Bolt Preload Measurements Using Ultrasonic Methods

JAMES S. NOTCH

Significant research efforts and technological advances have occurred over the past years with regard to the design of high-strength bolted connections. The development of quality assurance programs aimed at evaluating whether sufficient bolt pre-tension has been achieved during field bolt-up is equally important. A high-strength bolted connection's superior strength characteristics are based on the development of frictional forces between the clamped plates or members. High-strength bolts are not, as in the eyes of many laymen, merely "bearing type" pins holding the joint together—they are fasteners which must achieve sufficient pre-tension to clamp the connection plies together and thereby provide adequate slip resistance. The importance of developing sufficient clamping force is even more important with today's prevalent use of oversize and slotted holes.

In addition to direct tension indicator devices which have shown merit, the most common recognized method of bolt tightening is the turn-of-the-nut method. Based primarily on strain control, the method relies on a specified incremental turn to elongate the bolt. Although simple in concept, the method is difficult to control under field conditions. The greatest variables are the definitions of "snug tight," the starting point for the incremental turn, and the accuracy of the rotational measurements. The testing program will show, however, that turn-of-the-nut procedures, if carefully followed, will in most cases result in an adequately bolted structure. The difficulty in the turn-of-the-nut method lies in the quality assurance phase of a project. Unless a knowledgeable inspector visually observes and/or matchmarks every bolt being tightened by turn-of-the-nut, the only commonly available and recognized means to assure proper bolt tension has been with the use of a torque wrench.

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The variability of torque control is well known. Torque times the rotation can be defined as the amount of work necessary to install a bolt. The amount of work, and consequently the torque, is integrally related to the conditions of bolt assembly. In field conditions, bolts are exposed to atmospheric conditions which can greatly change the frictional resistance values of the threads. Rust and dirt can accumulate and result in further increases in the amount of work necessary to tighten a bolt. Washers can dish and embed into oversize holes, thus building up galling forces between the nut or bolthead and the washer.

Again, work to tighten a bolt is increased and any type of torque-tension relationship is further distorted. As the time period between bolt-up and torque wrench application increases, the thread conditions are prone to increased corrosion and build up of frictional resistance. Torque wrenches may be acceptable to provide a ballpark check of bolt tightening procedures, but as a measuring device of bolt tension, it is this author's opinion that the method lacks reliability. The test results documented in this report and in a companion report have further confirmed this view.

Ultrasonic measurement of preload holds much promise for becoming an integral part of tomorrow's quality assurance programs for high strength bolting. As bolted fasteners are tightened at a joint, they undergo stretching or elongation. The amount of elongation of a bolt is directly related to the amount of pre-tension in the bolt and, subsequently, the clamping force at a connection. By precisely measuring the amount that a bolt stretches, a very accurate indication of internal bolt tension can be obtained. Several ultrasonic devices have been developed recently which can measure accurately bolt stretch. The ultrasonic devices operate by transmitting an ultrasonic pulse into one end of the bolt through the medium of a transducer. The transmitted sound pulse travels through the bolt length and is echoed back from the opposite end. Based on the time of travel for the sound pulse, a bolt length can be calculated. The speed of sound through a bolt is not only affected by the bolt material type, but also by changes in temperature and stress state of the bolt. The speed of a pulse echo decreases with increased bolt stress and with increased temperature. State-of-the-art ultrasonic testing devices compensate for these effects and can measure very accurately changes in bolt length. By measuring the length of an existing tightened bolt and then repeating the measurement after loosening the nut, a measurement of the original bolt stretch can be made. Likewise, for new bolt installations, the length is measured before tightening, and then after tightening to determine the change in bolt length. Based on a modified version of Hooke's Law, these length changes can be correlated to a bolt tension:

$$F_p = \frac{\Delta L \times E \times C}{(L_S/A_S + L_b/A_b)}$$

Where:

F_p = load (lb. or Newtons)

E = modulus of elasticity (psi or Newton/mm^2)

L_s = effective length of thread (in. or mm)

A_s = tensile area of thread (in.^{2} or mm^2)

L_b = length of body (in. or mm)

A_b = area of body (in.^{2} or mm^2)

C = stretch correction factor to compensate for specific material velocity and stress factor of the test specimen

A laboratory bolt testing program was initiated to obtain a data base of ultrasonic extensometer measurements of preload. The test results were utilized to calibrate preloads as induced by torque wrench, calibrated wrench and turn-of-the-nut procedural methods.

