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High Strength Bolting in the U.S.A.

L'assemblage par boulons haute résistance aux U.S.A.

Die HV-Schrauben in den USA

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Design Concepts in the U.S.A.

The original application of high-strength A 325 bolts in the U.S.A. was based upon friction-type joints only. The first specification in 1951 merely permitted the substitution of a like number of bolts for hot-driven rivets [1].

It is well known that friction-type joints are dependent on proper bolt tension and an adequate coefficient of friction. In the U.S.A. the faying surfaces are usually only clean mill scale, and numerous tests of A 7 steel joints have indicated that a slip coefficient of 0.35 is representative of values encountered in actual construction. Because of higher labor costs in the U.S.A. it is considered uneconomical to increase the slip coefficient by treating the faying surfaces. Generally it is less expensive to use a larger joint with more bolts. The recent introduction of the higher strength A 490 bolt [2] will allow the use of smaller joints because of higher clamping force per bolt; thus it can be expected that there will be even less of a tendency to make use of special faying surface treatments.

The concept of a bearing-type connection was first introduced when the specification was revised in 1954. At that time, the omission of paint was required to apply only to joints subjected to stress reversal or vibration, or where joint slippage would be undesirable. Tests conducted at the University of Washington had shown that painting the faying surfaces substantially reduced the slip coefficient [3]. It was recognized that many joints were erected in bearing and that slippage was not a problem. Movement of the connected parts bringing the bolts into bearing against the sides of the holes was in no way detrimental to the strength or shape of the structure. Also, the cost of leaving contact surfaces bare was estimated to cost \$.10 to \$.15 per bolt used and was time consuming during fabrication.

In the 1960 revision of the Specification of the Research Council on Riveted and Bolted Structural Joints a clear distinction was made between friction-type and bearing-type connections. Up to this time the greater shear strength of the high-strength bolt was not recognized. In 1960, the stresses used to proportion bearing-type connections were increased when threads were excluded from the shear planes. Thus, the allowable stresses used in friction-type joints reflect the ability of the joint to resist slip whereas the values for the bearing-type joint reflect the shearing strength of the bolt.

The allowable "shear stresses" used to proportion friction-type joints correspond to a factor of safety against slip of 1.40 under gravity and live loads. It is recognized that the bolts are not actually stressed in shear nor is bearing a consideration in friction-type connections. However, it is convenient to specify an allowable "shear" stress in order that proportioning of friction-type connections may be carried out using the same well-established methods as are used in the design of riveted joints.

Allowable stresses for bearing-type connections are based on the ultimate shear strength of the fastener. Extensive tests of large A 7 and A 440 steel joints have shown that the factor of safety varies from about 3.3 for short connections down to 2.2 for joints up to 50 inches long [4, 5]. In bearing-type joints, even though the bolts are tightened so that friction may carry the working load, frictional resistance is not required and the design is properly based on the shearing strength of the bolts.

Experience with Bolted Connections

1. Fatigue Tests of Joints Connected by A 325 Bolts without Washers

During the past few years a number of fatigue tests on bolted lap splices were conducted at the University of Illinois [6]. These tests included specimens designed for extreme conditions: oversized holes, no washers, and in most cases, minimum clamping was employed. When the turn-of-nut method was used to preload the bolt none of the specimens failed until at least 2.4×10^6 cycles were applied at a 0—30 ksi stress cycle. This was true even though a number of the specimens slipped into bearing during the first cycle of loading.

One specimen with no washers and oversized holes ($^1/_8$-in. instead of $^1/_{16}$-in.) slipped into bearing during the first cycle of loading and ran 3×10^6 cycles at 0 to 30 ksi without failure.

2. Relaxation Tests of A 325 and A 490 Bolts

Relaxation tests to determine loss of clamping force with time were also conducted by the University of Illinois on high-strength bolts [6]. There was no difference in bolt load for bolts with $^1/_{16}$-in. oversize holes whether or not a washer was under the bolt head. The maximum relaxation after 90 days was about 5% of the initial tension when no washers were used. Most of this small loss generally occurred during the first day. Measurement on bolts tightened by the turn-of-nut method in test joints agreed with these special relaxation tests [5]. Even after 10 months, elongation measurements indicated no significant additional relaxation other than what occurred immediately after the initial tightening.

