

# Comparative Effectiveness of Tightening Techniques for A490 1¼-in. Diameter Bolts

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## INTRODUCTION

Since the approval of the first high-strength bolt specifications by the Research Council on Riveted and Bolted Structural Joints (RCRBSJ) in 1949 there have been concerns of ensuring that the bolts are properly tightened.<sup>1</sup> In certain applications, such as slip critical and direct tension, current practice requires that all bolts be tightened to reach or exceed a minimum specified preload. Considerable research has been invested on high-strength bolts and the techniques used to tighten them. Most testing on bolt behavior during tightening has been performed using smaller diameter bolts, such as 7/8-in. For larger diameter bolts, the results of these tests have been extrapolated to develop criteria used in establishing the RCSC *Specification for Structural Joints Using ASTM A325 or A490 Bolts*,<sup>2</sup> hereafter referred to as the RCSC *Specification*. An extensive study at Delft University in the Netherlands explored many different tightening methods including the turn-of-nut as well as load indicating washers. This study detailed the advantages and disadvantages of the different techniques.<sup>3</sup> The significant influence of lubrication on the bolt threads was revealed by Eaves in 1978.<sup>4</sup> Notch showed that hardened washers were needed for the proper tightening of large diameter bolts, and to attain a uniform "snug" condition.<sup>5</sup> Early testing of load indicating washers with bolts in the vertical position was performed in 1973 by Struik, Oyeledun, and Fisher.<sup>6</sup> This testing provided a basis for the validity of the washers as load indicators. In 1987, Kulak, Fisher, and Struik published the second edition of the *Guide to Design Criteria for Bolted and Riveted Joints*<sup>7</sup> and included much of the previous research performed on bolts and bolt

tightening techniques. The information on bolt properties and installation contained in this book was extensively used in the course of this investigation.

## OBJECTIVES

Large diameter bolts conforming to the ASTM A490 specification,<sup>8</sup> hereafter referred to as A490 bolts, are often used in heavy steel construction. The use of bolts with diameters over one inch are more prevalent in high-rise building construction.<sup>9</sup> The present research program explored the techniques and relative merits of the turn-of-nut and the direct tension indicator methods of tightening A490 1¼-in. diameter bolts. The direct tension indicator methods used the load indicating washer.<sup>10</sup> The load indicator washer (Figure 1) is a washer with protrusions which flatten as the bolt assembly is tightened. The primary objective of the study was to determine the relative effectiveness and efficiency of the two tightening techniques in achieving the required pretension for a given number of variables. A secondary objective was to determine if the extrapolation from small bolt testing is valid for large diameter bolts.

One tightening method that was considered but not examined was the direct tension loading system. The direct tension loading device cannot be used with A490 1¼-in. diameter bolts since the bolts, especially shorter ones, are not ductile enough to handle the necessary excess preload or pre-elongation from the loading device. This preload is needed to load the bolt over the required pretension in order to compensate for its elastic "springback" once the device transfers the load to the bolt.<sup>11</sup> Also, in most applications for building construction, the direct tension loading device is too bulky for use in a joint with closely spaced bolts.

## TEST PROGRAM

The program was divided into two phases: pre-testing and testing. In the pre-testing phase, samples of the materials used in the tests, including the bolts, hardened washers, and load indicators, were tested to measure their properties. Another purpose of the pre-testing was to identify the load vs. strain relationship of the bolts and to calibrate the strain gages for measuring bolt preload. The testing phase consisted of tightening 17 different joint assemblies and measuring the performance.

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### Pre-Testing:

Two lengths of 1/4-in. diameter A490 steel bolts were tested: a 14 1/4-in. "long" bolt and a 5-in. "short" bolt. The bolts are shown in Figure 2 along with a 7/8-in. diameter bolt to give an indication of the scale. The bolts were loaded to failure in a 300K-capacity universal testing machine, load vs. strain relationships were identified for the two lengths, and the yield and tensile strengths were checked for compliance with the specifications.

In conjunction with the direct tension tests, the bolts were also tested in a Skidmore-Wilhelm hydraulic bolt calibration device to determine the axial load or tension vs. strain relationship of the bolts using the torque/tension loading effect of the impact wrench. The Skidmore-Wilhelm, which is a tension measuring device, was also used to ensure that the impact wrenches were capable of tightening the bolts.

The hardened washers and the load indicating washers were tested for hardness. The load indicator washer was also tested in compression, with the use of a universal test machine, to measure the load at the required gap thickness.

### Testing:

#### Preparation:

The following procedure was used in the preparation of each bolt. First, the bolt was machined. The machining process included the installation of small, cone shaped holes drilled into the center of the head and the bottom of the bolt. These holes guided a C-clamp dial gage to determine the bolt elongation to the same point for each measurement.

Two 1/8-in. strain gages were epoxied to the bolt on each of two flat areas which were milled on opposite sides of the bolt shank directly beneath the head. The strain gage wires were fed through two small holes which were previously drilled through the head to the milled flat areas. The wires connected the gages to a data acquisition system which displayed the strain measurement during the testing. The two strain gage measurements were averaged in order to compensate for any bending that might occur during tightening.

The strain gages in conjunction with the data acquisition

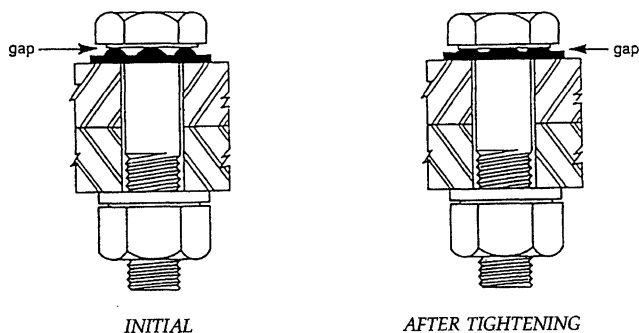


Fig. 1. Direct tension indicator method #1 (ref. 12).

system were the primary source of measurements for the testing. The dial gage was a secondary measurement source and used only to confirm the strain gages. The strain gage connections were untouched during tightening unlike the dial gage, which had to be removed each time the bolt was tightened.

