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TENSION CONTROL FOR HIGH-STRENGTH STRUCTURAL BOLTS

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and

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with a discussion on the

TURN-OF-THE-NUT METHOD

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Association of American Railroads

Reprinted from the Proceedings of the
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Dec. 15, 1955

MONDAY AFTERNOON SESSION

April 18, 1955

The meeting was reconvened at two-fifteen o'clock, p.m., Mr. T. R. Higgins, Director of Engineering & Research, American Institute of Steel Construction, presiding.

CHAIRMAN HIGGINS: If there is any one aspect to this afternoon's program that may be somewhat different than the rest of the conference program it is the fact that the topics are very closely related to the A.I.S.C. program for research.

The first subject, as those of you who have been coming to these conferences since they first started are aware of, has a life span just about equal to these conferences.

We have, from time to time, reported the developments with regard to the experimental work in the laboratory in the perfection of the use of high strength bolts.

Our first speaker this afternoon has had an opportunity within the past twelve months to study rather comprehensively just what is involved in the tightening of high strength bolts and being sure of the necessary free tension.

Dr. Adrian Pauw received his Bachelor of Science degree from the University of Washington in 1937, and his master's and doctor's degrees from the California Institute of Technology. He was an assistant research engineer at the California Institute of Technology before he taught at Rice Institute. Currently, Dr. Pauw is Associate Professor of Civil Engineering at the University of Missouri.

Tension Control for High Strength Structural Bolts

PROFESSORS ADRIAN PAUW and LEONARD L. HOWARD*

Introduction

The introduction of the high-strength bolt as a structural fastener has revolutionized structural practice in recent years. Primarily through the efforts of the Research Council on Riveted and Bolted Joints, information on the economic and structural advantages to be derived from the use of these bolts has been widely disseminated.[1]‡ The results of an intensive research program sponsored by the Council and culminating in the preparation of a specification entitled, "The Assembly of Structural Joints Using High Strength Steel Bolts," (January, 1951; Revised February, 1954) has led to wide acceptance of the high-tensile bolt as a superior structural connector.

Concept of High-Tensile Bolt Connections

Joints using high-strength bolts differ from other types of bolted joints both in the nature of the bolt used and the method of stress transfer. Bolts, nuts and washers are manufactured to conform to A.S.T.M. specification A325, and to dimensions established by the American Standards Association. The bolt is made from a medium carbon steel, heat treated, quenched and tempered. The bolt head is given a distinctive marking of three radial lines to distinguish it from ordinary machine bolts. The nut is made from a steel similar to that used in the bolt, but the nut is not heat treated. Washers are either quenched and tempered, or carburized, quenched and tempered.[2] These heavy, hardened washers are used both under the nut and under the bolt head. They perform an important function—by distributing the clamping force over a wide area surrounding the hole, they enable the development of a permanent high clamping force. The compressive stress built up in the plies of the joint is also desirable in that this stress tends to inhibit the formation of fatigue cracks at the edge of the holes.[1e]

The concept of stress transfer in structural joints using high-tensile bolts is quite different from that in riveted connections or in joints employing ordinary or fitted bolts. Although most riveted joints, under working loads, will transfer the load by the frictional forces developed between plies during cooling of the rivet—the existence of these frictional forces under sustained or under vibratory load is not dependable. The design of such joints is therefore necessarily based on the premise that slip will take place and that the load is transferred from one element of the connection to another by direct shear on the rivet. Herein lies the principal structural advantage of the high-tensile bolt—when joints are properly designed and

* Presented by Prof. Pauw.

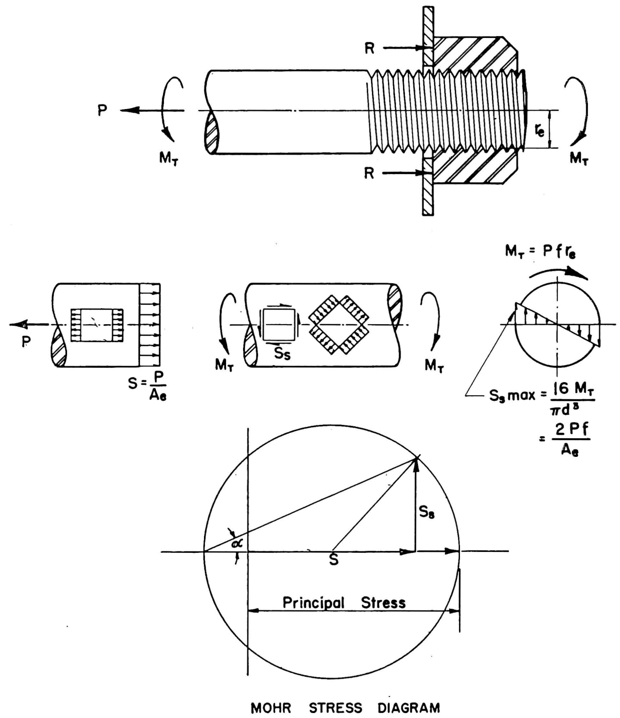
‡ Numbers in parenthesis refer to references at end of paper.

assembled with these bolts, the clamping force is permanently retained, hence slip is prevented and loads are transferred by frictional forces alone. The resulting connections have structural properties which are generally superior to equivalent riveted joints.[3]

Importance of Tension Control

For optimum structural performance of bolted joints it is necessary that slip between the several plies of the connection be prevented. Slip may be affected by paint or by such defects as dirt, oil, loose scale, burrs and pits, which prevent solid seating of the parts. The Council's assembly specifications therefore require that contact surfaces be descaled, or carry only normal tight mill scale, and that the surfaces be free from any of the aforementioned defects. Where contact surfaces are subject to stress reversal, impact or vibration, or where stress redistribution due to joint slippage would be undesirable, the specifications further require that the joints be free of paint and lacquer. The most important requirement of the specification, however, is that all bolts must be tightened to induce a required minimum bolt tension equal to at least 90% of the specified proof load of the bolt. Slip cannot be prevented, regardless of the condition of the faying surfaces, unless sufficient clamping force is provided to develop the necessary friction required for stress transfer. Merely specifying the use of high-tensile bolts is not sufficient—it is also necessary that their structural capabilities be mobilized by proper pretensioning. Tension control is therefore of paramount importance in the assembly of joints using high strength bolts.

The clamping force in joint assemblies is mobilized by torquing the nut. For low clamping forces the shearing stress due to torquing is only a small percentage of the total stress. As the axial load approaches the elastic proof load, or when bolts are unloaded and reloaded by torquing, the shear rises rapidly due to the galling action which occurs in the threads. The theoretical shear stress at the bolt surface can become very large under these conditions, and the surface fibers will tend to flow plastically due to the high combined stress. These stresses are shown in Fig. 1. The shear stress can be resolved into equivalent diagonal tension and compression stresses. The magnitude of the combined stresses are readily determined by means of the Mohr Stress diagram. From this diagram it can be seen that small shearing stress components do not affect the combined stress appreciably, but large shearing stresses can increase the combined stress by as much as fifty or sixty per cent of the axial stress component. The direction of the principal combined stress is given by the angle α. Failure of the bolt is prevented only by the reinforcing effect of the material adjacent to the surface fibers where the shear stresses and hence the combined stress are lower. It is therefore clear



COMBINED STRESS — AXIAL TENSION AND TORQUING SHEAR

FIG. 1

that it is impossible to develop by torquing the ultimate clamping force indicated by axial tensile load tests. Under torquing, failure of the bolt tends to occur either by stripping the thread or by twisting the bolt off. Lubrication does not appreciably ameliorate this condition—probably due to the fact that the high stress intensities at the mating thread surfaces tend to break down the lubrication film.

Although this friction in the threads limits the maximum clamping force that can be developed, it does serve a useful purpose in that it prevents loosening of the nut. No self-locking nut, or lock washers are required and threads need not be burred when these bolts are properly tensioned.

