bolt, providing it has been installed to at least the minimum required clamping force. In general, the higher the initial clamping force, the better the connection, both under static loadings and in joints that are subjected to fatigue loadings.

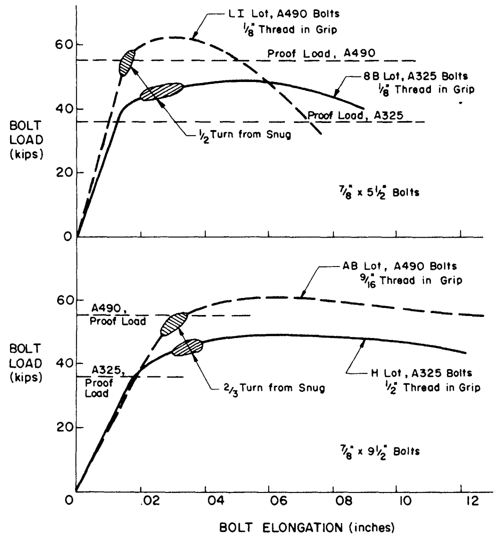

Fig. 10. Load-elongation relationships for A325 and A490 bolts. Both torqued in a hydraulic calibrator (Ref. 7)

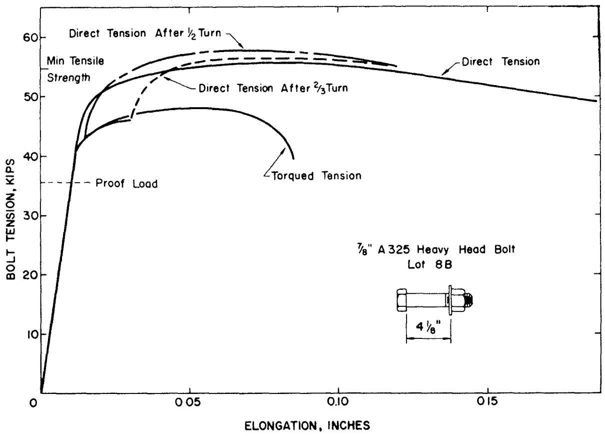

Fig. 11. Load-elongation behavior of bolts either torqued or loaded in direct tension (Ref. 8)

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* *Specification for Structural Joints Using ASTM A325 or A490 Bolts*

Relaxation—Once achieved, will the high clamping force in a high-strength bolt relax? (See Fig. 12). Examinations of bolt tension over an extended period of time during fatigue tests demonstrate that some relaxation does take place in high-strength bolts which are torqued up to or beyond their proof load. However, this relaxation is relatively small and almost disappears within a short period of time. Load-cell studies conducted over a period of several months indicate that the relaxation may be only 5 or 6 percent and not more than possibly 10 percent over the life of a structure that is subjected to static loadings. Thus, bolts torqued to a high initial clamping do retain most of their clamping force and can be expected to provide the desired behavior in structure for long periods of time.

Re-use of Bolts—In some instances it has been found necessary to loosen and retighten high-strength bolts. Since the initial installation requires torquing of these fasteners into the plastic range, the reuse of the bolts has often been questioned. However, laboratory studies (Fig. 13) clearly show that the A325 bolts may be used several times without causing any serious damage to the bolt. The number of times a bolt may be tightened to ½ turn-of-nut depends upon the length of the bolt and also the length of thread within the grip. Nevertheless, even the shorter grips and thread lengths can be expected to permit two or more applications of ½ turn-of-nut.

Torque Tightening—Initially torque wrenches and fixed values of torque were used for the installation of high-strength bolts. However, it has been found that the bolt tensions achieved with this torque were quite variable (Fig. 14). Available data suggest that the bolt tension may vary from one lot of bolts to another by as much as ±20 percent for a given torque. As a result, torque controlled installation often provided bolts which were either undertorqued, or on occasion torqued to failure. Because of this variability, other more reliable procedures have been developed for high-strength bolting. These are the calibrated wrench and the turn-of-nut tightening procedures.