There were 17 tests in this program. Each test included 12 bolt assemblies in order to give enough data to allow for conclusive observations to be made about the different tightening techniques. Each bolt assembly consisted of one bolt, one nut, two hardened washers and, for some tests, a load indicating washer. The bolts, nuts and washers were supplied from a variety of American manufacturers.

Steel plates conforming to ASTM A36 specifications were used as connecting material in the joint. A36 steel was chosen since it is the lowest strength material that would be used with an A490 bolt. The A36 steel plates which made up the connected plies were drilled with over-sized holes. Eight 1 1/2-in. plates were used for the long grip bolts (Figure 3) while three 7/8-in. plates were used for the short grip bolts (Figure 4). Each plate was drilled separately to best simulate a field connection at a construction site. There was concern that if the holes were drilled through a stack of plates at the same time, the joint would be too neat and therefore align unrealistically.

The following parameters were studied in the test program:

1. Tightening techniques
  - a. Turn-of-nut
  - b. Direct tension indicator method #1
  - c. Direct tension indicator method #2
2. Bolt length
  - a. Short bolt
  - b. Long bolt
3. Plate orientation
  - a. Vertical
  - b. Horizontal
4. Thread condition
  - a. Waxed

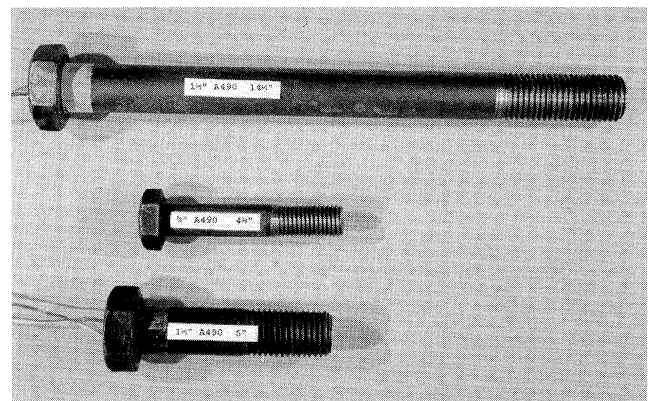


Fig. 2. Short and long A490 bolts.

b. Lightly oiled

In addition to these variables, two different brands of impact wrenches were used in each test. They were two of the largest one-man impact wrenches commercially available. The manufacturers of the load indicating washer used for this test program, recommended a CP-614 to tighten the A490 1¼-in. diameter bolts.<sup>12</sup> A Cleco W-2119 was also chosen because it had the required torque capabilities for tightening these bolts. It was also selected because Cleco products had been used in previous bolt tightening studies. The impact wrenches were fed a constant supply of air at approximately 90 psi through a ten foot, ½-in. inside diameter hose.

*Parameters*

*Tightening Technique:*

The turn-of-nut and load indicator washer both require a “snug” condition be achieved as the first step in the tightening process. Snug is defined by the RCSC Specification as the condition reached when the plies of the joint are in firm contact. The RCSC Specification suggests that a snug condition can be achieved by either a few impacts of an impact wrench or the full effort of an ordinary man using a spud wrench. For consistency throughout the testing, snug was achieved by tightening with a torque wrench to 200 ft-lbs which is approximately the torque generated by the full effort of an ordinary man using a spud wrench. Each bolt is tightened in sequence from the most rigid part of the assembly to the free edges (Figures 5 and 6) until all are snug. This may require a number of iterations.

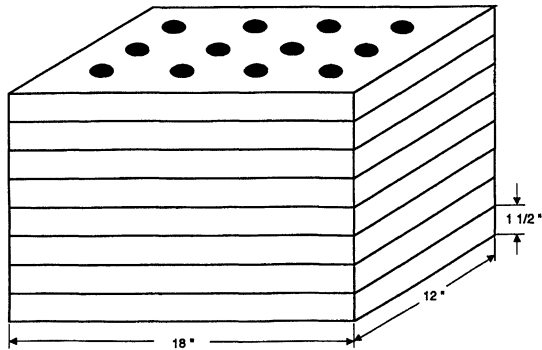


Fig. 3. Plate setup for long bolts.

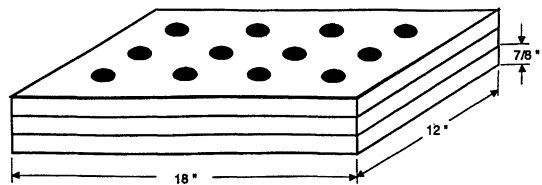


Fig. 4. Plate setup for short bolts.

In the turn-of-nut method, once all the bolts are snug, the installer marks the bolt assembly with the required rotation with paint or crayon. This rotation is a function of the diameter to length ratio of the bolt. The bolt length is the length measured from the under side of the head to the end. Short bolts, those up to a ratio of four, receive a one-third turn. Medium bolts, which have a ratio between four and eight, get a one-half turn. A long bolt which has a ratio of more than eight receives a two-thirds turn. Each bolt is then tightened with an impact wrench until the required rotation is achieved, following the same sequence as in the snug process.