Tests were conducted on 1-in. and 1¼-in. dia. A490 high-strength bolts. Testing proceeded as follows:

Apparatus

1. PDX934 Bolt Gage (Raymond Extensometer) as manufactured by Raymond Engineering, Inc., 217 Smith St., Middletown, Conn.
2. 2,000 ft-lb. torque wrench coupled to a 4:1 Snap-On-Tool GA-186 Torque Multiplier
3. Skidmore-Wilhelm Tension Indicator
4. Chicago Pneumatic Impact Wrench Model 6120

Calibration Procedures

1. PDX934 Bolt Gage was properly calibrated to the National Bureau of Standards provisions using a Sony Magnescale Digital Micrometer. Sample lots of bolts were furnished to the testing lab prior to the test date such that the equipment could be calibrated for the specific bolt grade and dimensional bolt size to be tested. Equipment was adjusted at the test site to compensate for bolt specimen temperature.
2. Torque wrench/torque multiplier was calibrated and certified by the independent testing laboratory.
3. Skidmore-Wilhelm Tension Indicator was properly calibrated and certified by an independent testing laboratory.

Laboratory Testing Sequence (see Table 1)

1. Measure bolt length with bolt gage.
2. Tension assembly to snug tight (approx. 10,000 lbs. tension, approx. 175 ft-lb. torque).
3. Measure bolt length with bolt gage.
4. Match mark bolt assembly.
5. Tighten bolt assembly using turn-of-the-nut procedures to one-third turn with the torque wrench/multiplier. Record Skidmore-Wilhelm Indicator reading. Measure bolt length with bolt gage and record. Measure torque directly from torque wrench and record.
6. Repeat Item No. 5 using turn-of-the-nut procedures to the following incremental values: one-half turn, two-thirds turn, three-quarter turn, one turn.
7. Loosen bolt, record bolt length with extensometer.

The preceding laboratory test sequence was performed on several different bolt specimen configurations.

Test assembly No. 1:
1¼-in. A490 heavy hex structural bolt, 1 ASTM F436 standard round washer, ASTM A194, Gr. 2H heavy hex nut

Test assembly No. 2:
1¼-in. A490 heavy hex structural bolt, 1 ASTM F436 standard round washer, ASTM A194, Gr. 2H, heavy hex nut, and direct tension indicator washer

Test assembly No. 3:
1-in. A490 heavy hex structural bolt, 1 ASTM F436 standard round washer, ASTM A194, Gr. 2H, heavy hex nut

ADDITIONAL DATA AND OBSERVATIONS—LABORATORY TEST

In laboratory Test Assembly No. 2, load indicator washers were installed on the bolt specimen (test specimen 2, 6, 7, 8, 11, 12). Load indicator washers were installed under the nut end in accordance with manufacturer's literature. The indicator protrusions were oriented toward the nut and were separated from the nut by a hardened washer. The nut was the turned element of the bolt assembly.

The load indicator gap was closely observed during the test sequence. It was reported that in all cases, the specified gap reading of 0.005 in. was reached at preloads slightly less than the 102.0-kip minimum. The indicator gap may have closed prematurely due to galling action on the washer protrusions. In most cases the hardened washer was observed to be turning against the indicator face of the washer thus damaging the protrusions. This apparent wearing down of the washer "bumps"