Calibrated Wrench Tightening—In the calibrated impact wrench technique a calibrating device, such as the Skidmore-Wilhelm Calibrator (Fig. 15), is employed to measure the bolt tension developed with a given wrench. The air pressure and wrench are adjusted in such a manner as to induce a bolt tension 5 to 10 percent in excess of the desired or minimum bolt tension. These wrenches should be calibrated at least once each working day, using not less than three typical bolts of each diameter of bolt to be installed. The power wrenches should be adjusted to stall or cut out at the selected tension. If a manual torque wrench is to be used, the necessary torque shall be established also using a calibrating device and the procedure described for the impact wrench.

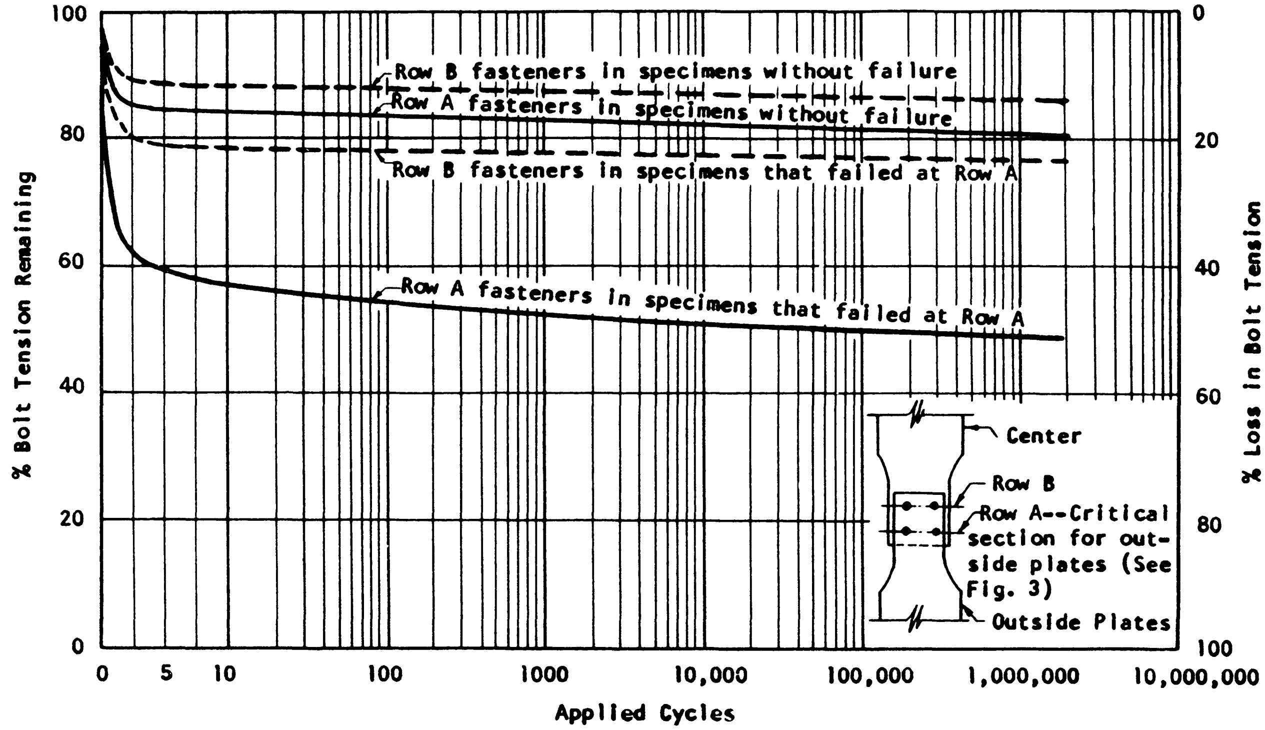

Fig. 12. Relaxation of bolt tension during fatigue loadings of a bolted connection (Ref. 9)

