

# The Torque-Tension Relationship Gets STRETCHED

by Christopher Bunai

**Most fasteners are tightened using traditional methods, such as manual torque wrenching, pneumatic impact wrenching, or automatic torque cutoff tools.**

As a result of this trend, a common question from many engineers, mechanics, maintenance personnel and assemblers is: "How much torque do I need to install this fastener?" The best, but perhaps not very helpful, answer is: "Whatever amount of torque is needed to develop the proper tension."

The problem with this response is that under most circumstances, the ability to measure tension is not available. What has traditionally been available, however, are torque wrenches, and thus the ability to measure torque.

Attempting to answer this question leads us to the torque-tension relationship and a brief explanation of how torque and tension relate. Torque is the *rotational force* used to turn the nut or fastener head in a bolted joint. As torque is applied to the nut, it attempts to climb up the threads of the bolt reducing the grip length; however, when the components within the grip resist, the bolt is forced to stretch. As the bolt elongates, it behaves like a spring and develops *tension*, also known as preload. The tension developed within the bolt has an equal and opposite reaction[1] on the bolted components, which creates the all-important clamp force, the compressive force holding the bolted joint members together.

When installing a bolt, a common practice is to find a torque table and look up the torque value listed by size, thread, grade, plating, presence or absence of lubrication, and other various properties of the bolt being used. An abbreviated torque table example is shown in Figure 1. As an example, we will use a 1/2″-13 SAE Grade 5 Zinc Dichromate bolt. For our bolt sample, this table recommends an installation torque of 75 ft. lbs. Where does this value come from?

The torque value is actually a calculated quantity from the short form torque-preload equation. Bickford (1995) states the equation as, $T = K \cdot F \cdot D$, where T, K, F, and D are the input torque, the "nut factor," the achieved preload, and bolt's nominal diameter, respectively (Bickford, 1995, p. 226).

The nut factor is an empirical value that linearly models the rate at which tension is developed within a fastener when torque is applied. The nut factor conveniently describes all of the many variables that are known to influence the torque-tension relationship. Properties affecting this relationship include: the material and size of the bolt, nut and washer, type of plating, surface finish, corrosion and wear on threads, presence and type of thread lubricant, and the number of times the bolt has been previously fastened, to just name a few.

For a more in-depth look at the use of the short form torque preload equation, a well presented discussion can be found in the article "Dissecting the Nut Factor" written by Dave Archer.

Ideally, the desired preload should be known and based on the bolted joint requirements as well as bolt strength limitations. As a note, many torque charts like the one shown earlier use a standard value of 75 percent of the bolt's proof load. The desired preload can then be used within this equation along with the experimentally determined nut factor. In our example, a 1/2″-13 SAE Grade 5 bolt has a proof load of approximately 12,000 lbs., and 75 percent of this is 9,000 lbs. Clearly, the bolt's nominal diameter is the easiest piece of information to determine and is conveniently specified in inches for this case first. The product of these variables result in an input torque value with units of in. lbs., although the equation can be divided by 12 to convert to ft. lbs. As can be seen from the equation below, we are able to produce the value of

| | | SAE Grade 5 | | |
|---|---|---|---|---|
| | | Torque Values in ft. lbs. | | |
| Bolt Diameter | Threads per inch | K = 0.15 | K = 0.2 | K = 0.25 |
| 7/16" | 14 | 37 | 50 | 62 |
| 1/2" | 13 | 56 | 75 | 94 |
| 9/16" | 12 | 82 | 109 | 136 |

**Figure 1.** Abbreviated Torque Chart Example
The torque calculations in this chart are provided as a guide only. Due to the many factors that affect the torque-tension relationship, such as material, surface finish, lubrication, etc., the torque-tension relationship should be established experimentally. Use at your own risk.

[1]Usually, but not always. See p. 182 of Bickford for more information on the exceptions.

75 ft. lbs. shown in the provided torque chart.

$$T = K \cdot F \cdot D = (0.2) \cdot (9{,}000 \text{ lbs.}) \cdot (0.5 \text{ in.}) = 900 \text{ in. lbs.} \cdot \left(\frac{1 \text{ ft.}}{12 \text{ in.}}\right) = 75 \text{ ft. lbs.}$$

So where is the problem? The quick answer is the nut factor, K, can vary. One thing you may notice about any published torque chart is a disclaimer that reads something like "*The torque calculations in this chart are provided as a guide only. Due to the many factors that affect the torque- tension relationship, such as material, surface finish, lubrication, etc., the torque- tension relationship should be established experimentally. Use at your own risk.*" This disclaimer is there for a reason: The nut factor not only varies between sizes, materials and finishes; it can vary between identically specified bolts. It can even vary for the same bolt!