The direct tension indicator method, using a load indicator washer, follows similar initial tightening steps as the turn-of-nut method. First, all the bolts are tightened to the snug condition. The tightening of each bolt resumes, again beginning with the most rigid part, with an impact wrench, until the average gap created by the load indicator washer is less than or equal to specification (ASTM F959). When using a pointed feeler gage to measure gap thickness, as in this test program, the average gap conforms to specification when the feeler gage cannot enter at least one half the specified number of places the feeler gage must be applied. For the A490 1¼-in.

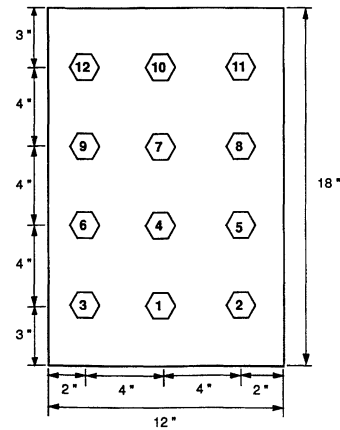


Fig. 5. Bolt tightening sequence for vertical plates.

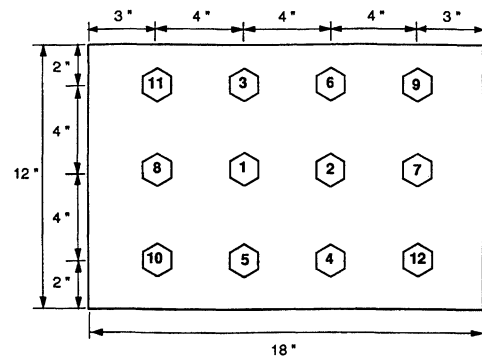


Fig. 6. Bolt tightening sequence for horizontal plates.

diameter bolt, there are eight places, around the circumference, the gage must be applied; four of which must not allow the feeler gage to pass through in order for the bolt to pass inspection. Tightening continues on the same bolt until the inspection is satisfied. Once a bolt passes inspection, the next bolt in the sequence is fully tightened.

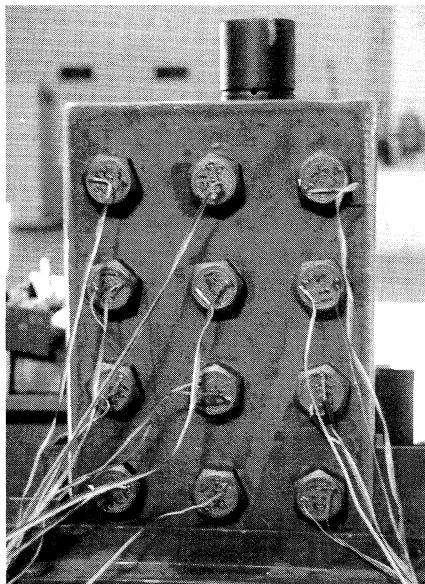
In the present tests, direct tension indicator method #1 had the load indicating washer underneath the head of the bolt and used a 0.015-in. thick feeler gage. Direct tension indicator method #2 used a 0.005-in. feeler gage, and the load indicating washer was placed under the nut with a hardened washer between it and the nut. These procedures are in accordance with ASTM F959.

#### *Bolt Length:*

The two bolt lengths chosen for the study reported herein were approximately 5 inches (4 bolt dia.) and 14¼ inches (11.4 bolt dia.). These lengths represented both ends of the spectrum. Since its length is no more than four times the diameter, the 5-in. long bolt is a short bolt, requiring a one-third turn of the nut after the snug condition for the turn-of-nut method. The 14¼-in. long bolt, with a length-to-diameter ratio over eight but less than twelve is a long bolt, requiring a two-thirds turn of the nut after the snug condition for the turn-of-nut method. Installation by the direct tension indicator method is independent of the bolt length.

#### *Plate Orientation:*

The plates were oriented in both the vertical and horizontal position in order to simulate usual construction conditions. The vertical position was closely scrutinized, because uncertainty existed as to whether the pretension results would be affected by the washers hanging on the bolts between the



*Fig. 7. Vertical A36 steel plate setup.*

threads which could cause the nut and washers to bind, or by the bolts lying on the plates which could cause eccentric loading.

#### *Thread Condition:*

The conditions of waxed and lightly oiled threads were included because the installation of bolts by direct tension indicator methods required wax. The manufacturer of the load indicator washers used in the study recommend Chem-Trend Stick Wax 140 to lubricate the threads of the bolts.<sup>12</sup> This wax was used with the bolts designated as waxed. The RCSC Specification requires bolts to be lightly oiled and free of dirt and rust.

Typically, the manufacturer provides the bolts with a light coat of oil. However, the bolts could not be used in the “as received” condition with the manufacturer’s coating. After preparing the bolts for the strain gages, many steel shavings adhered to the bolt due to the manufacturer’s oil. Therefore, the oil had to be removed. The “as received” condition was simulated by lightly oiling the threads with a machine oil before they were put into the joint. In order to do effective parallel testing, both conditions were used for the turn-of-nut method and the direct tension indicator methods.

#### *Test Designation:*

A listing of each of the tests and the variables is given in Table 1. Each test is labeled with a series of letters. The letters designate the following variables:

- T: Turn-of-nut
- D1: Direct tension indicator method #1
- D2: Direct tension indicator method #2
- S: Short bolt length
- L: Long bolt length
- W: Waxed threads
- O: Oiled threads
- V: Vertical plate orientation
- H: Horizontal plate orientation

For example, a test designation of T-LWH represents data from the turn-of-nut installation of a long bolt with waxed threads in a horizontal plate assembly.

#### *Procedure:*

The procedure was similar for each test to ensure consistency. After preparation, the threads were either oiled or waxed as dictated by the variable being tested. The bolts were then placed into the steel plate setup (Figure 7). The steel plates were placed on one beam for testing with vertical plates (Figure 8). Horizontal plates were placed on two beams so that the bolt heads could hang freely without the interference of a supporting beam. The gages were then checked to ensure all the gage connections were working properly.