As a result of these studies, washers are no longer required under the turned element when A 325 bolts are installed by the turn-of-nut method. They are used under the turned element to minimize irregularities in the torque-tension relationship when bolts are tightened by the calibrated wrench method.

The use of washers in the U.S.A. practice is specified in order to provide a non-galling surface under the part turned in tightening as tests have shown they only play a minor role in distributing pressure due to bolt tension.

3. Static Tests of A 7 and A 440 Steel Joints

Numerous tests of connections of structural carbon steel connected by high-strength bolts have indicated that for clean mill scale a slip coefficient of 0.35 is representative [3, 4, 5 ,7]. Neither length nor width was found to appreciably affect the slip resistance [5]. Reference [8] reported similar results.

Tests at Lehigh University on A 440 high-strength steel connected by A 325 high-strength bolts showed a slight decrease in the mean slip coefficient [10]. More recently, tests of A 440 steel connections connected with the higher-strength A 490 bolt have given a slip coefficient slightly higher than that reported in Ref. [10]. The tests are too few to give conclusive results; however, the indication is that the higher clamping force of the A 490 bolt may improve the slip coefficient. A few constructional alloy steel joints connected by A 325 or A 490 bolts were also tested at Lehigh and have yielded similar results.

Recently a theoretical solution was developed for the unequal distribution of load among the bolts in double-lap tension splices which have non-linear behavior [11]. Analytical studies supported by tests have shown that an increase in net plate area increases the average shear strength of the fasteners in the longer joints. Fig. 1 summarizes the analytical and experimental findings.

4. Joint Movements in a Railroad Bridge

During the summer of 1959 an investigation was undertaken in conjunction with the through-truss bridge for the Michigan Central Railroad near Chicago, Illinois. A cooperative investigation by the Association of American Railroads Research Laboratory and the University of Illinois was initiated at the time of fabrication. Initial readings were taken in the fabrication yard during final assembly and reaming. Additional readings were taken after erection and at periodic intervals thereafter. The readings were taken at all joints of one truss. The bolts were installed by the turn-of-nut method.