Table 1. Lab

Specimen No. 1–12, 13–18, 19–24

Specimen No.	Test Assembly No.	SNUG TIGHT Measured Torque (ft-lb.)	SNUG TIGHT Measured Bolt Tension (kips) (Skidmore-Wilhelm)	SNUG TIGHT Measured Bolt Tension (kips) (Ultrasonic Extensometer)	1/3 TURN Measured Torque (ft-lb.)	1/3 TURN Measured Bolt Tension (kips) (Skidmore-Wilhelm)	1/3 TURN Measured Bolt Tension (kips) (Ultrasonic Extensometer)	1/2 TURN Measured Torque (ft-lb.)	1/2 TURN Measured Bolt Tension (kips) (Skidmore-Wilhelm)	1/2 TURN Measured Bolt Tension (kips) (Ultrasonic Extensometer)
1	1	—	—	10.4	1,650	—	92.3	2,200	—	115.4
2	2	—	—	7.2	840	54.0	48.9	1,180	—	63.4
3	1	—	10.0	7.5	1,800	83.0	79.9	2,200	109.5	114.3
4	1	—	10.0	7.5	1,700	84.0	79.9	2,200	110.0	111.3
5	1	—	10.0	5.2	1,800	91.5	85.9	2,200	100.0	106.8
6	2	—	10.0	7.9	1,120	54.0	48.4	1,280	65.0	622
7	2	—	10.0	8.7	1,100	55.0	48.4	1,400	65.0	60.7
8	2	—	10.0	8.7	1,000	55.0	52.0	1,200	66.0	62.9
9	1	—	—	8.9	1,520	85.0	84.2	2,000	118.0	122.1
10	1	—	—	7.4	1,560	90.0	83.4	2,000	110.0	108.7
11	2	—	—	9.4	1,120	55.0	65.6	1,400	67.0	77.8
12	2	—	—	8.6	1,000	52.5	49.7	1,240	67.0	64.8
13	3	—	10.0	11.0	900	64.0	62.0	—	—	—
14	3	—	10.0	8.6	975	63.0	—	—	—	—
15	3	—	10.0	9.4	850	61.5	62.0	—	—	—
16	3	—	10.0	7.9	925	62.5	57.8	—	—	—
17	3	—	10.0	6.3	1,000	63.0	62.8	—	—	—
18	3	—	10.0	8.6	850	60.0	54.2	—	—	—
19	3	—	10.0	7.9	875	62.5	56.7	—	—	—
20	3	—	10.0	4.2	950	64.5	61.2	—	—	—
21	3	—	10.0	7.9	925	66.0	68.7	—	—	—
22	3	—	10.0	6.3	1,000	69.0	62.0	—	—	—
23	3	—	10.0	8.3	975	62.0	61.2	—	—	—
24	3	—	10.0	11.8	1,000	69.0	76.3	—	—	—

1 kip = 1,000 lb. = 454 kg, 1 ft-lb. = 1.356 N-M

Test Results

→ $3^1/_2$-in. ⎤
→ $2^3/_4$-in. ⎬ Bolt Grip
→ $3^1/_4$-in. ⎦

$^2/_3$ TURN			$^3/_4$ TURN			1 TURN			1 + TURN		
Measured Torque (ft-lb.)	Measured Bolt Tension (kips) (Skidmore-Wilhelm)	Measured Bolt Tension (kips) (Ultrasonic Extensometer)	Measured Torque (ft-lb.)	Measured Bolt Tension (kips) (Skidmore-Wilhelm)	Measured Bolt Tension (kips) (Ultrasonic Extensometer)	Measured Torque (ft-lb.)	Measured Bolt Tension (kips) (Skidmore-Wilhelm)	Measured Bolt Tension (kips) (Ultrasonic Extensometer)	Measured Torque (ft-lb.)	Measured Bolt Tension (kips) (Skidmore-Wilhelm)	Measured Bolt Tension (kips) (Ultrasonic Extensometer)
2,800	—	133.0	2,440	—	133.0	2,880	—	133.0	3,200	—	133.0
1,200	—	74.9	1,500	88.0	79.2	1,600	100.0	95.8	1,640	—	104.4
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
1,520	78.0	77.3	1,600	84.0	80.9	2,080	105.0	110.6	—	—	—
1,600	77.5	78.8	1,800	84.0	85.3	2,420	101.0	105.5	—	—	—
1,640	78.0	78.8	1,680	83.0	96.1	2,320	105.0	109.1	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
1,600	72.0	85.7	1,800	87.0	95.8	2,000	105.0	104.4	—	—	—
1,600	79.0	79.2	1,800	84.5	85.7	—	102.0	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
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—	—	—	—	—	—	—	—	—	—	—	—

by the spinning washer under the turned element appears to be treated in the manufacturer's literature by specifying a 0.005-in. gap in lieu of the standard .015-in. gap. It appears, however, that for the tested specimen the protrusion deterioration may have exceeded the manufacturer's estimates.

The load indicator gap completely closed at the following values of preload:

Test Specimen	Measured Bolt Preload (kips)
2	100.0
6	105.0
7	101.0
8	105.0
11	105.0
12	102.0

Although data was limited in quality and some abbreviations of data were caused by washer protrusion damage, the load indicator washers appeared to give consistent and reasonable indications of preload.