Before the bolt was loaded, initial readings were taken of both the dial gage and the strain gages. The bolts were then tightened according to the method used. Once the snug con-

Table 1. Test Program and Variables						
Test Name	Bolt Length		Thread Condition		Orientation	
	Long	Short	Waxed	Oiled	Vertical	Horizontal
<b>Turn-of-Nut Method</b>						
T-LWV	X		X		X	
T-LWH	X		X			X
T-LOV	X			X	X	
T-LOH	X			X		X
T-SWV		X	X		X	
T-SWH		X	X			X
T-SOV		X		X	X	
T-SOH		X		X		X
<b>Direct Tension Indicator Method #1</b>						
D1-LWV	X		X		X	
D1-LWH	X		X			X
D1-LOV	X			X	X	
D1-SWV		X	X		X	
D1-SWH		X	X			X
D1-SOV		X		X	X	
D1-SOH		X		X		X
<b>Direct Tension Indicator Method #2</b>						
D2-LWV2	X		X		X	
D2-SWV2		X	X		X	

dition was achieved, dial gage and strain gage measurements were recorded at the snug condition. At this point, all the plates were in visual contact. The impact wrench was then applied to each bolt to achieve a fully tight joint in the required sequence. After ten seconds of tightening each bolt with an impact wrench toward the fully tight condition, dial gage and strain gage measurements were recorded, since the RCSC Specification requires that a bolt be tightened in approximately ten seconds. Some background on a 10 second tightening time is found in an early paper by Drew.<sup>13</sup> The tightening then resumed with the impact wrench until the bolt satisfied the installation procedure. When the impact wrench had to be stopped during the tightening process, the stop watch which timed use of the impact wrench was also stopped. The first six bolts in each test were tightened with the CP-614, and the last six were tightened with the Cleco W-2119. Dial gage and strain gage measurements of all twelve bolts in the connection were then recorded after complete installation.

The bolts were then unloaded to a point where the nuts could be loosened by hand. A strain gage measurement was recorded after the bolts were unloaded to check if any inelastic or permanent deformation of the shank had occurred during tightening.

## RESULTS

### Pre-testing:

Both impact wrenches were capable of tightening the bolts. However, neither could tighten the bolts within the requirement of ten seconds or less. The CP-614 wrenches, which were not new, were slower in tightening the bolts than the Cleco W-2119, which was new. Two CP-614 wrenches failed early in the testing, but a reconditioned CP-614 completed the

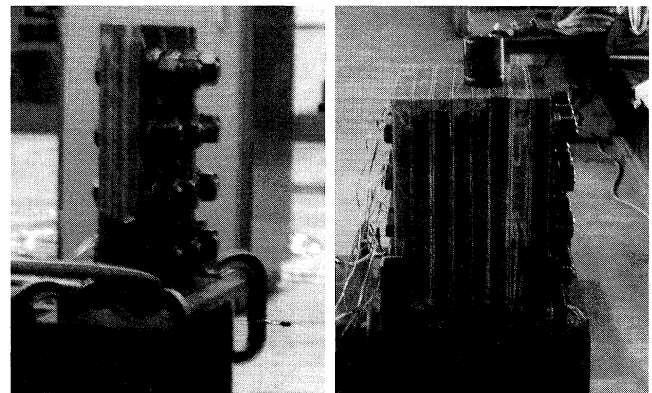


Fig. 8. Short and long bolt vertical setup.

tests without any problems. The new Cleco W-2119 was used without any problems throughout the program.

The direct tension pre-tests developed the elastic load vs strain relationships for both A490 1¼-in. diameter bolt lengths (Figure 9). They also verified that the short bolts satisfied the requirements of tensile strength between 150 and 170 ksi. The measured tensile strengths were 171 ksi and 168 ksi. The long bolts had tensile strengths of 199 ksi and 201 ksi, and hence exceeded the permissible tensile strength of the A490 bolt. No measurements were taken between the elastic zone and the ultimate tensile strength. In comparison with these pre-test results, the certification sheets for the bolts, provided by the bolt supplier, indicated tensile strengths of 168.2 ksi and 163.6 ksi for the 5-in. and 14¼-in. long bolts, respectively. Thus, the supplier data agreed with the pre-test data for the short bolt, but in contrast to the pre-test data, suggested that the long bolts were within the permissible tensile strength range. Table 2 summarizes the tensile strength, chemical composition, and hardness data for the bolts, as furnished by the supplier. Although the ultimate strength of the 14¼-in. long bolts were significantly higher than the short bolts and the maximum specified ultimate strength, the preload will not be adversely effected since the

Composition, % wt	5-in. Bolts	14¼-in. Bolts	ASTM A490 Requirements
C	0.41	0.39	0.28–0.50
Mn	0.90	0.86	—
P	0.015	0.012	0.045 max
S	0.005	0.021	0.045 max
Si	0.24	0.28	—
Cr	—	0.86	—
Ni	—	0.16	—
Mo	—	0.20	—
Cu	—	0.27	—
Tensile Strength, ksi	168.2	163.6*	150–170
Hardness, HRC	34	35	32–36

\*When tested in the laboratory, the tensile strength was recorded at 200 ksi, as opposed to the 163.6 ksi reported by the supplier.

