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Research on Large Compact Joints with High Strength Steel Bolts

Essais de traction statique sur des assemblages compacts par boulons à haute résistance

Statische Zugversuche an kompakten Verbindungen mit hochfesten Schrauben

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Introduction

The first US Specifications for Assembly of Structural Joints using ASTM-A 325 High Strength Steel Bolts [1]) were approved by the Research Council on Riveted and Bolted Joints in January of 1951. This specification essentially permitted the substitution of a high strength steel bolt (A 325) for a hot-driven rivet (A 141) of the same diameter. Whereas it was originally required that all contact surfaces within the joint be free paint, a revision in February of 1954 specified that the omission of paint was only required for cases "where stress redistribution due to joint slippage would be undesirable". Hence it was recognized that in a great many cases movement of the connecting parts that will bring the bolts into bearing is in no way detrimental.

Since 1954 extensive studies have been conducted in order to determine the actual strength of bolted joints. Together with improvements in the installation practice the results of these investigations have lead to the revision of the specification [1] [2]) in 1960. Part of these studies were conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa. with the objectives [1] to determine the slip characteristic and the ultimate strength of large compact joints and [2] to check the installation practice of high tensile

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[1]) This and subsequent designations refer to the Standards of the American Society for Testing Materials.

[2]) Refers to list of references.

bolts by the so-called "turn-of-nut method". Since the oral presentation of the results at the Congress in Stockholm a comprehensive paper has been published [2]. Hence this report presents only a short summary of the results with emphasis on certain aspects reflected in the revised specification.

Tension-Elongation Curves of High Strength Steel Bolts

The structurally significant property of a high strength steel bolt is best illustrated in a Tension-Elongation plot. Fig. 1 shows a representative curve for a $^7/_8$ inch diameter bolt (A 325) with a grip length of 4 inches. The threaded part of the bolt extends $^1/_2$ inch into the grip length. It is significant to notice that the application of direct tension to the bolt produces a higher ultimate

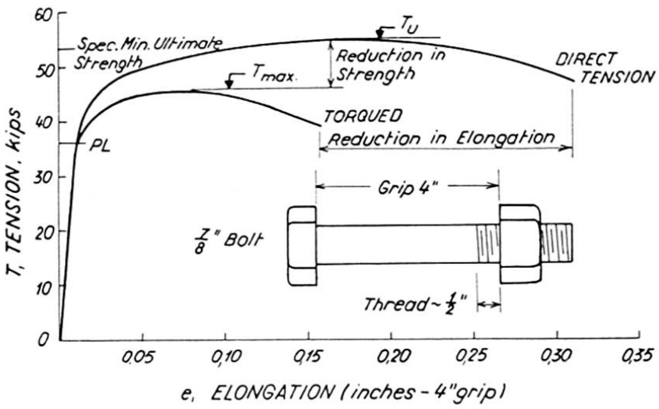


Fig. 1. Tension-Elongation Curve.

load as well as a greater total elongation at failure than the case of tension induced by torque. The differences may range from 5 to 25% for the load and from 20 to 60% for the elongation. They result from the different stress conditions when the bolt is tensioned by turning the nut. Frictional resistance transforms part of the applied torque into shear stresses that change the tension-elongation curve.

In standard erection practice the turn-of-nut method is already widely used as an economical and reliable method of inducing a high bolt tension. Fig. 2 shows on a tension-elongation curve for a $^7/_8$ inch diameter bolt with 4 inch grip length the tension obtained by rotating the nut $^1/_2$, 1 and $1^1/_2$ turn starting from the so-called "snug" position. The latter expression describes the tightness of a bolt before beginning the turn-of-nut. It is indicated by an impact wrench when impacting begins and corresponds to approximately 8000 pounds tension (8 kips). The scatter of the results is indicated by the cross-hatched zones. It should be especially noted that a $^1/_2$ turn produces a tension equal to about 90% of the ultimate load and considerably in excess of the Proof Load (PL)[3]). On the other hand the corresponding elongation is less than $^1/_5$ of the elongation at rupture.