Tensioning of Bolts and Measurement of Bolt Tension

In the early applications of high-strength bolts, bolts were tightened manually and tension was controlled by torquing to a specified torque reading. The Council's recommendations that this torque be equivalent to a bolt tension approximately 15 per cent in excess of the *Required Minimum Bolt Tension* was made to insure that all bolts are tightened to the required minimum. This margin is necessary due to the fact that the relationship between torque and clamping force is not a precise one but depends on such variable factors as the coefficient of friction between the nut and bolt, the nut and the washer, and the slope of the abutment surfaces under the bolt head and nut. The recommended bolt tension is therefore a "target" value set at a level which will insure that bolts tensioned by this method satisfy the Council's specification for minimum bolt tension. Approximate equivalent torques have been established by test, but for optimum tension control it is desirable that torque wrenches be calibrated to produce the desired tension in the bolts under conditions equivalent to those encountered in the actual installation. Several methods of measuring clamping force have been devised. These may be classified as direct methods and indirect methods. In the direct methods the clamping force is measured in a calibrated device. Such a device may consist of suitable abutment surfaces attached to the grips of a testing machine or to a hydraulic capsule, so that bolt tension can be read directly on a gage in terms of equivalent pressure. The abutment surfaces can also be attached to a cylindrical device to which electrical strain gages are attached, in which case equivalent bolt tension is determined with an electrical strain meter. The latter method was employed in a series of tests performed at the University of Missouri. Direct tension measuring methods, of course, can not be used to determine bolt tensions in an actual application—their usefulness lies in the calibration of torque wrenches or the evaluation of other methods for measuring the clamping force indirectly. Such instruments can be constructed to yield very accurate results and they can readily be calibrated by loading them in a testing machine.

Indirect measurement of the clamping force can be subdivided into two groups—those methods which depend on strain measurement and those which depend on measurement of torque or torque effort. Each of these methods is subject to certain inherent inaccuracies. The latter group of course includes the manual torque wrench method already discussed. Other procedures include control of torque effort and are used with mechanical impact wrenches. These procedures were the principal concern of the studies conducted at the University of Missouri.

The second group, those depending on strain measurement, include such methods as measuring the elongation of the bolt with a micrometer, the use of electrical strain gages on the bolt shank, and the so-called "turn-of-the-nut" method. The latter procedure will be discussed by Mr. E. J. Ruble. In this group the clamping force is determined on the basis of the elastic and plastic properties of the bolt itself.

Studies on Tension Control for Bolts Tightened with Impact Wrenches

As the high-strength bolt gained favor as a structural fastener, it was found that manual tightening of the bolts was uneconomical. Steel fabricators and erectors in their search for a more practical method of bolt installation began experimenting with pneumatic impact wrenches. It was found that a certain degree of control of bolt tension could be achieved by adjusting the air pressure of the impact wrench. As for the case with manual wrenches a "target" value of 15% above the specified minimum bolt tension was recommended for wrench calibration to take care of discrepancies in the bolts and in the impact wrenches. At first, tension of bolts tightened by power wrenches were commonly checked by manual torque readings on about 5% of the bolts; this specification was abandoned by the Council at its February, 1954, meeting.

Very little information has been published on the variations in bolt tension which might be expected when high strength structural bolts are tightened by controlled-air supply pneumatic impact wrenches. Also, no published data could be found on the relationship between torque and bolt tension after these bolts had been tensioned in this manner. A research project was initiated by Professor L. L. Howard at the University of Missouri in the fall of 1953 with the following aims:[4]

(1) To study the variation in bolt tension that can be expected in bolts tightened by pneumatic impact wrenches operating at a set pressure.
(2) To determine the degree of correlation between bolt tension of bolts tightened with a pneumatic impact wrench and the torque required to start the nut turning in either a tightening or loosening direction.

Professor Howard's report embodied tests on approximately 1200 high strength structural bolts. The following variables affecting clamping force were investigated:

(a) Position of the wrench—horizontal or vertical
(b) Type of wrench—3 types representing 3 wrench manufacturers
(c) Size and length of bolt—two sizes, ¾″ and ⅞″ —three lengths, 4″, 5″ and 5½″.

The pneumatic wrenches used in these tests and the

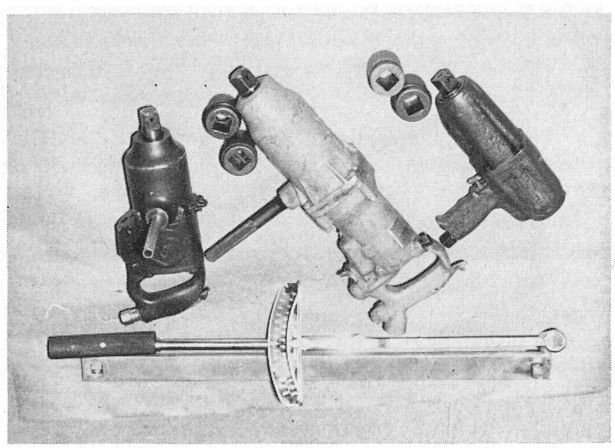
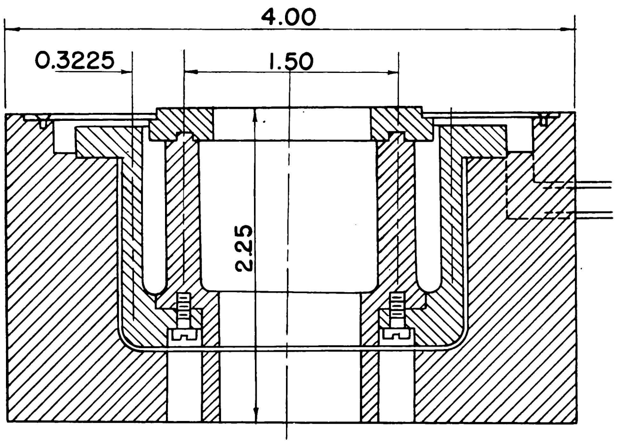


FIG. 2

manual torque wrench used for torque correlation studies are shown in Fig. 2.

Test Equipment

The first consideration was the development of a dynamometer for measuring the clamping force. A cross section of the final design for a 30-ton unit is shown in Fig. 3. This dynamometer consists of three concentric



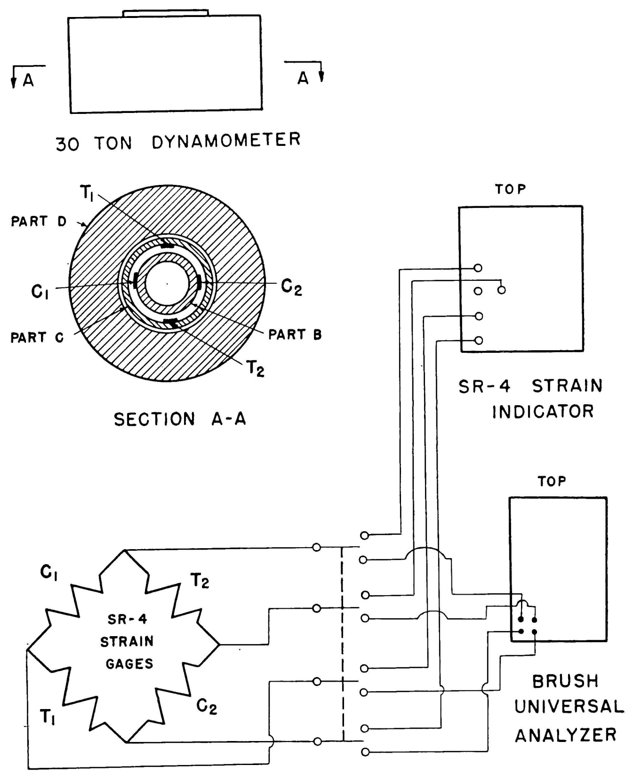
SECTION

30 TON DYNAMOMETER

FIG. 3

cylinders assembled so that an applied clamping force produces compression in the inner and outer cylinder and tension in the intermediate cylinder. Type ABD-7 electric resistance gages were bonded to the inner and intermediate cylinders with Araldite AN-100 bonding resin. Two gages were mounted on each cylinder, one in each quadrant, in order to average out any bending strains induced by eccentric load application. These gages were wired in a bridge circuit as shown in Fig. 4, and connected to a Baldwin Strain Indicator and to a Brush Amplifier and Recorder by means of a double-pole, double-throw switch to permit recording of both static and dynamic strain measurements. The dynamometer was calibrated in a 60,000 lb. Baldwin Southwark-Emery testing machine.