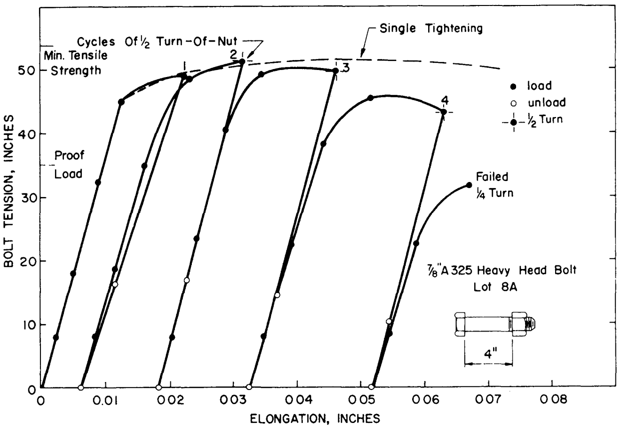

Fig. 13. Retightening of high-strength bolts (Ref. 8)

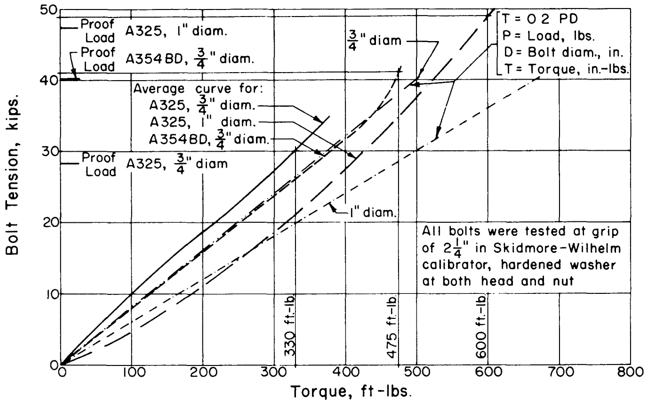

Fig. 14. Torque relationships for high-strength bolts of various diameters (Ref. 5)

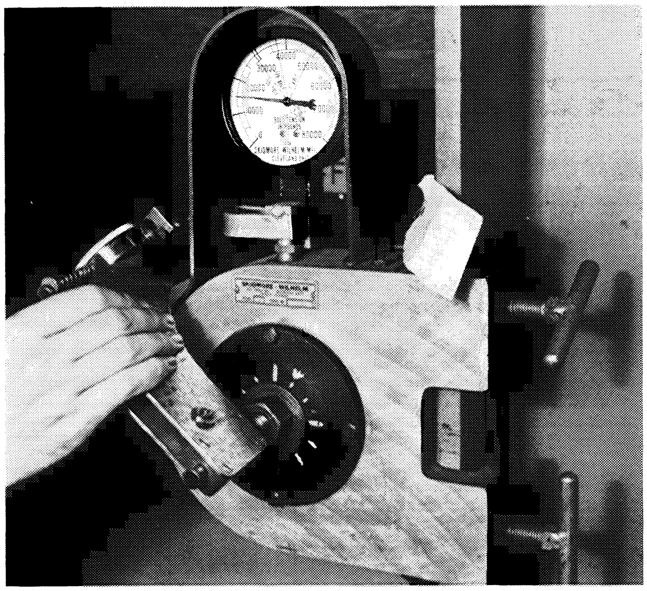

Fig. 15. Calibrator for high-strength bolts

Turn-of-nut Tightening—The second procedure now commonly in use is the turn-of-nut method. When this procedure is used there shall be enough bolts brought to a snug-tight condition in the joint to insure that all parts are in *full* contact with each other. This snug-tight condition is defined as the tightness obtained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench. Once this initial snug condition is obtained, then additional tightening in the amount specified in Table 4 shall be applied. This will provide the minimum required bolt tensions if properly used.