OBSERVED TORQUE-TENSION RELATIONSHIPS

The empirical equation often used to provide a relationship between torque and preload is as follows:

$$T = \frac{K \times D \times F_p}{12}$$

Where

T = torque (ft-lb.)
K = nut factor or torque coefficient
D = nominal bolt diameter, in.
F_p = bolt pre-tension, lbs.

or

$$T = \frac{K \times D \times F_p}{1{,}000}$$

Where

T = torque, Newton m
K = nut factor or torque coefficient
D = nominal bolt diameter, mm
F_p = bolt pre-tension, Newtons

The value of K was back-calculated using the data obtained from the bolt testing program. In a companion report entitled "A Field Problem with Preload of Large A490 Bolts," an extensive field testing program of bolts in actual jobsite connections was performed. Nut factors extrapolated from some of this test data are shown below (refer to the referenced report for specific details).

A summary of the histogram statistics appears in Table 2.

The nut factor K is affected by many variables at a connection. All the following conditions may affect the torque-tension relationship and their effects are included in the nut factor term:

1. Clamped material thickness and hardness
2. Washer thickness and hardness
3. Hole size
4. Perpendicularity of bolt to joint
5. Concentricality of bolt to hole
6. Thread fit
7. Surface roughness
8. Area of bearing surface
9. Lubrication of bolt threads
10. Relative resilience of fastener and joint material
11. Plastic deformation of bolt threads

An observation of test results will show that nut factors calculated for bolt assemblies in the Skidmore-Wilhelm device are consistently lower than for the bolt assemblies in actual field conditions. This observation remains true even when results of the laboratory test

Table 2. Nut Factor Tabulation

Specimen Description	Specimen Number	No. of Data Points	Incremental Rotation	Nut Factor		
				Mean	Standard Deviation	Range
Lab Test: 1 in. dia. A490	13–24	12	1/3 turn	.176	.009	.166 .190
Lab Test: $1^1/_4$-in. dia. A490	1,3–5,9,10	6	1/3 turn	.189	.021	.166 .216
		6	1/2 turn	.182	.012	.163 .198
Field Test: 1 in. & $1^1/_4$-in. dia. A490	——	44	1/3 turn	.262	.056	.170 .438

specimens are compared with field test results of bolts in standard size holes with thick hardened washers. The Skidmore-Wilhelm device with its parallel surfaces and constant surface finish cuts down on the number of joint variables, thus reducing both the magnitude and range of the nut factor values.

The actual field joints, with more variables to contend with, have *K* factors with both higher values and broader range. Based on these observations, it appears most prudent to determine job inspecting torques using the actual joint assembly—procedures using the Skidmore-Wilhelm Tension Indicator device as currently outlined in the code appear to be non-conservative and may result in undertightened bolts.

CONCLUSION

In Sect. 6 of the *Specification for Structural Joints Using ASTM A325 or A490 Bolts,* specific requirements are outlined for conducting bolt inspections. The torque wrench is the basis of the recommendations. Specifically, the procedure attempts to simulate the field connection in a Skidmore-Wilhelm direct tension indicating device, and then determines an acceptable lower bound torque value associated with the minimum required pretension. In the bolt testing program as conducted, several calibration studies were performed which related to Skidmore-Wilhelm measured values, ultrasonic extensometer values, turn-of-the-nut incremental values and load-indicator washer deformations. Based on these test results, the inspection procedure as defined in the specification may be non-conservative. There was found to be significant variation between the torque/tension values in actual field connections and the Skidmore-Wilhelm device simulated field connection. The torques measured by the specified job-inspecting torque procedure were consistently less than those required in the actual field conditions. The rigid face plate on the Skidmore-Wilhelm device does not adequately model the actual joint conditions consisting of several non-planar element plies with irregular hole preparations. Of equal concern, bolt manufacturers should be cautioned against furnishing suggested torque values for bolt tightening to erectors. Manufacturer's suggested torque data as reviewed by the author was found to be very non-conservative.

Based on an observation of the torque value correlations as studied in the test, one can quickly see why torque control has been a vigoriously debated topic. Perhaps some commonly acceptable form of ultrasonic testing procedure could be developed to replace the code allowed torque control inspection procedure; or perhaps in lieu of using the Skidmore-Wilhelm device, the actual field connections with tensions measured using the ultrasonic extensometer device could be used to define job inspecting torques. Torque values would then be correlated to such a degree that the torque wrench could serve an important function.

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