The bolts were tested as received from the bolt companies. All bolts tested had a lubricant on the bolt shank and nut. The impact wrench was connected to the air line through a 38-foot 3/4″ whip-hose and a pressure gage calibrated to read to 5 lb. increments. The regulator was connected to a 1/2″ air line and was located about 75 feet from the compressor tank. The compressor was regulated to operate at between 135 and 160 psi pressure. Under load the pressure gage between regulator and oiler pulled down about 2 1/2 pounds. Pressure readings were recorded under "load" conditions and were maintained to ±2 lbs. Fig. 5 shows the test stand for



WIRING DIAGRAM FOR DYNAMOMETER

FIG. 4

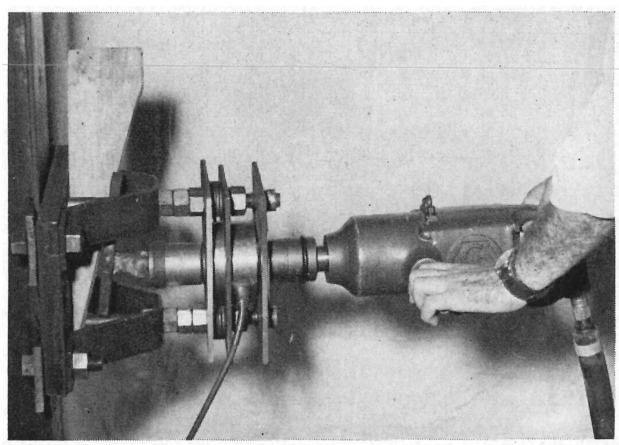


FIG. 5

4″ bolts were tested in this manner at pressures ranging from thirty-five to fifty-three psi. All of the bolts were tightening bolts in the horizontal position and Fig. 6 shows the recording equipment used.

Test Procedure

The first set of tests were made to investigate the "stall" phenomena of impact wrenches. This "stall" is

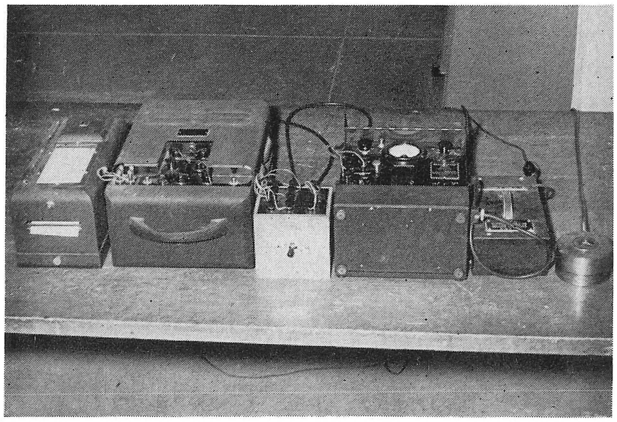
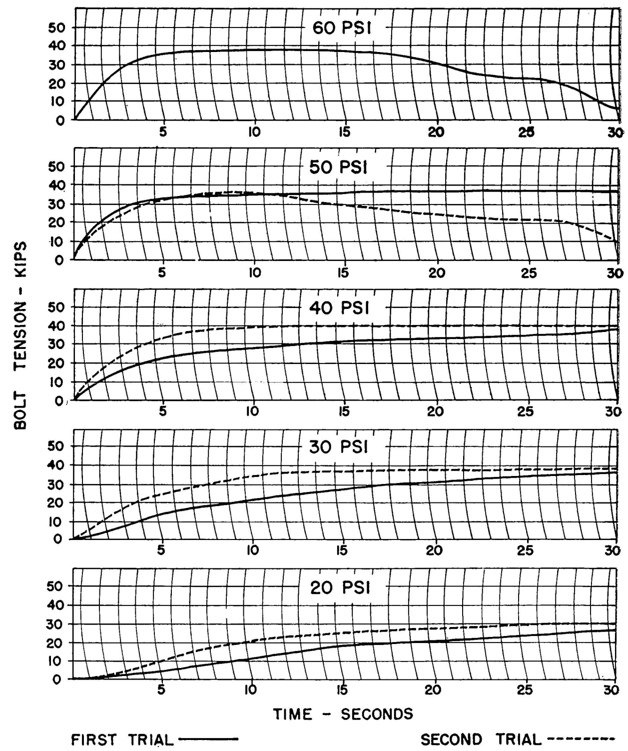


Fig. 6

determined by the excess vibration of the wrench due to recoil of the tightening socket after each impact. Preliminary tests were made with air pressures set as recommended by the Bethlehem Steel Company and with 15 seconds as a maximum time limit. Thirty-nine ¾″ x tensioned in excess of the required minimum and only one failed to reach the recommended value by a very small margin of 170 lbs. The maximum recorded tension was 38.52 kips or 33 per cent in excess of the "target" value of 29 kips.

In order to obtain a better understanding of the torque-tension characteristics, in the second test series a Brush Recorder was connected to the dynamometer by means of a double-pole, double-throw switch. With this equipment a tension record could be obtained while torquing and static end values could be checked with the strain indicator. About fifty each of the ¾″ x 4″ bolts and ⅞″ x 4″ bolts were tested in this manner. In these tests, bolts were tightened until there was no noticeable increase in bolt tension. At this point the tensioning time was recorded and the end value of the clamping force checked with the strain indicator. It immediately became apparent that for a fixed target value, tension control by tensioning until a complete stall is obtained is impractical because a prohibitive time limit is required. The point of preliminary stall was found to be difficult to detect. The bolts in these tests were loosened and retightened until a noticeable decrease in bolt tension was observed indicating damage to the bolt or nut thread. Comparative tension-time curves for first and second trial are shown in Fig. 7. It is evident from these curves that for the lower pressures and for low clamping forces the initial tensioning cycle tends to "run in" the threads, resulting in a more rapid development of clamping force in the second tensioning cycle.

On the basis of these preliminary tests a systematic testing procedure was set up. The subsequent tests fall into two classifications: time-tension studies, and bolt tension and torque variation studies. In the time-tension



TIME VERSUS BOLT TENSION
TYPE AR ¾″ϕ x 4″

Fig. 7

studies the Brush Recorder was used to determine the effect of air pressure on the rate of development of clamping force. The same test procedure was used for all wrenches and bolts studied. Bolts were tested in groups of five. Bolt groups were tested with the several wrenches at various air pressures, starting at the lowest 10 psi increment at which the wrench would operate and at increased air pressures in 10 psi increments. The bolts were placed in the dynamometer and tightened for 30 seconds. Automatic time-tension records were obtained by means of the Brush Recorder. Bolts were then subjected to several cycles of loosening and retensioning until a marked decrease in the clamping force was observed or until the threads stripped. Zero and end loads were cross-checked with the strain indicator.

The air-pressures used in the bolt-tension and torque variation studies were selected on the basis of the tension-time tests. Air pressures were determined for each bolt size and wrench type to give the desired "Recommended Bolt Tension" for a selected torquing time interval of either 10 seconds or 15 seconds. These time intervals were selected to correspond to present field practice.