An indication of the relationship obtained between tension in the bolt and the nut rotation is shown in Fig. 10. It is evident in this diagram that for the A325 bolt employed, the specified ½ turn-of-nut was sufficient to provide the proof load, the minimum required bolt tension. However, in the case of the A490 bolt, the ½ turn-of-nut or even ⅔ turn-of-nut may not develop the proof load. The reduction in minimum bolt tension previously discussed will make it possible to achieve the required clamping force with the nut rotations specified in Table 4.

Table 4 Nut Rotation[a] from Snug Tight Condition*

Disposition of Outer Faces of Bolted Parts		
Both faces normal to bolt axis, or one face normal to axis and other face sloped not more than 1:20 (bevel washer not used)		Both faces sloped not more than 1:20 from normal to bolt axis (bevel washers not used)
Bolt length[b] not exceeding 8 diameters or 8 inches	Bolt length[b] exceeding 8 diameters or 8 inches	For all length of bolts
½ turn	⅔ turn	¾ turn

[a] Nut rotation is rotation relative to bolt regardless of the element (nut or bolt) being turned. Tolerance on rotation: 30° over or under.
For coarse thread heavy hex structural bolts of all sizes and length and heavy hex semi-finished nuts.

[b] Bolt length is measured from underside of head to extreme end of point.

* *Specification for Structural Joints Using ASTM A325 or A490 Bolts*

It would be well also to note that when a slope exists on the faces of the parts being connected, a greater rotation of the nut is necessary. This is because of the bending or deformation that takes place in the fastener as it is torqued (Fig. 16). An increase of approximately ¼ turn-of-nut is necessary to achieve the same degree of tightening in a member which has two 1:20 beveled surfaces. Following the specified nut rotations of Table 4, suitable bolt tightness will be obtained.

INSPECTION OF HIGH-STRENGTH BOLTING

The question of inspection has received much attention at meetings of the Research Council on Riveted and Bolted Structural Joints, and many inspection problems have been discussed. Most of the difficulty lies in the fact that the inspection procedures and techniques now available are no more accurate than the bolt installation techniques employed for the assembly of the structure. Consequently, inspectors often find it difficult to verify that the minimum required tensions have been achieved.

In many instances manual torque wrenches have been employed to verify the bolt tension. However, as noted previously, the use of torque may not be an accurate method of checking the tension in a bolt. When hardened washers are employed the required torque, as shown in Table 5, will generally be equal to:

Torque = 0.2 × bolt diameter × bolt tension

Table 5 Approximate Torque for Minimum Tension

Bolt Size	A325 Bolt (ft-lb)	A490 Bolt (ft-lb)
⅝	200	280
¾	355	500
⅞	525	805
1	790	1215
1⅛	1060	1720
1¼	1495	2425

Thus, the torques necessary to verify or check the initial tension become extremely large for the large size bolts (Table 5). For this reason inspectors find it difficult if not impossible to verify the bolt tension in the larger size bolts.

In addition, when hardened washers are not used, a condition now permitted by the specification, the surfaces of the material may be galled to some extent (Fig. 17) and the necessary torque requirements for inspection extremely difficult to establish. When the washers are eliminated this torque may reach a value twice as great as that given in Table 5.