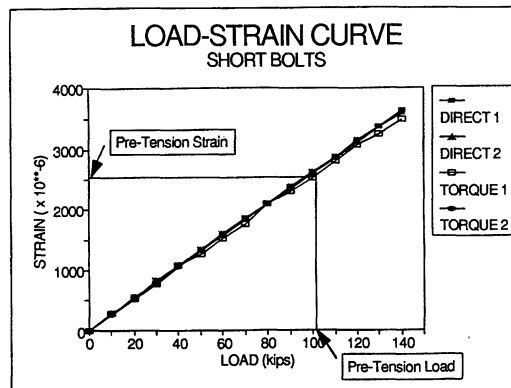
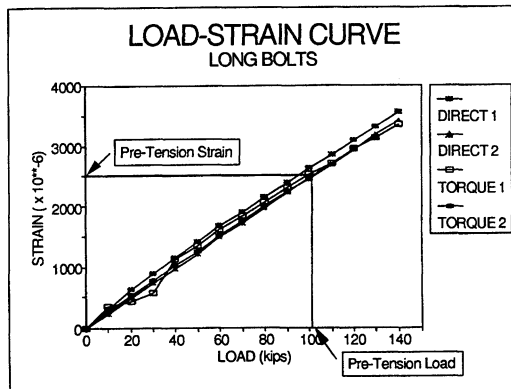


Fig. 9. Load-strain curves.

bolts threads undergo less inelastic deformation during tightening.

The pre-tests using the impact wrench and the Skidmore-Wilhelm verified the elastic load vs. strain relationship. However, the impact wrenches did not have the ability to generate bolt tension exceeding 140 kips (144 ksi). Therefore, the torque/tension pre-tests could not be used to obtain the load at which the bolt shank would yield under the combined load.

The minimum pretension for bolts is 0.70 times the minimum specified tensile strength.<sup>2</sup> For A490 1¼-in. diameter bolts the minimum specified tensile strength is 150 ksi; therefore, the pretension stress is 105 ksi or a pretension load of 102 kips. The graphs from the tension pre-tests (Figure 9) indicate that the minimum pretension of 102 kips corresponds to a measured strain of approximately 2,500  $\mu$ strain in the shank. Since both tension and torque/tension responses did not vary significantly, the effect of shear strain of the gage could be neglected. However, it is worth noting that an increase in shear strain due to torsion would increase the measured longitudinal strain data. Thus, data would be biased to indicate greater tension than actually exists.

The hardness pre-tests on the hardened washers indicated average hardness readings of 40 to 44 HRC and showed that they all met the ASTM F436<sup>14</sup> requirement of 38 to 45 HRC. Measurements indicated they met dimensional tolerances as well. The load indicating washers had an average measured hardness of 40 HRC on the flats and 41 HRC on the protu-

sions. Hardness requirements are not specified as part of ASTM F959.

A load test of the load indicator washer was conducted according to ASTM F959. The results of the test indicated that the required gap was achieved at approximately 106 kips, thereby, conforming to ASTM F959.

**Testing:**

The performance of each tightening technique with the given set of parameters was measured by two factors: the final strain in each bolt, and the impact wrench operating time. The final strain is indicative of the effectiveness of the technique. The operating time is representative of the required work to tighten a bolt, thus indicating the efficiency of the installation technique. The average final strains and operating times are given in Table 3. The average final strains are based on the bolt gage pairs. When at least one gage of a pair did not function, the axial strain data was not considered. The strain was then computed from the dial gage data with the use of the calibrations performed in the pre-testing.

**Turn-of-Nut:**

The results obtained for the turn-of-nut installation are shown in Figures 10 through 13. The data reveals three general trends. First, the waxed bolts (solid squares and triangles) attain higher preload than do the oiled bolts (open squares and crosses), with less scatter. Second, the horizontal plate assemblies attained higher preload than the vertical. The third is that the operating time required to turn the prescribed amount is shorter for the oiled threads. Each of these trends is consistent with the initial condition of joint compactness or stiffness at snug.

As the bolts in the joint were tightened, the joint compactness increased. With the long bolts, there was an upward trend in the final strain reading at each successively tightened bolt in the joint. The first bolts tightened in the sequence had lower final strains than the bolts tightened later in the sequence.

After the recommended rotation, the short waxed bolts generally had a very high strain which indicated a load significantly higher than the minimum specified 102 kips per bolt. However, all of the bolts, with the exception of two, remained elastic at the shank indicated by the freedom of

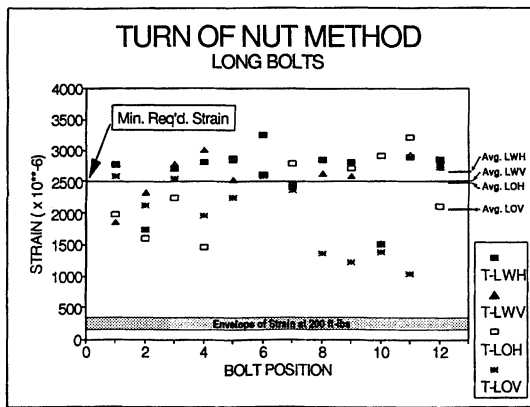


Fig. 10. Turn-of-nut method—long bolts.

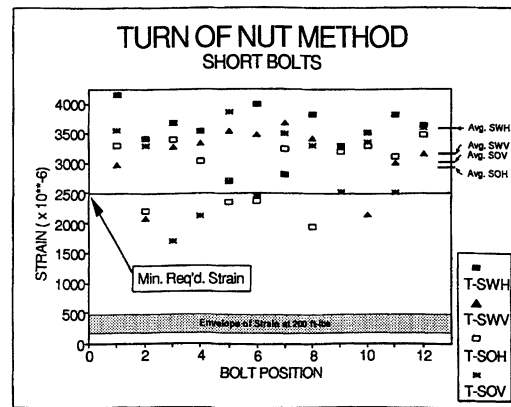


Fig. 12. Turn-of-nut method—short bolts.