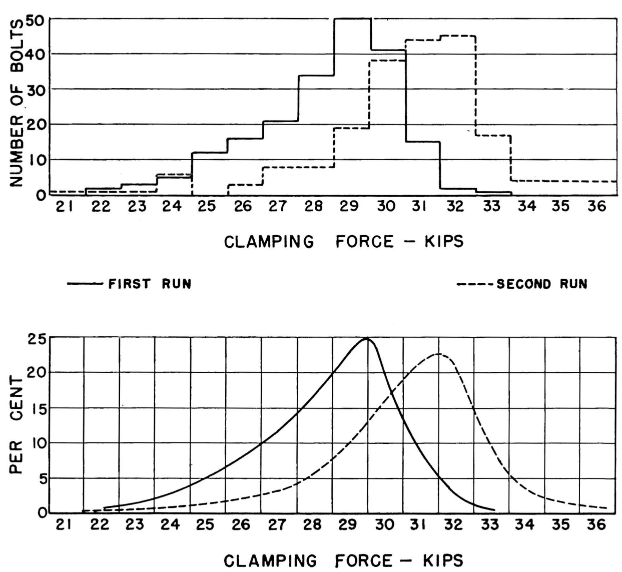
Bolts in this study were tested in groups of about 25 each using the air pressures and time interval given in

TABLE I

Wrench Type	*Bolt Size*	*Air Pressure psi*	*Time secs.*
A	3/4″	30	15
	7/8″	35	15
B	3/4″	50	10
	7/8″	60	10
C	3/4″	65	15
	7/8″	70	15

Table I. The clamping force was measured with the dynamometer and the strain indicator. For one-half of the bolts tested, the starting and running torques, to loosen the nut an eighth turn with the manual torque wrench, were recorded. The bolts were then loosened and retensioned with the impact wrench and the clamping force again measured. The torques to start the nut turning in the tightening direction were then measured with the manual torque wrench. In the remainder of the bolts tested, the order in which the manual loosening and tightening torque values were obtained was reversed.

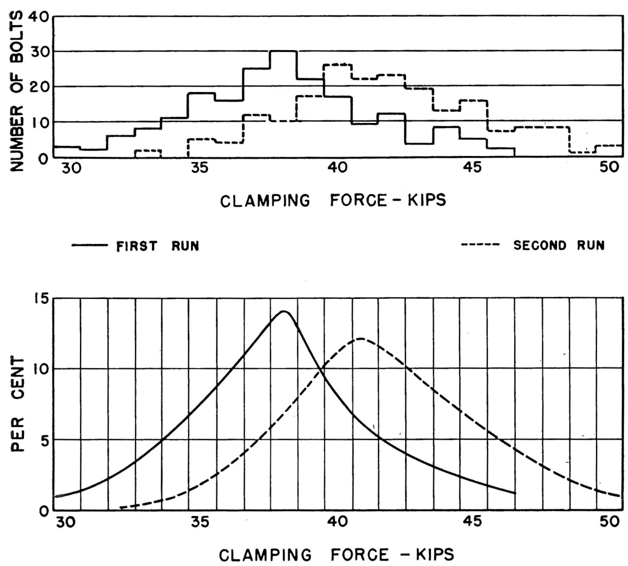
Although some difficulty was encountered due to a change in wrench characteristics, the resulting tension control obtained was generally good. The histogram in Fig. 8 shows the clamping force distribution for 202-



3/4" BOLTS – CLAMPING FORCE DISTRIBUTION

FIG. 8

3/4″ x 4″ bolts tensioned under wrench conditions for which the calibration was applicable. This graph includes tests on bolts furnished by three suppliers and tensioned with three different wrenches. The clamping force distribution for both the initial tightening and the second tightening are shown. It should be noted that, in general, the clamping force developed in the second run is considerably higher than that for the initial tightening. This phenomenon is due to the "running-in" effect and was also noted in Fig. 7. The distribution curves shown below were obtained by applying a smoothing function to the data shown in the histogram. It should be noted that the frequency distribution is not symmetrical or "normal." This is due to the fact that the "target" value lies close to the maximum stress which can be developed by torquing, as can be seen from the time-tension curves in Fig. 7. As a result the average magnitude of deviations above the target value is smaller than that of the deviations below the target value. The histogram and frequency distribution curves for the clamping force of 198-7/8″ bolts are shown in Fig. 9. For these bolts the fre-



7/8" BOLTS – CLAMPING FORCE DISTRIBUTION

FIG. 9

quency distribution diagram for the initial tightening cycle is more nearly "normal", whereas that for the second run is somewhat skewed due to the proximity of the modified target value to the maximum developable clamping force.

With controlled time and controlled air pressure, the mean standard deviation for all the 3/4 inch bolts tested was 2.80 kips, and 3.72 kips for the 7/8 inch bolts. These values include the tests for which the wrench calibrations were patently no longer applicable. The maximum standard deviation recorded was 5.89 kips for a set of 7/8″ x 5 1/2″ bolts, and the minimum standard deviation was 1.25 kips for a set of 3/4″ x 4″ bolts. These values are based on the assumption of normal frequency distribution.

On the basis of these tests the following conclusions were drawn:

1. With time and pressure controlled and pneumatic wrenches calibrated at frequent intervals:
   a) Two-thirds of all $\frac{3}{4}$ inch bolts tightened with this procedure of tension control can be expected to deviate less than 2.8 kips from the target value of 29 kips.
   b) Two-thirds of all $\frac{7}{8}$ inch bolts, should deviate less than 3.72 kips from the target value of 37 kips.

   The range of the mean standard deviation is approximately ten per cent of the bolt tension desired, (i.e., target value).
2. Grip of the bolts does not appreciably affect the bolt tension developed.
3. Slightly higher bolt tensions appear to be developed when the bolt axis is vertical. Additional data are required to substantiate this result.
4. Bolts furnished by the three different manufacturers had similar tensioning characteristics.
5. The wrenches tested gave results of about equal consistency. Wrenches having excess impacting capacity must be operated at relatively low air pressure for satisfactory control.
6. Wrench characteristics tend to change with time and continued use. For time-pressure tension control, wrenches should be calibrated at least daily and possibly oftener.

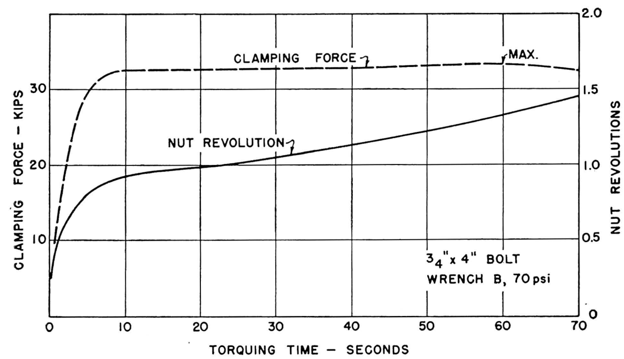
For a group of $\frac{3}{4}$ inch bolts whose tension ranged from 28.5 to 29.5 kips as measured by the dynamometer, the mean starting torque required to loosen averaged 320.5 lb. ft. This mean is in good agreement with the Council's specification, but the range of torque deviation was from 240 lb. ft. to 400 lb. ft. with a mean standard deviation of 49 lb. ft. This means that the range of the mean standard deviation is about 15 per cent of the target value. The mean running torque for the first eighth turn for the same group of bolts was 292.4 lb. ft. The values ranged from 200 to 360 lb. ft. with a mean standard deviation of about 34 lb. ft. The range for the mean standard deviation of the running torque is therefore somewhat better than that of the starting torque, being only 12 per cent of the mean value. But in either case, the percentage range of the mean standard deviation of the manual torque-wrench readings was greater than the percentage deviation in clamping force to be expected when bolt tension is controlled by the fixed time-pressure method.