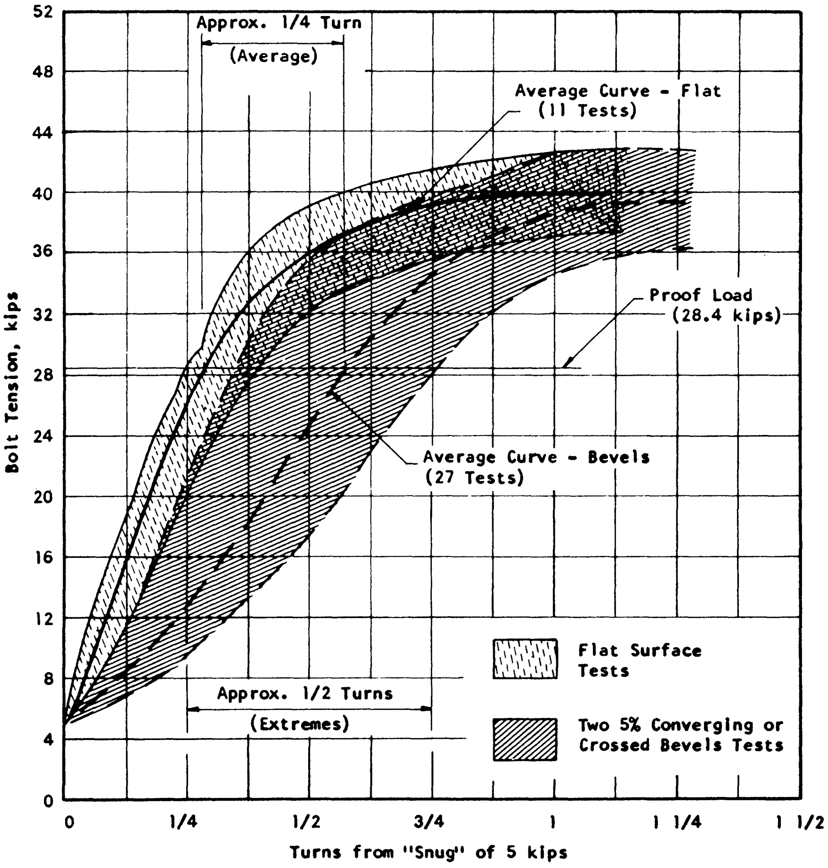

Fig. 16. Effect of beveled surfaces on bolt installation requirement (Ref. 4)

Fig. 17. Galled surface under nut torqued without hardened washer

Because of the inspection difficulties noted above, several suggestions might be offered to assist the inspector. First of all, a nut which has been impacted may show a rounding of the nut corners. This will at least indicate to an inspector that an impact wrench has been applied to the nut. Then, if a manual torque wrench is applied to a limited number of the bolts, using the approximate torques shown in Table 5, the inspector will at least know that the impact wrench had been maintained on the nut sufficiently long to develop a relatively high bolt tension, even if no washer has been used. However, because of the extreme variability in the relationship between torque and tension when no washer is used, it may be difficult to verify that the minimum bolt tension has been achieved. Nevertheless, this manual torque checking procedure will generally insure that, (1) if washers are used, a bolt tension above the minimum required bolt tension, has been achieved, and (2) if no washers are used, a bolt tension probably equal to at least 80 percent or more of the minimum required tension has been achieved. This should provide for a safe and sound structure. Also, if an inspector finds that a torque twice as great as that shown in Table 5 is needed to turn the nut, this does *not* mean that the bolt has been "overtorqued". As noted previously, if the bolt has not failed when initially installed, it is generally a good bolt.

FUTURE APPLICATIONS OF HIGH-STRENGTH BOLTING

Before completing this discussion it would be well to do a little "crystal ball gazing" at some of the possible future applications of high-strength bolting.

One of the areas currently under study and possibly of considerable importance to the bridge engineer is the use of galvanized bolts and structures. Several installations in galvanized structures have already been made with galvanized bolts. However, the frictional resistance in a galvanized joint has generally been found to be somewhat below that of a joint with dry mill-scale surfaces. With further study and some modifications in design procedure, however, it may be possible to utilize galvanized bolts and structures in the near future.

Another area receiving considerable attention at the present time is the application of high-strength steels to large bolted structures; extensive studies are currently underway, both under static loadings and fatigue loadings. Improved design procedures for bolted structures of high-strength steel should be available soon. This may result in more complicated design specifications and design procedures, but should make it possible to use the materials more effectively.

A final question, and one that soon should be better defined, concerns the problem of bolts under tensile loadings. The specifications presently indicate that prying action shall be taken into account in the design of bolts loaded in tension but does not indicate how the prying forces may be determined. Studies currently underway should help greatly to alleviate this problem and provide methods of analysis that will make possible a more reasonable determination of all the forces to which the bolts are subjected.

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