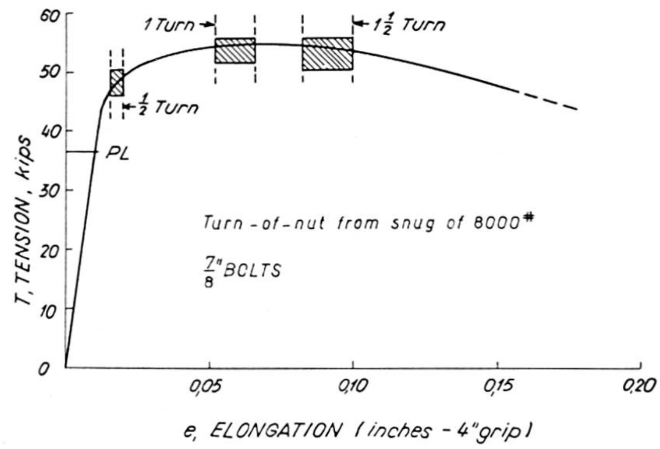


Fig. 2. Bolt Tension and Elongation in Function of Turn-of-Nut.

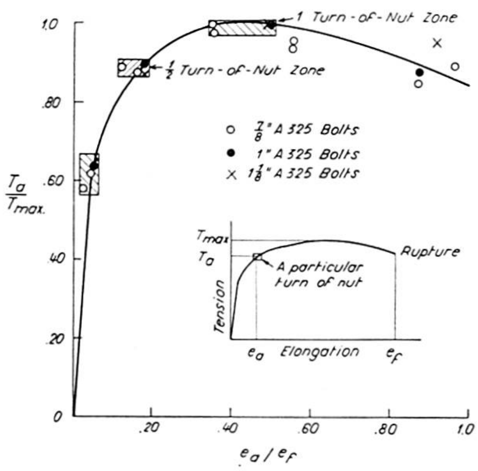


Fig. 3. Efficiency of Turn-of-Nut Method.

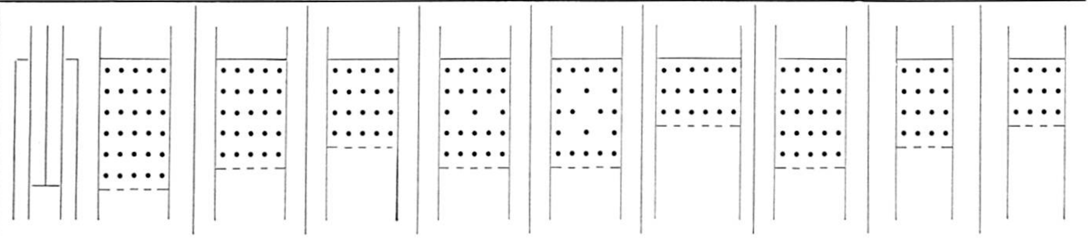
The results for the $^7/_8$ inch bolts are generalized for other bolt sizes in a non-dimensional plot in Fig. 3. Here a particular bolt tension T_a is divided by the ultimate tensile strength T_{max} and a particular bolt elongation e_a by the elongation at rupture e_f. It can be seen that the three sizes of bolts, namely $^7/_8$, 1 and $1^1/_8$ inch diameter, show completely similar behavior.

Tests of Large Compact Joints

A total of 8 bolted joints were fabricated and bolted up using the turn-of-nut method. The pertinent information of these joints, including an additional riveted joint BR 2 for comparison purposes, is summarized in Table 1. Gage

[3]) The 1951 Specification required a minimum tension equal to 0.9 PL.