At the suggestion of Mr. F. P. Drew, Association of American Railroads, the number of turns of the nut were recorded on 166 bolts in the last series of tests of the program. This data has not been evaluated as yet by the authors, but the data has been made available to the members of Project IV Committee of the Council and has been studied by Mr. T. R. Higgins. Mr. Higgins' conclusions were as follows:

(1) When bolts are loosened and retensioned, the same tensions are achieved on the second trial as on the first, with approximately one quarter less turn of the nut.

(2) The tension values for the $\frac{7}{8}$ inch bolts were obtained with 0.6 to 0.9 tightening revolutions of the nut. All tension values observed were at least equal to the minimum specified elastic proof load. (35.97 kips)

(3) The tightening studies on the $\frac{3}{4}$ inch bolts covered a wide range of nut revolutions—from 0.8 to



TENSION-TIME & NUT REVOLUTION-TIME CURVES

FIG. 10

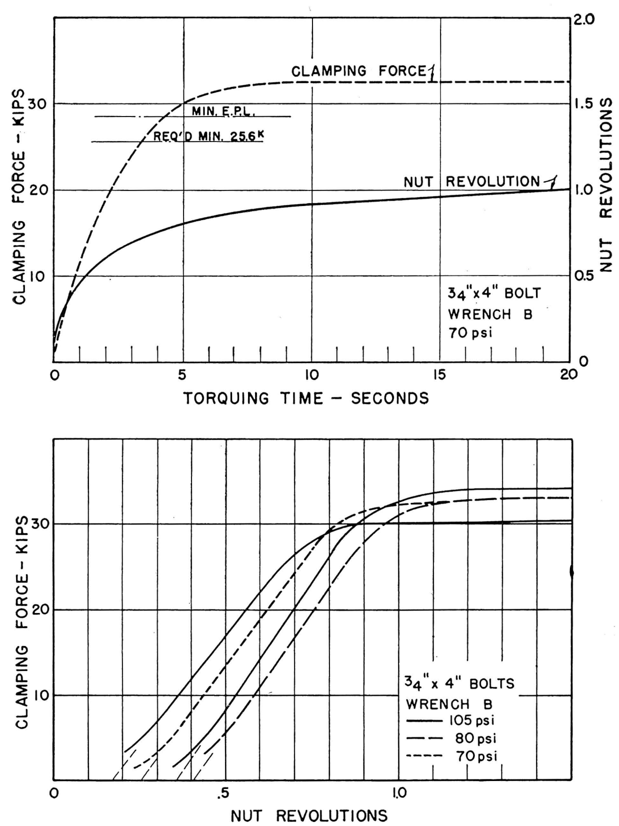


FIG. 11

1.5. All tension values were substantially higher than the minimum specified elastic proof load and a number of them (all associated with more than one revolution of the nut) exceeded the minimum specified ultimate proof load.

(4) After the nut is tensioned to produce nearly the full ultimate proof load, this tension value is maintained through quite a large amount of nut revolution.

Since Mr. Howard's report was issued several additional tests were made using an automatic "turn of the nut" recording device. A typical set of tension-time, nut revolution-time curves is shown in Fig. 10. An expanded portion of these curves is shown in Fig. 11. This figure also shows the clamping force—nut revolution relationship for several bolts. It should be noted that, although the tension-time, nut revolution-time curves are similar in shape, the ordinates in the latter continue to increase, albeit slowly. It can be seen that when the air pressure is adjusted properly, the tensioning time is not critical if the target clamping stress is permitted to approach the maximum value developable by torquing.

Summary and Conclusions

Three methods of tension control have been proposed to date for pneumatically tightened high strength bolts. They are:

(1) Checking a representative sample of the tightened bolts by means of a manual torque wrench.

(2) Calibrating the wrench for the desired "target" value of tension by adjusting the air pressure for a specified torquing time.

(3) Control of bolt tension by relating tension to nut revolution.

The first procedure is not only uneconomical if pneumatic wrenches are to be employed, but the accuracy is relatively lower than can be obtained by the second method. The second method has two principal disadvantages—1) it requires a calibrating device, and 2) results depend somewhat on the stability of wrench performance. In addition the human element factor is involved in achieving proper time control. This problem could possibly be overcome by some automatic device which would shut off the air supply after the proper impacting interval.

The third procedure seems to cut the Gordian Knot. It has the merit of simplicity, and it insures that the required minimum bolt tension is obtained. Under normal conditions this method should prove to be a satisfactory basis for tension control provided only a minimum clamping force requirement needs to be satisfied. On the basis of presently available data this seems to be the case; especially fatigue resistance appears to continue to increase up to the ultimate bolt strength. In cutting the Knot, however, there are a few loose ends left which warrant further study. The most important of these are:

(1) The effect of accuracy of the initial starting point. The manual starting point is specified as "finger-tight." Bolt threads may have slight imperfections requiring the use of a wrench in "making up" the bolt assembly. Even with a small wrench a 1/4 turn is readily obtained. This problem is clearly evident from the results shown in the Tension-Nut Revolution curves in Fig. 9.

(2) The effect of the grip and the number of threads under the nut. The greater the grip and the more plies, the greater the pickup in the steel. Also, since the bolts are strained into the plastic region, the number of exposed threads under the nut is important. Short grip bolts with little pickup in the steel and few exposed threads may be stretched sufficiently to throw the threads off lead.

(3) The effect of the condition of the faying surface and the slope of the abutment surfaces. Slopes of one in twenty are permissible without bevelled washers. This would account for about an additional half turn.

(4) Damage to the bolts when bolts are used for make-up bolts. One of the advantages to be derived from the use of high-strength bolts is that make-up bolts can be eliminated. The turn-of-the-nut method, however, produces a permanent set equivalent to about a half turn. Retightening with a full turn of the nut may then produce excessive strains causing stripping of the threads.

(5) The effect on the bolts and nuts of stressing into the plastic zone. More data is required to determine if any harmful after effects may be caused due to the biaxial stress condition or metallurgical changes due to a degree of cold working when bolts are tensioned to this extent. The effect on the friction factor also warrants further study.

In the final analysis the problem of bolt tensioning is a problem in quality control. Applied with a little common sense either the tension-time or the turn-of-the-nut method should yield satisfactory results. A combination of the two methods may be possible whereby the need for special devices for field calibration of the wrenches is eliminated and whereby occasional checking of nut revolution can be used to check constancy of wrench calibration, thus providing a method for quality control. For either method the practice of loosening the nut to check bolt tension by applying a manual torque wrench seems futile. In this respect the authors are in sympathy with Winston Churchill's sentiments when he said, "When you have a thing where you want it, let it alone!"

References

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CHAIRMAN HIGGINS: Our next speaker needs no introduction to this group since he was one of the three panel speakers who first introduced the subject of high strength bolts to the Conference in 1950. Since then Mr. E. J. Ruble, Research Engineer (Structures), Association of American Railroads, has become chairman of the Research Council on Riveted and Bolted Structural Joints.

Turn-of-the-Nut Method

E. J. RUBLE

I first became interested in high strength bolts when Professor W. M. Wilson, who had been doing considerable research on connections at the University of Illinois, kept insisting that the bolts would make good fasteners. I insisted that they would not stay tight in railroad bridges or in any structure subjected to heavy vibration. To prove that Professor Wilson was wrong, I arranged to put from 1,500 to 2,000 bolts in locations where we had been having considerable trouble with rivets. I will admit that our method of installing them was quite crude, yet, at the end of a few years when we made an inspection, we found that they were still tight. After the second inspection, when we found that the bolts had still stayed tight, I decided that maybe Professor Wilson was right.

Many bridge members subjected to high fatigue and vibration present the problem of keeping the rivets tight. In some places the rivets work loose every year, but the high strength bolts have stayed tight although some of the bolt tension has been lost in a very few minor locations.