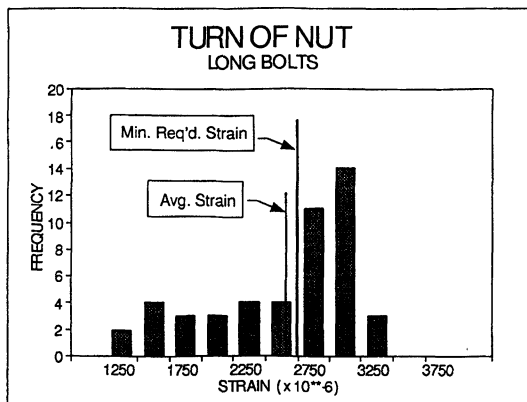


Fig. 11. Frequency diagram for turn-of-nut method—long bolts.

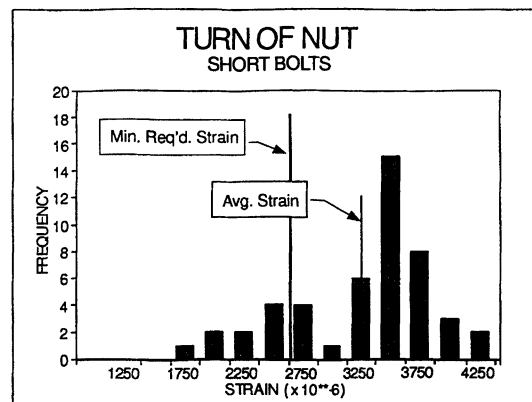


Fig. 13. Frequency diagram for turn-of-nut method—short bolts.

residual strains in the unloaded state. After unloading, the nut rotation on all of the bolts was uninhibited.

Figure 11 shows the frequency distribution for all of the long bolts using turn-of-nut method. It shows 28 of the bolts reached or exceeded the minimum strain, while 20 did not. The turn-of-nut method required between 13 and 38 seconds to tighten the long bolts (Table 3).

Figure 13 shows the frequency distribution for the turn-of-nut method for short bolts. It shows 9 bolts did not reach the minimum strain reading, while 39 successfully reached or exceeded the minimum strain reading. The time range for tightening the short bolts was between 16 and 37 seconds (Table 3).

**Direct Tension Indicator Method #1:**

The results for bolts installed using the direct tension indicator method #1 are shown in Figures 14 through 17, and there are similarities to bolts where the turn-of-nut method was used. With the exception of the short bolts in vertical plate assembly with oiled threads, the same three trends existed. The presence of increased strains of bolts tightened later in the sequence using the direct tension indicator method #1 is

similar to that of the turn-of-nut method (Figure 14). However, only three of the long bolts installed by the direct tension indicator method reached or exceeded the minimum required strain, while 32 did not (Figure 15). Moreover, the time required for tightening a long bolt was between 50 and 52 seconds (Table 3).

The short bolt strains are shown in Figure 16. The frequency diagram for short bolts tightened by direct tension indicator method #1 is shown in Figure 17. With this method, 30 short bolts did not reach the minimum required pretension, while 18 reached the required minimum pretension. The time needed to tighten the short bolts ranged between 26 and 37 seconds (Table 3).

**Direct Tension Indicator Method #2:**

The final strains for tests D2-LWV2 and D2-SWV2, tightened using direct tension indicator method #2 with long and short waxed bolts in vertical plate assemblies, are shown in Figures 18 through 21. Seven of the eleven long bolt strain readings were lower than the required minimum pretension (Figures 18 and 19). However, all of the short bolts reached or exceeded the required minimum pretension (Figures 20 and 21).

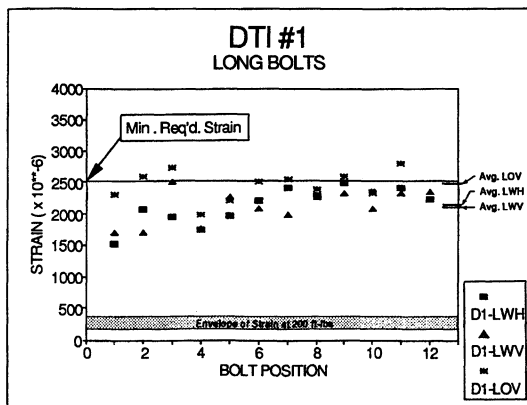


Fig. 14. Direct tension indicator method #1—long bolts.

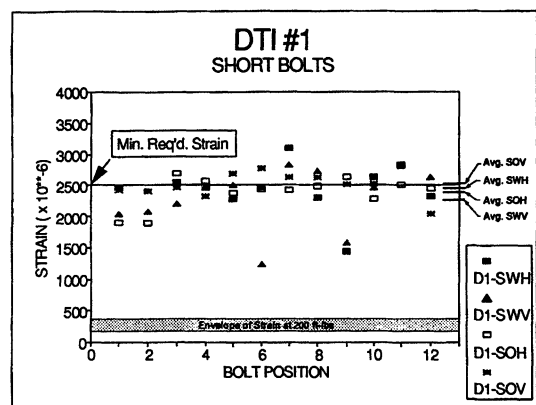


Fig. 16. Direct tension indicator method #1—short bolts.

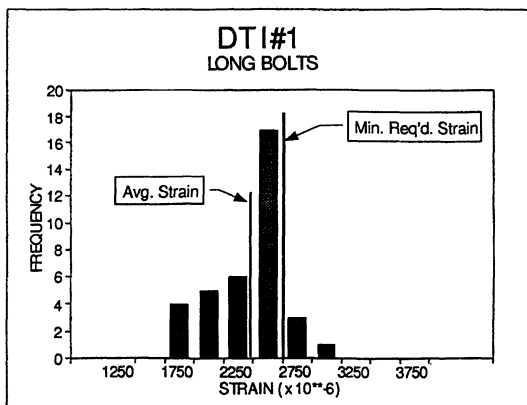


Fig. 15. Frequency diagram for direct tension indicator method #1—long bolts.