Table 1. Description of Test Joints

	B 1	B 2	B 3	B 4	B 5	B 6	BR 2	A 3	G 1
									
Plate Material	Main Plate: 2 PLs 18″×1″ ASTM – A 7 Lap Plates: 2 PLs 18″×1″ ASTM – A 7								
Number of 7/8″ A 325 Bolts	30	25	20	23	20	18	25–7/8″ A 141 Rivets	16–1″	12–1 1/8″
T:S Ratio	1:0.74	1:0.89	1:1.11	1:0.96	1:1.11	1:1.15	1:0.89	1:1.10	1:1.11
Gage, g	3 5/8″	3 5/8″	3 5/8″	3 5/8″	3 5/8″	3″	3 5/8″	4 1/2″	4 1/2″
g/d	3.87	3.87	3.87	3.87	3.87	3.20	3.87	4.24	3.79
Pitch, p	3 1/2″	3 1/2″	3 1/2″	3 1/2″	3 1/2″	3 1/2″	3 1/2″	4″	4″
p/d	3.73	3.73	3.73	3.73	3.73	3.73	3.73	3.76	3.37

"d" is the diameter of the drilled holes

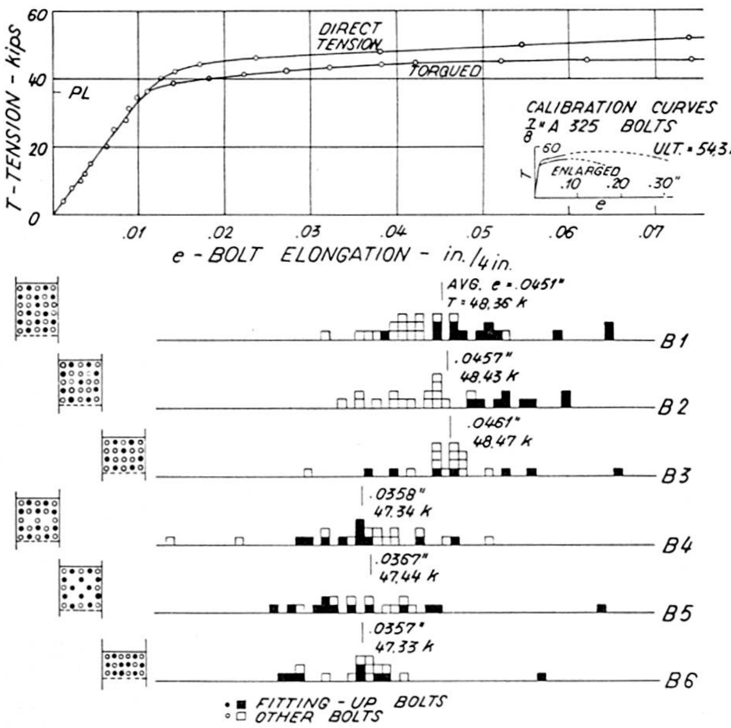


Fig. 4. Bolt Tension Distribution.

and pitch specify the distances between the bolt holes. The holes were $^1/_{16}$ inch larger than the bolt diameters. The plate material was A 7 Structural Carbon Steel with an average static yield stress level of 36.6 ksi and an average ultimate tensile strength of 65.5 ksi (1 ksi = 1000 pounds/square inch). In assembling the joints the contact surfaces were cleaned of loose mill scale and burrs, but no other preparations were applied. The bolts were installed by a field crew using the current field procedure of $^1/_2$ turn-of-nut from the "snug" position. For all joints the bolt elongation was measured. The corresponding results for the joints with $^7/_8$ inch bolts are represented in Fig. 4 in the form of a histogram. Entering with the elongation of a particular bolt, represented by a square in the figure, the corresponding bolt tension can be determined from the tension-elongation curve on top of the figure. Despite the fact that the bolt elongations show a scatter between about 0.012 to 0.067 inches the induced tension is rather uniform due to the fact that the bolts were stressed beyond the elastic limit into the plastic range. Even the few extreme values of $e \geqq 0.06$ have still a margin of safety of over 2 against rupture as may be seen from Fig. 1. Using the average bolt elongation of each joint the average bolt tension T was determined using the direct tension calibration curve. The values are also listed in Fig. 4.