Since many bridges will have anywhere from twenty to forty rivets work loose, setting up a compressor at the site and calibrating the guns is not a very practical method of putting in new bolts. The use of a torque wrench is also not very practical, so a method was needed that would insure proper installation of the bolts when the nuts had been tightened.

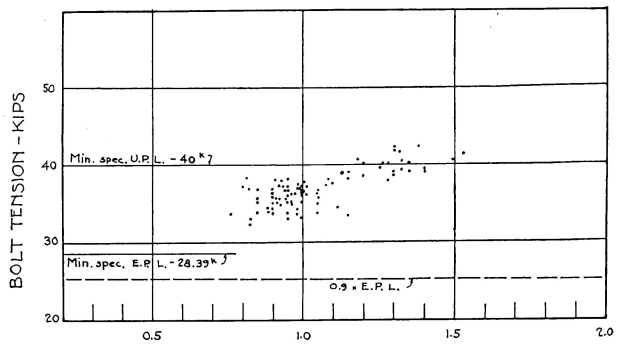
Committee 15 of the American Railway Engineering Association realizing that the high strength bolt was making a good fastener, yet feeling that tightening the bolts was a serious matter, asked the Research Staff of the A.A.R. to develop some means of tightening the bolts that would be practical. The turn-of-the-nut method, having been satisfactorily used by the automotive industry, appeared to be the solution. An investigation of this method was carried on at the A.A.R. Research Center during 1954.

All bolts were tightened through a grip of several plies of $3/8''$ steel plate or $3''$ steel slab depending on bolt size and length. Both torque wrenches and impact wrenches were used.

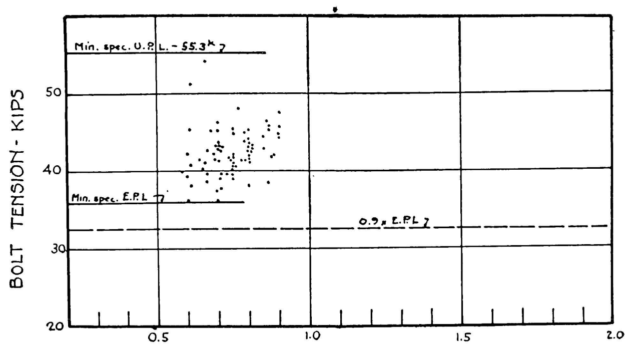
In accordance with the "Specifications for Assembly of Structural Joints Using High Strength Steel Bolts" approved by the Research Council on Riveted and Bolted Structural Joints of the Engineering Foundation, the bolts were tightened to the equivalent torque for required minimum bolt tension. It was found that about one-half a turn of the nut was sufficient to develop the required torque. Further, it was found that no failure, i.e., bolt breaking or thread stripping, occurred until the nut had been turned between two and three revolutions.

This ability of the bolts to withstand a high clamping action, already discussed by Professor Pauw, is very important, since laboratory tests have shown that the higher the clamping action, the stronger the joint. In all field tests, even where the temperature has dropped as low as forty degrees below zero, bolts tightened into the plastic range have behaved very satisfactorily.

These two slides show the results of tests performed at the University of Missouri by Professors Pauw and Howard. Bolt tension is plotted against number of revolutions of the nut for both $3/4''$ diam. and $7/8''$ diam. bolts. In all the bolts tested one-half turn of the nut produced a tension equal to at least the minimum specified elastic proof load. The bolt tension increases with the turn of the nut until about one and one-half revolutions when the curve begins to flatten out. Thus, as a result of the A.A.R. and University of Missouri tests, the A.A.R. recommended one turn of the nut as a satisfactory criterion for proper tension.



3/4" BOLTS - TIGHTENING REVOLUTIONS OF NUT



7/8" BOLTS - TIGHTENING REVOLUTIONS OF NUT

The complete field procedure is as follows:

1) Draw the steel together using high strength fitting-up bolts,
2) Install the remaining bolts finger tight and then give them one full turn,
3) Give the fitting-up bolts an additional one-half turn.

At first it was recommended that the fitting-up bolts be loosened, tightened finger tight and given one turn of the nut. However, experience has shown the revised procedure to be more satisfactory and checks have shown the bolts to have the required torque.

All sizes of impact wrenches were used in conducting these tests. It was found that any combination of air pressure and size wrench which produced one turn of the nut in about ten seconds was satisfactory. Any faster time does not permit the operator to closely control the revolution of the nut.

In one building using the method of loosening the fitting-up bolts after the rest of the bolts had been tightened, an experiment was made on one of the column splices. Instead of re-tightening the fitting-up bolts one turn from the finger tight position, they were tightened one and one-half turns. This proved to be too much since the fitting-up turn of about three quarters of a revolution had introduced a permanent set in the threads.

A Southern Railroad bridge across the Wabash River was completely bolted using the turn-of-the-nut method. A check of one of the floor-beam-to-hanger connections, showed the torque in the 30 7/8" diam. bolts to vary from 540 ft.-lbs. to 840 ft.-lbs. with an average of 615 ft.-lbs. In another joint the torque varied from 470 ft.-lbs. to 800 ft.-lbs. with an average of 590 ft.-lbs. Thus in both cases none of the bolts checked were below the required minimum torque of 470 ft.-lbs. Although this may seem like a wide variation in clamping action a check of a riveted joint showed the clamping action in individual rivets to vary from 3,000 to 14,000 pounds.

On one bridge the erectors had trouble drawing the steel together so they decided to use all the high strength bolts as fitting-up bolts. Then after the steel was drawn up the bolts were given an additional half turn. A check indicated all bolts to be well above the minimum torque.

In all cases cited the check consisted of giving the nut an additional 1/16th of a turn and recording the torque as the nut moves.

There has been considerable field experience gained using this method. In both buildings and bridges the turn-of-the-nut has proved to be a practical and satisfactory solution. ☆ ☆ ☆

MR. HIGGINS: To open the discussion I would like to call on Mr. J. R. Stitt, Research and Welding Engineer for the R. C. Mahon Co. Mr. Stitt will show some slides of the calibrating mechanism which he will demonstrate tomorrow afternoon during our inspection trip through the Kansas City Structural Steel Company plant.

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MR. STITT: I have a few slides to show you of the equipment which we plan to demonstrate tomorrow afternoon. Our equipment was built to satisfy the need for a portable device to set the proper air pressure on the wrench when tightening a bolt up to or above the minimum required tension. It does very much the same thing as Professor Pauw's equipment except that it can be carried right on to the job. This device has been used in the

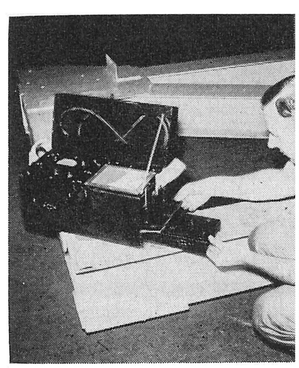

FIG. A

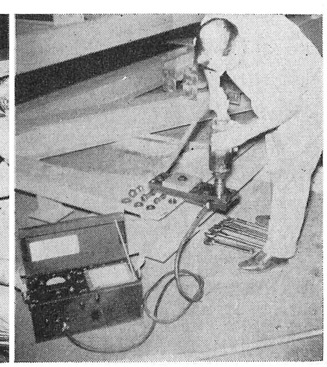

FIG. B

field for approximately two years on a number of jobs.

The box is approximately nineteen inches long, and everything is self-contained in a fifty-seven pound unit (Fig. A). The channel which carries the load cell fits in the bottom of the box and slips out the end door. A ten-foot cable goes from the control box to the channel so that the channel can be bolted to the face of a column or beam with the box several feet away (Fig. B). This rugged cable is going to stand up under the treatment that an iron worker gives it out in the field.

A microammeter has been calibrated to read a certain value for each minimum tension. The required minimum tension for each size of bolt is shown on the printed chart. A "B" radio battery is all that is needed to operate the control circuit.