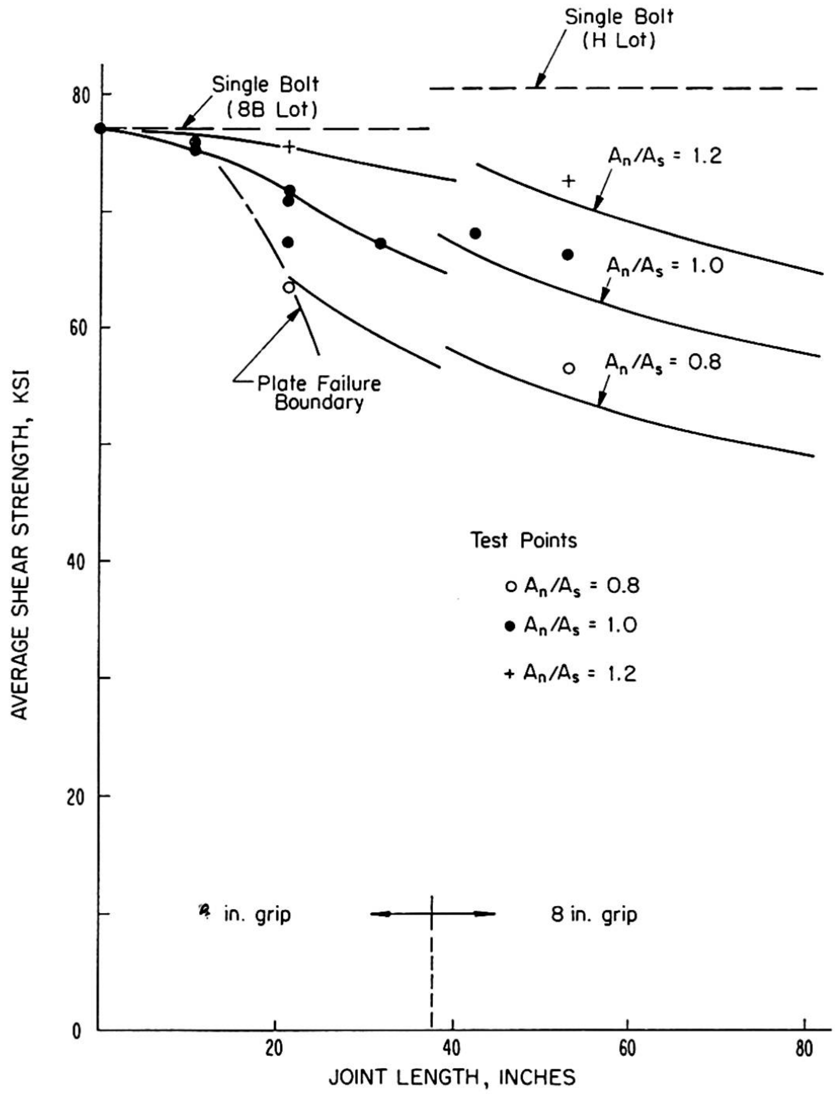

Fig. 1. Summary of Analytical and Experimental Results for A 325 Bolts in A 440 Steel Joints.

Reference [12] presents the results of the measurements which were conducted over a 3½-year period. In general, this study has shown that little if any change has occurred in the structure. During erection, movements up to $^1/_{16}$-in. were noted in random directions. Joint movements measured over 3 years of service averaged only 0.002-in. and were so small that experimental techniques could have caused the variation. No significant change in camber has occurred. The erection movements were random in direction and magnitude and did not always coincide with the direction of dead load stressing [12].

5. Tests of Bolted Steel Moment Connections

Three identical beam splices with lap connections were tested in a project at Cornell University [13]. The bolts were designed on the basis of 22 ksi shear stress as permitted in bearing-type connections. None of the connections slipped below the working load P_w and all of the connections developed the full plastic moment of the gross section and showed satisfactory deformation characteristics. A similar test at Cambridge University with the bolts designed for 30 ksi shear stress also developed the full plastic moment [14].

Installation of High-Strength Bolts

Early U. S. specifications stated the well-known formula relating torque to bolt tension and listed a table of torque-tension values [1]. However, a number of later studies indicated that such relationships are unreliable because of the great variability of thread condition, surface conditions under the nut, lubrication and other factors that use up the torque energy without inducing tension in the bolt.

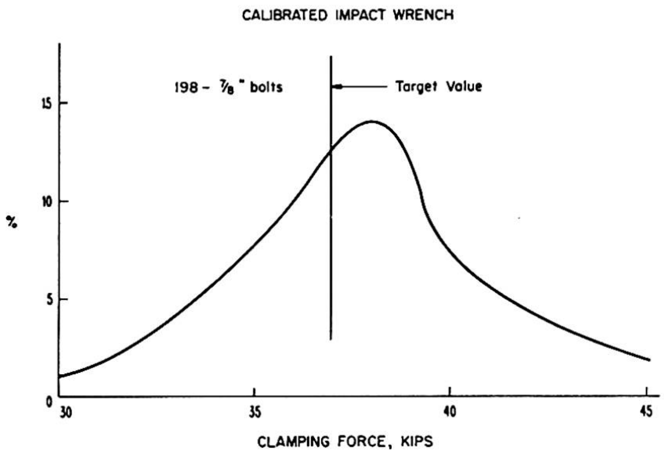

Fig. 2. Histrogram of Internal Bolt Tension.

Studies at Northwestern University in 1946 [15] and at the University of Missouri in 1955 [16] have shown that the standard deviation of torque was about 15%. Bolt tension based on applied torque could vary as much as $\pm 30\%$ from the average of a group of similar bolts as shown in Fig. 2 [16]. This is considerably above the 5% mentioned by Messrs. TOMONAGA and TAJIMA [8]. The 15% value is considered to be realistic for installation conditions in the U. S. The torque relationship becomes especially erratic when bolts are tightened into the inelastic range and the threads begin to deform. In addition, installation costs are high for the torque wrench method of installation and with the large diameter A 325 bolts and the new A 490 bolt considerable torque is required to preload the bolt.