The problem of relaxation of the bolt tension with time has not been studied specifically in this program. However it is well known that even if the absolute amount of relaxation of a bolt stressed into the plastic range is greater than the relaxation of a bolt stressed to a lower initial value, its final tension will still be larger. Hence it follows that a higher initial tension of a bolt will always lead to a higher final tension after relaxation. This fact should be fully recognized in order to appreciate the turn-of-nut method.

All joints were loaded in direct tension up to failure. The results are summarized in Table 2 giving the slip as well as the ultimate load and the type

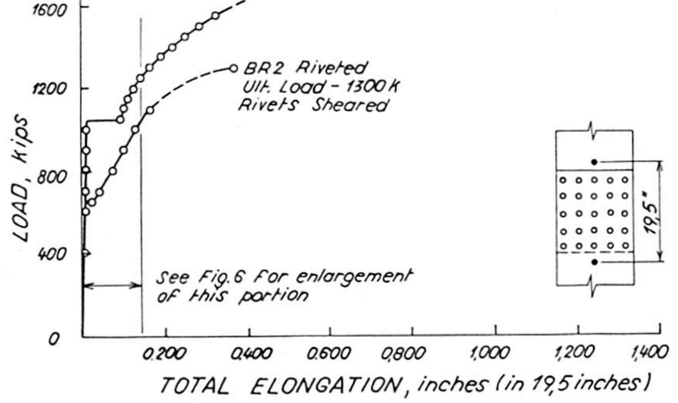
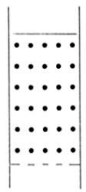
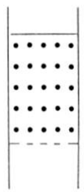
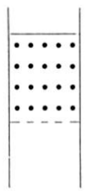
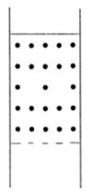
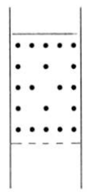
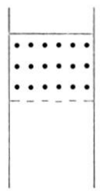
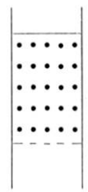
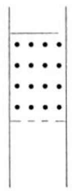
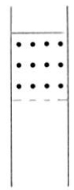


Fig. 5. Loads vs. Total Elongation for Joints B 2 and BR 2.

Table 2. Results of Joint Tests

	Units	B 1	B 2	B 3	B 4	B 5	B 6	BR 2	A 3	G 1
Pattern										
Number of 7/8″ A 325 Bolts		30	25	20	23	20	18	25–7/8″ A 141 Rivets	16–1″	12–1 1/8″
Nominal Gross Area	sq in	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Nominal Net Area	sq in	26.6	26.6	26.6	26.6	26.6	24.8	26.6	27.5	26.5
Nominal Shear Area	sq in	36.1	30.0	24.0	27.7	24.0	21.6	30.0	25.1	23.9
Tension-Shear Ratio		1:0.74	1:0.89	1:1.11	1:0.96	1:1.11	1:1.15	1:0.89	1:1.10	1:1.11
Slip Load	kips	1238	1047	911	850	609	673	654	843	920
Nominal Bolt Shear	ksi	34.3	34.9	38.0	30.7	25.4	31.2	21.8	33.6	38.5
Tension on Net Section	ksi	46.5	39.4	34.2	32.0	22.9	27.1	24.6	30.7	34.7
Avg. Extension of Bolts	in	0.0451	0.0457	0.0461	0.0358	0.0367	0.0357		0.0317	0.0519
Initial Clamping Force	kips	1451	1211	970	1089	949	852		968	936
Coefficient of Slip		0.427	0.432	0.469	0.390	0.321	0.395		0.435	0.491
Ultimate Load	kips	1956	1948	1750	1786	1680	1550	1300	1820	1798
Nominal Bolt Shear	ksi	54.2	64.9	72.9	64.5	70.0	71.8	43.3	72.5	75.2
Tension on Net Section	ksi	73.5	73.2	65.8	67.1	63.2	62.5	48.9	66.2	67.8
Type of Failure		Tear at net section main plate	Tear at net section one lap plate	Shear of bolts	Tear at net section one lap plate	Shear of bolt	Shear of bolt	Shear of rivets	Shear of bolts	Shear of bolts