The hole in the load cell is slightly over one inch in diameter so that we can use one-inch diameter bolts; or with sleeve inserts, 3/4″ and 7/8″ bolts. The load cell is machined from a solid piece of tool steel. The eight permanently mounted variable resistance wire strain gages measure the compression which is developed by the tension in the bolt.

We have found that as you tighten a bolt to the prescribed torque value you will have the required minimum tensile strength in the bolt. If you slack off with a torque wrench, tighten, slack off, and tighten a few times, however, you get a different amount of torque with the same amount of tension in the bolt. So instead of using a torque wrench, we depend on this portable device to calibrate our air wrenches for proper tension.

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MR. C. L. KREIDLER (Lehigh Structural Steel Co.): Is it possible to use high strength bolts and rivets in the same connection?

MR. RUBLE: We had that problem come up in our study of floor beam hangers where we were developing a large number of fatigue failures. From our laboratory work we know that the fatigue strength of a bolted joint is considerably higher than that of a riveted joint. Therefore, we concluded that one way to eliminate our failures in the floor beam hangers was to substitute high strength bolts in lieu of the lower line of rivets.

The question then arose as to whether or not our bolts and rivets would be working together. We fabricated some full size joints in which we placed bolts in the two lower lines of holes, and found the rivets were working right along with the bolts since they both produced clamping action.

MR. H. B. CORLETT (A.I.S.C., San Francisco): Could you have a pair of standard connection angles on the end of a beam framing into the web of a column where one angle is riveted to the web of the column in the shop and, for erection reasons, the other angle is left loose to be bolted to the column web?

MR. RUBLE: Yes, I would say that you could, because the two are going to work right together. Your rivet is producing clamping action just like the bolt, even though you do not design it that way.

MR. CORLETT: Well, unless you loaded it highly, the bolted connection would be rigid and would not slip so you would take all of the load on one angle.

MR. RUBLE: The riveted leg will possibly slip a little more than the bolted will.

If you were to consider it up to the ultimate load, you would have a little different condition since your rivets would go into shear and the steel around your bolts would undoubtedly slip and then your rivets would possibly have to carry more than the bolted connection.

CHAIRMAN HIGGINS: It is rather a hypothetical case, I believe, because in general the clamping developed by high strength bolts is comfortably above the shear value of a fastener. The slip load of the high strength bolt is considerably above the allowable working stress of a rivet, so that for a modest overload, I would suspect that the angle which was bolted and the angle which was riveted would share the beam reaction rather evenly.

I will concede that at some level of overload the bolted angle might start to slip, and if it did then any added overload would then be thrown on to the rivet. Whether that riveted single angle, by reason of the loading, would have failed completely at any lower beam reaction than a similar connection with both angles riveted, I think that you would have to do some testing to say one way or the other.

MR. T. P. NOE (Carolina Steel & Iron Co.): How much would painting the contact surfaces reduce the load carrying ability if you disregard any slip that might occur?

CHAIRMAN HIGGINS: Painting the contact surfaces would not reduce the load carrying ability at all, but rather the capacity would depend on what the criteria of failure in a particular joint was. If the criterion were to be tension of the net section, the capacity would be the same for the riveted connection and the bolted connection. If it were the failure of a fastener, the bolted fastener has a much higher shear value, and if you are not concerned with slip, there would be no reason for omitting the paint because it would not weaken the joint any.

MR. R. W. DERBY (Frank M. Weaver & Co.): If a high tensile bolt is so much stronger than a rivet, even though it has slipped, why do we put so much emphasis on tightening them? Why not use the high tensile bolts and tighten them up with a hand wrench and use them that way in the structure that is not subjected to impact loads?

CHAIRMAN HIGGINS: If we have a structure where slip is unimportant and where we do not expect a stress reversal, we are not really concerned with a high clamping force. The economic answer may be machine bolts because in all probability the shear value of any high strength bolt would be something in the order of twice the present allowable shear value of a machine bolt, while the cost is considerably more than twice.

MR. DERBY: Then I think it is up to us to educate our engineers and our architects along that line, because so often they use rivets or some equivalent fastener where it is not entirely necessary.

MR. H. J. STETINA (A.I.S.C., Philadelphia): We have been using the unfinished common and ordinary rough bolts for many years. If you will recall, going back about twenty-five years, we had a specification that permitted the use of ordinary bolts in one-story structures and also in multi-story structure secondary beams—beams that were twelve inches and less in depth.

About 1934, we expanded the A.I.S.C. Specification to provide a more liberal use of ordinary bolts than had ever been exercised prior to that time. I would say, off hand, that a building up to fifteen stories in height can be entirely rough bolted.

To give you an example of thousands of buildings that have been rough bolted, I would like to point out just one. Perhaps the most monumental is Stuyvesant Town in New York City, where, if my memory is correct, there are about thirty-five units each of about sixteen stories in height. The total tonnage involved is about forty-two thousand tons and every bit of it was rough bolted. Now, I believe that this was done for economical reasons because at that time the cost of riveting was prohibitive.

We have been emphasizing high strength bolts for about the last four years. The bolt manufacturers have been advertising—"Do it the modern way—use high strength bolts." Our own organization has several publications on high strength bolts for distribution to engineers and architects, but what has become of rough bolts?

Are we ready to throw them aside? The average architect and engineer has the wrong opinion that the high strength bolt is nothing more than an improved rough bolt. The high strength bolt is competing with the rivet and not with the ordinary bolt which is an economical method of construction.

Has the Council on Riveted and Bolted Joints any information or any literature to show the architects and engineers that this practice of using rough bolts over the past twenty years has been a successful one and something that we want to continue in every possible place where they can be used in this country?

CHAIRMAN HIGGINS: The Council, a research organization, has no program for proving the validity of ordinary rough bolts. It has been proven and you have cited a very good example of it. I don't know what sort of tests could be conducted that would add anything more convincing than the number of large structures that are put together with common bolts. The use of common bolts is recommended in the Institute Specification; objection to their use results from individual contrary opinion.

I think that this is a selling job, to convince the few doubters that the use of unfinished bolts, as recommended in our specification for the past twenty years, is sound. We all know that it is economical; I don't believe that there is more testing required.

MR. COOK (Kansas State Highway Commission): We have been concerned with tension in the bolt. Is there any way of telling when we have reached the danger point if the bolt doesn't break in two?

CHAIRMAN HIGGINS: Since the bolt's purpose is to produce clamping force, if the bolt hasn't broken or the thread hasn't stripped when you remove the wrench, it is a good clamp for the rest of time. It will prevent slip with no appreciable relaxation and continue to do it.

Now, if the nature of the loading is such that the fastener, after it has been heavily prestressed, is going to resist tension, one might expect that there is some upper limit at which the initial tension would have an effect upon the endurance strength of a bolt.

At the University of Illinois, a series of tees were bolted together with their flanges back to back. The prestress in the bolts was varied in each joint and the joint subjected to various loading cycles. In every case, for any given cycle of loading the endurance limit of the bolt was improved by pretensioning. Even the bolts that were over-stressed twenty per cent, (pretensioned to 120 per cent of the elastic proof load), had a higher endurance value under cyclic loading than similar bolts pretensioned by a lesser amount.

Therefore, I think that we can safely conclude that there cannot possibly be any injury to the structure in any way if your bolts are pre-tensioned in the order of twenty per cent beyond the elastic proof load.

MR. L. A. VILLARD (Bethlehem Fabricators, Inc.): From the kind of structures that have been described I strongly suspect that we are talking about conditions where the holes have been drilled or sub-punched and reamed.

What, if any, tests have been made on punched holes that would come from an average fabricating plant?

CHAIRMAN HIGGINS: There is a program under way now. It was not the thought of the Council at the time that it approved the program that there would be a significant difference in the behavior of a joint which had punched holes and a joint which had drilled holes, because it is a matter of clamping force rather than the bearing of the fastener against the side of the hole. That subject, however, is being stressed in connection with the condition of some of the holes being out of line, so that some of the fasteners are practically in bearing before any slip of the joint as a whole has taken place.