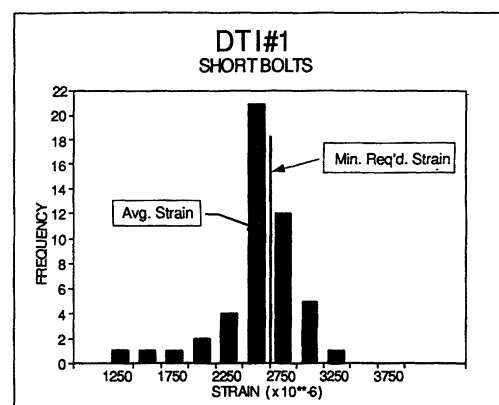


Fig. 17. Frequency diagram for direct tension indicator method #1—short bolts.

Test	Time per bolt (seconds)	Total test time (minutes)	Average Final Strains** ( $\times 10^{-6}$ )
T-LWH	29	31	2621
D1-LWH	52	55	2132
T-LWV	38	32	2496
D1-LWV	50	53	2108
D2-LWV2	36	54	2457
T-LOH	22	36	2444
T-LOV	13	29	2012
D1-LOV	50	51	2448
T-SWH*	37	32	3536
D1-SWH	30	55	2444
T-SWV	17	30	3120
D1-SWV	37	57	2300
D2-SWV2	34	42	2765
T-SOH	16	23	2905
D1-SOH	36	53	2391
T-SOV	19	25	2988
D1-SOV	26	32	2517

\*First test: procedure was being developed, therefore slower than other tests.  
\*\* $2500 \times 10^{-6}$  is the minimum acceptable final strain reading.

Using the direct tension indicator method #2, the time to tighten the bolts was 34–36 seconds (Table 3).

### **OBSERVATIONS AND COMPARISONS OF TIGHTENING TECHNIQUES**

The results of this program are not unique. There has been a field investigation conducted which reported a significant percentage of installed 1¼-in. A490 bolts using load indicating washers not achieving the required minimum preload.<sup>15</sup> These bolts had grip lengths of 8½ and 10 inches. Likewise, tests conducted at McMaster University have shown that the average torque required to properly preload 6½-in. long 1¼-in. A490 bolts is 14 percent larger for bolts installed using load indicating washers than installed using the turn-of-nut method.<sup>16</sup> This report also confirms the greater nut rotation and increased work required to install the bolts using the load indicating washers.

#### **Turn-of-Nut:**

This method was easiest and the least time consuming to accomplish. It was also the most effective and efficient. Tightening the bolt was the easiest with this method since the markings for the rotation were clearly visible at all times on top of the wrench socket. The impact wrench operator could

tell when the rotation was complete. Most of the bolts tightened by the turn-of-nut method reached or exceeded the minimum required preload for both bolt lengths. Therefore, this method was the most accurate of all the methods tested. It was less time consuming both for the operating time of the impact wrench and the time for the whole tightening procedure for the joint. However, this time was greater than the RCSC<sup>9</sup> specified time of ten seconds to tighten the bolt.

A drawback to the turn-of-nut method is the difficulty of bringing bolts to a consistent snug condition. The difference in final strains between waxed and oiled threads, especially for the long bolts, showed that the plates were compacted more when the bolts were waxed than when they were oiled. “Snug” depends on torque, and wax significantly reduces the torque during tightening. A deficiency noted with the turn-of-nut method is that the 200 ft-lb snug condition was not sufficient to bring all the plates into contact for joints with a large number of plies. This can be seen in the difference between the final strains for the short bolts and the long bolts. The long bolts demonstrated a distinct upward trend in strain during the tightening sequence of the joint. Bolts that were tightened earlier in the sequence had a lower strain than the bolts that were tightened later in the sequence. This variation is likely caused by the differences in local plate assembly compactness or stiffness at the time of final tightening; bolts tightened later likely encountered a stiffer assembly of plates resulting in higher pretensions for the turn-of-nut method and/or caused some reduction in tensions of previously tightened bolts.

#### **Direct Tension Indicator Method #1:**

An advantage noted for direct tension indicator method #1 was that it had very consistent readings for all of the tests. The condition of oiled or waxed threads did not have a major bearing on the final strains. The position of the plates, whether horizontal or vertical, did not significantly affect the final strains. Previous concerns about the washers getting caught in the threads or eccentric loadings were seemingly unfounded because these behaviors did not occur in these tests. However, this may in part be attributed to the high tensile strength of the longer bolts which minimized inelastic distortion in the threads.

There were several disadvantages to this system. Most importantly this method did not successfully bring all the bolts or the average of all the bolts to the minimum strain reading. Also, the time required to tighten each bolt was longer than the turn-of-nut method and longer than the RCSC Specification<sup>9</sup> of ten seconds. The impact wrench had to operate longer and often turned the nut farther (¾ to 1 turn for the short bolts and 1 to 1¼ turns for the long bolts). The procedure, as a whole, required more time since the tightening had to stop, the impact wrench removed, and then the load indicating washer checked with the feeler gage. If the washer gap was too large, the procedure had to be repeated.

Direct tension indicator method #1 had the same deficiency as the turn-of-nut method with regard to the increase in final strains for the last-tightened long bolts. Not all the plates were in full contact at the 200 ft-lb snug condition. The installation guidelines supplied by the manufacturer of the load indicating washers requires that the bolts not be fully tightened at once, but rather they should be all tightened to a certain point and then fully tightened. From these tests it is obvious that the initial tightening point must be greater than the 200 ft-lbs used for the turn-of-nut and the load indicator washers.