of failure. For the two comparable joints B 2 and BR 2 with the same number of high tensile bolts and rivets respectively the load-elongation curves are shown in Fig. 5 and 6. The bolted joint B 2 was somewhat stiffer. Major slip occurred suddenly with a resounding "bang" at a considerably higher load than for the riveted joint. Despite the fact that the slip of B 2 was $^{8}/_{100}$ of an inch as compared to $^{2}/_{100}$ for the riveted joint BR 2 the latter always showed a larger elongation. This indicates that if slip can be tolerated in a riveted joint it should have no more adverse effects in a bolted joint. Finally it should be pointed out that the riveted connection failed at a much lower load. These two tests demonstrated clearly the superior behavior of the bolted joint.

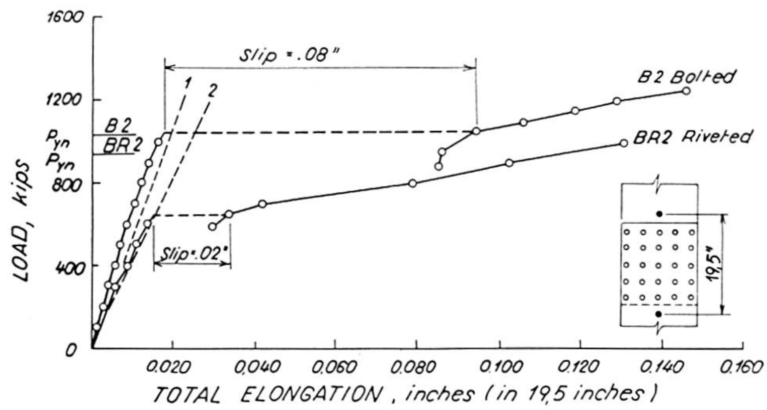


Fig. 6. Load vs. Total Elongation for Joints B 2 and BR 2 (Enlarged).
(1) Theor. Curve using Gross Area. (2) Theor. Curve using Net Area.

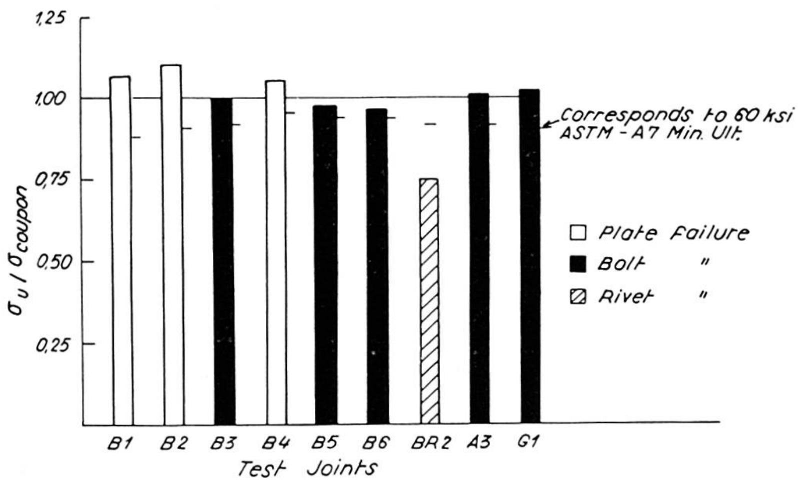


Fig. 7. Efficiency of Compact Joints,

Another presentation of the test results is shown in Fig. 7 giving the ratio of the tensile stress in the net section at ultimate load, σ_u, to the ultimate tensile strength of the plate material, σ_{coupon}, determined on a standard tensile coupon of the material. This ratio is a measure of the efficiency of the joint or the degree to which each joint developed its corresponding coupon strength.