MR. VILLARD: We have run into a situation on a series of buildings where an architect insists that these bolts be used in recommended holes, and I could not find any evidence that they had been tested in punched holes.

CHAIRMAN HIGGINS: I recall seeing specimens which were fabricated by punching, but I don't recall in which of the Council-sponsored programs. There is a program in progress at the University of Washington investigating a great many of these conditions, low temperatures, use of paints, the poor matching of holes, punching versus drilling,—a sort of a clean-up program to answer some of these questions which the Council up to this point never thought were significant factors.

MR. S. R. WEBB (Carolina Steel & Iron Co.): I saw an example a few days ago where an erector had used high strength bolts too short to go through the nuts. If that nut were securely tightened, would there be an element of danger in it?

MR. RUBLE: Well, most of the load is resisted by the threads from the machined underside of the nut to about three-quarters of the way up into the nut. In other words, the upper part of the nut does not carry a great deal of load. However, you certainly would not want to use it for any dynamic loading, but under static loading it would be satisfactory.

MR. J. S. DAVEY (Russell, Burdsall & Ward Bolt & Nut Co.): I would say that if the nut withstood the minimum required torque that it would be satisfactory.

MR. STITT: I have at times used bolt lengths that missed the last thread in the nut and had the threads strip right out of the nut. I think that if that last thread had been used there would have been no stripping. Therefore, I am not in agreement with the remark that only the three-fourths of the threads are operating.*

CHAIRMAN HIGGINS: Mr. Ruble pointed out that he was not offering that as a recommended practice but that in some of the experimental work there was evidence that there was very little contact on the outer threads.

MR. E. E. HANKS (A.I.S.C., Greensboro, N. C.): I would like to ask Mr. Stitt where the device for calibrating the impact wrenches can be obtained.

MR. STITT: The device, that we have here at the conference, is the first one that we have built and has been in use for several years on our own jobs. I am building two more at the present time but they are not for sale. They are not the easiest thing to make, and the price would have to be somewhere around a thousand dollars for the complete unit.

Of course, if Mr. Ruble had his way, we would not need any device since we would just turn the bolt 360 degrees.

However, if there is enough interest and demand for the calibrating device, we could possibly manufacture them for sale.

MR. D. A. BEAM (C.I.S.C.): Have you any idea as to the proper starting point for finger tightness on a nut and bolt through a sloping flange? Would we have had to have a partial turn to take care of the looseness of the nut due to the slope of the flange or could we get up to the proper starting point with some other method?

MR. RUBLE: I would throw away this one turn criterion entirely and just keep on turning the nut until you bring the steel into contact—until your nut bears completely on your washer. You must deform the bolt until all surfaces are in contact.

MR. BEAM: And then give the nut another turn?

MR. RUBLE: I wouldn't say that you give it another turn since you have already given it about three or four turns and deformed the bolt to obtain full contact on the washers.

QUESTION: Is there any difference in tightening the bolt by the head rather than by the nut? We have had conditions in railroad bridges where you cannot get at the nut and we tighten by the head so I am sure it works all right.

CHAIRMAN HIGGINS: I am sure that it is done very frequently. Mr. Ruble says that they do it where they have no access to the nut—they put the wrench on the head of the bolt. I can personally see no reason why that would not be the logical way to do it.

MR. P. J. FOEHL (Midwest Steel & Iron Works Co.): In tightening bolts where your metal does not come together to begin with, for instance, girder splice plates, with springness keeping them slightly apart, isn't it going to take more than that one turn to draw the bolt up to its full tightness?

CHAIRMAN HIGGINS: Mr. Ruble mentioned earlier that the recommendation of the Association of American Railroads is that you use enough fitting-up bolts to draw the parts up into intimate contact, just as if you were about to drive hot rivets, and then to insert high strength bolts into the other holes. First make the nuts on these latter bolts finger tight and then give each one a complete turn. That takes place after the parts have been brought into intimate contact.

MR. C. M. CORBIT (A.I.S.C., Los Angeles, Calif.): Has there been any thought given as to how an agency would inspect bolts that would be tightened with one turn?

MR. RUBLE: I would make a spot check of the bolts with a torque wrench. Of course, you recognize that the torque wrench is not a scientific instrument, but it is a practical tool for telling whether you are way off or not. Just put the torque wrench on, and turn the nut a sixteenth of a turn. We have found that where this method is used all the bolts have developed the minimum required clamping action.

CHAIRMAN HIGGINS: The ironworker's task is not a difficult one. Having noticed the position of the marker on the chuck when he starts to impact, all he has to do is to make one complete revolution. A plus or minus of ten degrees is not going to make any material difference.

* EDITOR'S NOTE: On the afternoon of April 19th, Mr. Stitt, in demonstrating his calibrating device, showed that the required tension could be obtained when the bolt did not extend completely through the nut.

If he is operating a wrench that could produce one turn in a reasonable length of time, there would be nothing to encourage the ironworker not to make a complete revolution. Therefore, I believe that the spot check that Mr. Ruble has in mind would be adequate to convince most inspectors that the work had been satisfactorily performed.

A further assurance to the skeptical inspector, if he is not going to be present to watch the one revolution, would be, after the bolts had been made finger tight, to put a mark on the nut and on the steel just outside of the nut. If both of these marks are opposite one another at the time of inspection, he would know that it had had one revolution or hadn't had any. It would not be much of a task to check with a spud wrench to determine which was the case.

DR. PAUW: I would like to say that we noticed, when we tensioned the bolts, that the wrench left definite markings on the nut and therefore there should be no question, if the inspector has average eyesight, whether the nut is tensioned.

MR. R. W. BINDER (Bethlehem Pacific Coast Steel Corp.): It is difficult to keep the threads of common bolts out of the holes, and, therefore, what value would we assign to a high strength bolt without washers to replace the common bolt with the threads out of the hole? Could we swap one for the other?

CHAIRMAN HIGGINS: I have never been able to quite convince myself as to what virtue there was in a one-eighth increase in allowable value of a bolt just because you had used washers under the nut to keep the bolt thread out of the grip. (See A.I.S.C. Spec. Sect. 22-e.)

The University of Illinois has tested to failure joints with high strength bolts where the thread went all the way through the grip and report no weakening due to threads in bearing.

MR. H. W. BRINKMAN (Phoenix Bridge Co.): Would you recommend the unlimited substitution of high strength bolts for rivets, say in a large plate girder?

MR. RUBLE: I do not see any reason why you should not use them. I believe that you have to get used to those nuts and washers sticking out.

MR. W. F. THOMPSON, JR. (Kline Iron & Metal Co.): Do you suppose that we are using the absolute capacity of these high tensile bolts, rating them equal to rivets? Is it possible that they may be given higher values at some future date?

CHAIRMAN HIGGINS: They are rated as only the equivalent of rivets in order to assure no slip of the joint. If you are not concerned about the slip of the joint there is no reason why they need be given a value as low as that of a rivet.

MR. THOMPSON: Could you give some idea as to what value could be assigned?

CHAIRMAN HIGGINS: A working stress of 20 ksi in shear would be on the low side, based on test results which have been reported from the University of Illinois, where the failure load of the bolt was between $1\frac{1}{3}$ to $1\frac{2}{3}$ that of rivets of the same size.

MR. RUBLE: The Council has a project to determine the static and fatigue strength of alloy steels. We cannot show exactly that the fatigue strength of alloy steel is any higher than that of carbon, using both A141 and A195 rivets. However, if high strength bolts are used with alloy steels, then the fatigue strength jumps way up, probably greater than that for carbon steel. It is more in line with the yield strength of the steels, so that eventually we can assign some values to alloy steels using high strength bolts which will be larger than is possible with rivets.

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