**Direct Tension Indicator Method #2:**

Direct tension indicator method #2 had similarities to the direct tension indicator method #1. The strains in the short bolts were adequate for a properly pretensioned joint. However, the average of the final strains in the long bolts was slightly less than the required minimum.

The direct tension indicator method #2 also had drawbacks. Like method #1, the time needed to tighten each bolt and, as a consequence, the entire joint was greater than that of the turn-of-nut method. Like the other methods, the long bolts

tightened later in the sequence had higher final strains. Again this was because the plates were not in full contact at the 200 ft-lb snug condition. Method #2 had the highest material cost since it required an extra hardened washer in addition to the load indicating washer.

**SUMMARY AND CONCLUSIONS**

The results of this study, which was limited to 1¼-in. diameter A490 bolts, show the following:

1. Turn-of-nut method was the most acceptable installation method for pretensioning short and long bolts with the demonstrated test parameter combinations used in this experimental study.
2. Direct tension indicator method #1 failed to produce minimum required tensions for both the short and long bolts.
3. Direct tension indicator method #2 was as effective as the turn-of-nut method but not as efficient.
4. The bolt length was by far the most influential factor and its effect is coupled with that of the stiffness of the plate assemblies: the thicker plies used with the long bolts

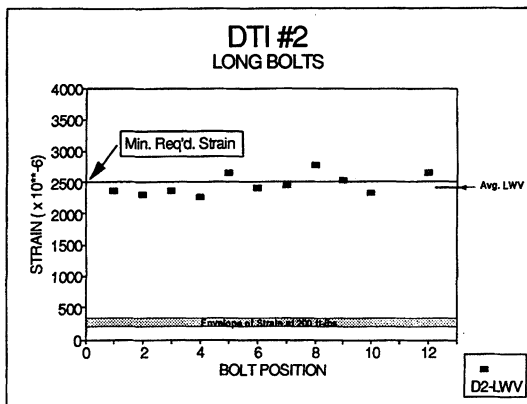


Fig. 18. Direct tension indicator method #2—long bolts.

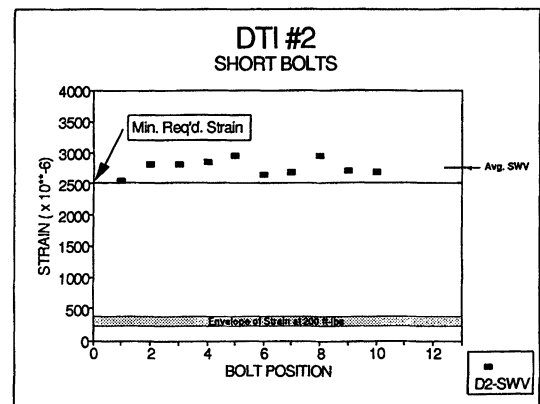


Fig. 20. Direct tension indicator method #2—short bolts.

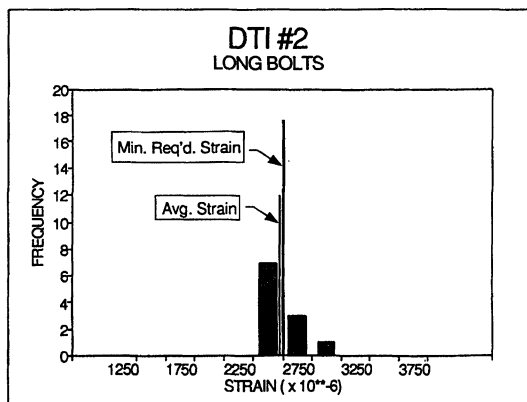


Fig. 19. Frequency diagram for direct tension indicator method #2—long bolts.

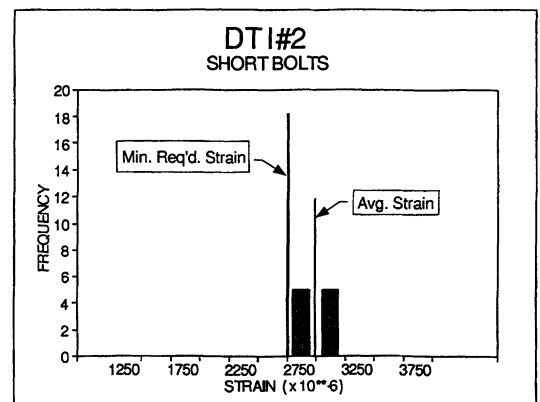


Fig. 21. Frequency diagram for direct tension indicator method #2—short bolts.

would require more force to bring them into contact compared to the thinner plies of the short bolt assembly. For all methods, the final bolt strains indicated that the pretension in the short bolts was significantly higher than that in the long bolts.

5. The condition of the threads, whether waxed or oiled, had a moderate effect on the preload of bolts installed by the turn-of-nut method. This effect was less significant for bolts tightened by the direct tension indicator methods, as would be expected.
6. The specified one-third turn resulted in a high elastic strain for the short A490 1¼-in. diameter bolts, ensuring that the installed bolts exceeded the minimum specified preload.
7. The 200 ft-lb snug condition did not bring all the plates into contact when there was a large number of plates. Since all the plates were not in full contact, there was a rise in final strains as the joint was tightened. Higher snug preloads are needed to fit-up heavy steelwork when using large high strength bolts.
8. The time to tighten each bolt is longer than the RCSC Specification of ten seconds, even after using the largest impact wrenches available. The tightening times for direct tension indicator methods #1 and #2 were longer than the time of twenty seconds recommended by the manufacturer of the load indicating washers.
9. Both the Cleco W-2119 and the CP-614 wrenches were capable of tightening the A490 1¼-in. bolts when they were in proper working order.

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