Two methods of controlling bolt tension are recommended by the Research Council — the calibrated wrench and the turn-of-nut method. The calibrated wrench method is essentially a torque control and success depends on using a hardened washer under the nut in order to limit the variation of friction between the underside of the nut and the gripped material. The wrench is usually calibrated in a hydraulic calibrator as shown in Fig. 3.

A number of factors led to the turn-of-nut method. As noted earlier, tests have indicated that bolts suffer no injury when tightened into their inelastic region. Secondly, bolts actually were being tightened far above their proof load due to faulty torque wrench inspection without any noticeable ill effect.

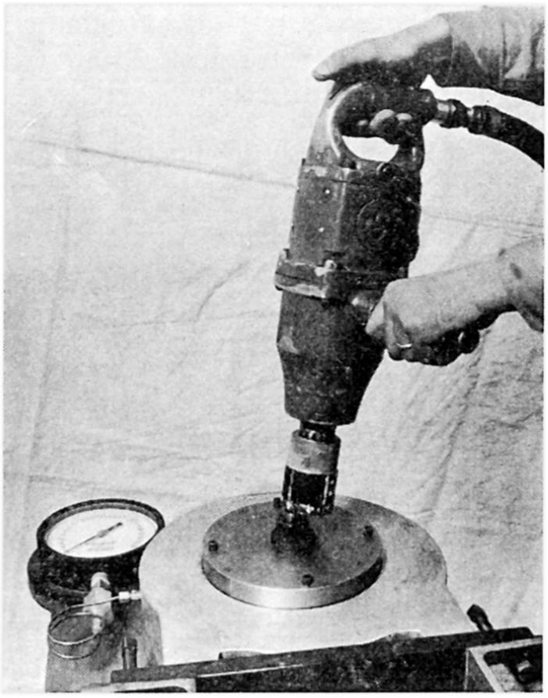

Fig. 3. Hydraulic Calibrator for Torqued Installation.

The turn-of-nut method utilizes a strain control and therefore is ideally suited to controlling tightening in the inelastic range. The procedures currently in use have shown that a uniform tension is achieved because relatively large variations in bolt elongations cause only minor variations in tension since the load-elongation curve is reasonably flat [17].

Numerous tests including those summarized by Dr. THÜRLIMANN in the Final Report of 6th Congress [18] have shown that the inelastically loaded bolts have performed well. In fact, hardened washers were once required under both the head and nut of A 325 bolts in order to provide a consistent torque relation, to prevent galling of the structural material and to prevent bolt relaxation. Tests have now shown that the washer is not needed for the last two reasons and since the turn-of-nut is a strain control rather than a torque control, no washers at all are required when this method of tightening is used for A 325 bolts [2].

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Summary

Current design concepts in the U. S. are discussed. Two types of connections are used: friction-type and bearing-type. The friction-type connection reflects the ability of the joint to resist slip whereas the bearing-type connection reflects the ultimate strength of the joint. Experience with bolted connection in the laboratory and in the field is summarized. Finally, the factors which have led to currently used installation procedures are discussed.

Résumé

Les auteurs exposent les principes de calcul actuellement appliqués aux Etats-Unis. Deux sortes d'assemblages sont utilisés: type «friction» et type «pression latérale». L'assemblage à friction correspond à la capacité qu'a l'assemblage de résister au glissement tandis que le type «pression» correspond à sa résistance limite. On décrit succinctement des essais effectués avec des assemblages boulonnés au laboratoire et dans la pratique; pour finir, on indique les facteurs dont la prise en considération a mené à l'adoption des méthodes actuellement suivies dans la mise en place des boulons HR.

Zusammenfassung

Es werden die in den USA allgemein üblichen Bemessungsgrundlagen besprochen. Zwei Arten von Verbindungen sind gebräuchlich: die Reibverbindungen, deren Tragwirkung auf der Verhinderung des Gleitens beruht, sowie die «bearing-type»-Verbindungen, bei denen die Bruchlast (Scherfestigkeit des Schraubenschaftes oder Lochleibungsdruck) maßgebend ist. Des weitern wird ein zusammenfassender Überblick gegeben über Laboratoriumsversuche und Erfahrungen im Betrieb mit geschraubten Verbindungen. Am Schluß werden noch diejenigen Faktoren erwähnt, welche zu den allgemein üblichen Einbauverfahren führten.