It is interesting to note that in all cases of plate failure the ratio exceeds unity indicating the beneficial effect of lateral restraint of the material within the net section. Bolt failure occurred for a Tension/Shear ratio, T/S = 1.00/1.10 to 1.00/1.15, i. e. for an average shear stress on the bolts slightly higher than the average tensile stress on the net section of the joint. For comparison it may be mentioned that the corresponding ratio for a riveted joint is about T/S = 1.00/0.75. Hence it follows that 2 high strength steel bolts (A 325) exhibit about the same shear strength as 3 rivets (A 141) of the same diameter.

In Table 2 the coefficient of slip $K = P_s/T_i$ is also recorded where P_s is half of the slip load (because the joints presented two slip planes) and T_i the initial clamping force of all fasteners. Because it is based on the clamping force existing before any load was applied and not on the actual clamping force at the moment of slip it is termed "slip coefficient" rather than coefficient of friction [4]). Two slip coefficients may be determined depending on the calibration curve used for calculating the clamping force (see Fig. 4). In order to make the slip coefficients reported here comparable to previously reported values the curve for direct tension has been used. The values listed in Table 2 show a scatter from $K = 0.321$ for joint B 5 with a rather open bolt pattern to $K = 0.491$ for joint G 1 with a compact pattern. Comparing the other joints it follows that the joints with compact patterns, B 1, B 3, A 3 and G 1 developed consistently higher slip coefficients than the joints with open patterns, B 4 and B 5. In the average a coefficient of slip of $K = 0.40$ was determined for joints whose contact surfaces were covered with dry mill scale. Loose mill scale and burrs were removed but otherwise no surface preparation was used.

Use of Calibrated Impact Wrench for Inducing High Initial Bolt Tension

In the course of this investigation a study has also been made of using the calibrated impact wrench for obtaining a high bolt tension similar to the one induced by the turn-of-nut method, i. e. about 90% of the ultimate load. Presently this method is used with a cut-off setting of the wrench at about 15% above the minimum required bolt tension prescribed by the specification. The turn-of-nut method on the other hand produces a considerably higher tension about 40% above this minimum. Looking at the tension-elongation curve of Fig. 4 it becomes quite obvious that for high bolt tensions in the inelastic range an elongation criterion as provided by the turn-of-nut method is more appropriate than a torque criterion inherent to the use of a calibrated impact wrench. Actual use of the calibrated wrench showed a much wider

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[4]) Previous investigations have not made this distinction using the term coefficient of friction indiscriminately.

scatter in tension and especially in bolt elongation than for the turn-of-nut method. In a few instances it even lead to fracturing the bolts. This should not be surprising when the different influences such as variation in bolt friction, variation in air pressure, inaccuracy in the cut-off device, etc. are considered. Hence it may be concluded that the turn-of-nut method presents a simpler and also more reliable method of tightening bolts to a high initial tension of about 90% of the ulimate load.

New Trends in the 1960 American Specifications

The research work just described and extensive investigations at other Universities[5]) are reflected in the new "Specifications for Structural Joints Using ASTM A 325 Bolts". Here only two important aspects will be pointed out, namely [1] the distinction of two classes of shear joints, the friction-type and the bearing-type connections and [2] a consequent adherence to a simple and at the same time reliable installation practice.

"Shear connections subjected to stress reversal, severe stress fluctuation, impact or vibration, or where slippage would be undesirable, shall be friction-type." Bolts in such joints are designed on the "substitution rule" permitting the replacement of a hot-driven rivet (A 141) by a bolt (A 325) of the same diameter in accordance with the old specifications. In bearing-type connections however, the allowable shear stress on bolts where threads are excluded from the shearing plane shall be equal to 1.1 times the basic design stress of the applicable code or specification for A 7 Structural Carbon Steel. This basic design stress being 20 ksi for the specification of the American Institute of Steel Construction leads to an allowable shear stress of 22 ksi on the bolts. Comparison of this value with the computed nominal bolt shear for the tested connections listed in Table 2 shows that the latter values are considerably greater. Hence even in a bearing type connection slip will not occur under normal conditions. However the margin of safety against slip is much lower than for the friction-type connection.

Since their first adoption the American Specifications have not required any elaborate preparation of the contact surfaces. "They shall be free of dirt, loose scale, burrs, and other defects that would prevent solid seating of the parts. Contact surfaces within friction-type joints shall be free of oil, paint, lacquer or galvanizing."

The new specification allows the use of three bolt styles and two types of nuts. Considerable simplification in installation may follow from the use of special heavy semifinished hexagon bolts and heavy semifinished hexagon

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[5]) See further references listed in the Commentary to reference [1].

nuts. The bolt head has same width across flats as the nut. Hence the same size socket for the impact wrench can be used for turning either the bolt head or the nut. Furthermore the iron worker needs to carry only one spud wrench. A further benefit from the use of the above bolt and nut type follows because the washer may be omitted under the bolt head or the nut when these are not the turned elements.

Tightening of the bolts can be done by either calibrated wrenches or the turn-of-nut method. For the former method the specification requires that both torque and impact wrenches be calibrated frequently using not less than three typical bolts from the lot to be installed. For the turn-of-nut method a rotation of $^1/_2$ to $^3/_4$ turns from the so-called "snug" position is required depending on the size of the bolt and the grip length. It is interesting to note that the permissible tolerance is $^1/_4$ turn over nothing under in order to be assured of a high clamping force. It also indicates that a small amount of overturning does not damage the bolt. The turn-of-nut method has been used in the United States and Canada very extensively over a number of years.

Acknowledgement

The experimental work reported in this paper has been conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa. It is part of an investigation sponsored by the Pennsylvania Department of Highways, the U.S. Bureau of Public Roads and the Research Council on Riveted and Bolted Joints. Dr. LYNN S. BEEDLE is serving as Director of the project. Dr. J. L. RUMPF was in direct charge of the part reported here. The author expresses his sincere thanks to his former collegues for the permission to present these results.

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1. Specifications for Assembly of Structural Joints Using High Strength Steel Bolts. Research Council on Riveted and Bolted Joints, 1960.
2. FOREMAN, R. T. and RUMPF, J. L. Static Tension Tests on Compact Bolted Joints. Proceedings ASCE, Vol. 86, ST 6, June 1960, p. 73.

Summary

Static tension tests on large compact bolted shear connections are described. Information on bolt tension induced by the turn-of-nut method proves the reliability of this method in furnishing a consistently high and rather uniform tension in the bolts. New trends in the American Specifications of 1960, namely the distinction between friction-type and bearing type shear connections and simplifications in the installation practice of the bolts are reviewed in the light of these tests.

Résumé

L'auteur décrit des essais de traction statique effectués sur des assemblages boulonnés, compacts et de grandes dimensions. Le contrôle de l'effort de préserrage introduit dans le boulon par la méthode «au tour d'écrou» montre que ce procédé permet d'obtenir avec sûreté un préserrage élevé et assez uniforme. Analysant ces essais, l'auteur décrit les tendances nouvelles des prescriptions américaines de 1960, spécialement la différence faite entre les assemblages agissant au frottement et ceux travaillant au cisaillement, ainsi que les simplifications dans l'exécution des assemblages.

Zusammenfassung

Statische Zugversuche an großen, kompakten geschraubten Verbindungen werden beschrieben. Die Information über die Klemmkraft von Schrauben, welche durch ein «Verdrehungskriterium» (turn-of-nut method) erzeugt wird, zeigt, daß diese Methode mit Zuverlässigkeit zu einer hohen und gleichmäßigen Klemmkraft führt. Die neuen Richtungen in den amerikanischen Vorschriften von 1960, nämlich die Unterscheidung von Verbindungen auf Reibung und auf Abscheren, sowie Vereinfachungen in der Ausführung von Schraubenverbindungen werden an Hand dieser Versuchsresultate besprochen.