The nut factor utilized, either from the charts or experimentally developed, should be based on a statistical sample. The sample mean and standard deviation can then be calculated. Using the mean and three standard deviations justifies the likelihood that the nut factor can easily vary between the values shown in the graph. This range of $0.15<K<0.28$ applies for normal conditions. This does not include the factors that could drastically change the torque-tension relationship, such as poor or damaged thread geometry, the use of a lubricant without knowing its effect on the nut factor, or irregular embedment of the underside face of the bolt into a soft washer, etc. If any of these conditions occur, the nut factor could range as high as 0.5 or as low as 0.1. The effect of the dramatic nut factor variation is shown by the "Over Lubricated" and "Excessive Friction" lines in Figure 2. It can be seen that using the recommended value of 75 ft. lbs. on the over-lubricated bolt would cause the yield strength of the bolt to be exceeded. In the case of the bolt experiencing excessive friction, the developed preload would be approximately 3,500 lbs., only 38 percent of the desired value.

Remember that the installer is intentionally keeping torque relatively constant during installation, and it can be seen that the vitally important fastener tension varies when the nut factor varies! Other than the potentially misleading "click" of a torque wrench, the bolt installer has little to no feedback that tension has been under, over, or properly developed. To be fair, fracture of the bolt would be noticeable feedback if the ultimate tensile strength were exceeded in the under-lubricated case or the ultimate shear strength were exceeded in the excessive friction case.

Referring back to Figure 2, the yellow area represents a standard torque wrench with an accuracy of +/-3 percent that can only reliably tighten a group of bolts to +/-30 percent of desired tension (Bickford, 1995, p. 222). At this point, it is worth noting that a more accurate torque wrench does not improve this discrepancy significantly. The red box is shown with a very narrow band on the installation torque axis, implying accurate installation torque monitoring. However, it also shows large variation in the developed tension axis under irregular, but plausible and potentially catastrophic, conditions.

So what is the solution? Stress Indicators, Inc. recommends side stepping error-prone torque completely and going straight to the source: tension. If tension measurement is available, measurement of torque is unnecessary and irrelevant. We advocate controlling tension while letting the torque vary. The green region in Figure 2 represents the predictable scatter area in which SmartBolts® perform. It is shown that SmartBolts® only respond to developed tension within the fastener and are immune to variations in applied torque.

The greatest advantage of measuring tension is joint security and confidence that the bolts are "doing their job." Monitoring bolted joint security becomes especially necessary in safety and economically critical bolted joints.

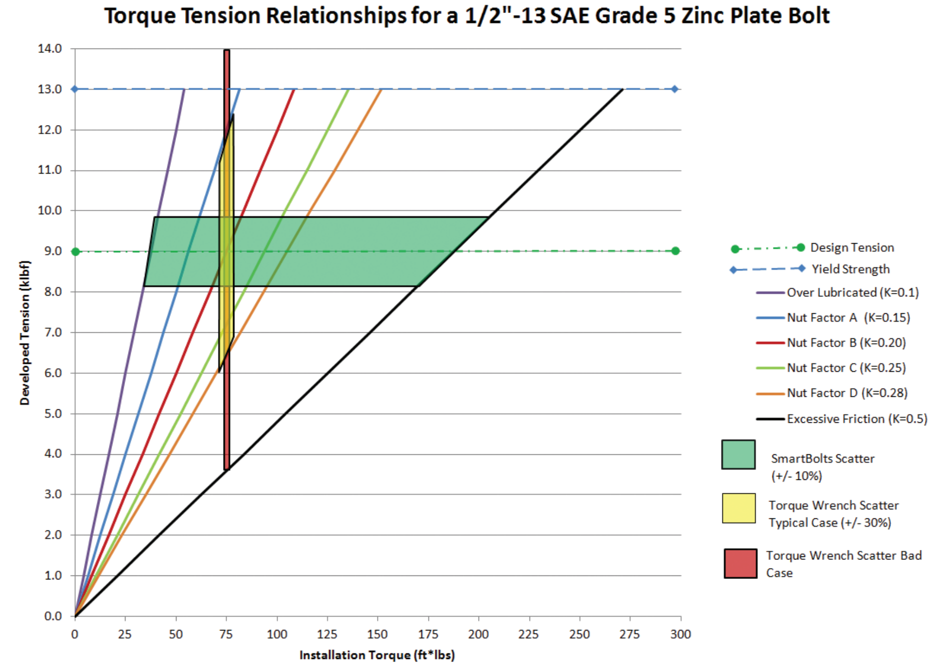


**Figure 2.** Torque-Tension Relationship illustrating the effect of varying nut factors on SmartBolts® and torque wrenches.

## KEY CONCLUSIONS FROM FIGURE 2

- When bolted joint security needs to be ensured, controlling the variation on the developed tension axis supersedes the need for accurate control of installation torque.
- The variation of the nut factor significantly affects the torque-tension relationship, thus impacting the ability to create the desired preload reliably using torque control methods.
- The accuracy of SmartBolts® Indicating Design Tension, shown in the green region, is not a function of torque or the nut factor.

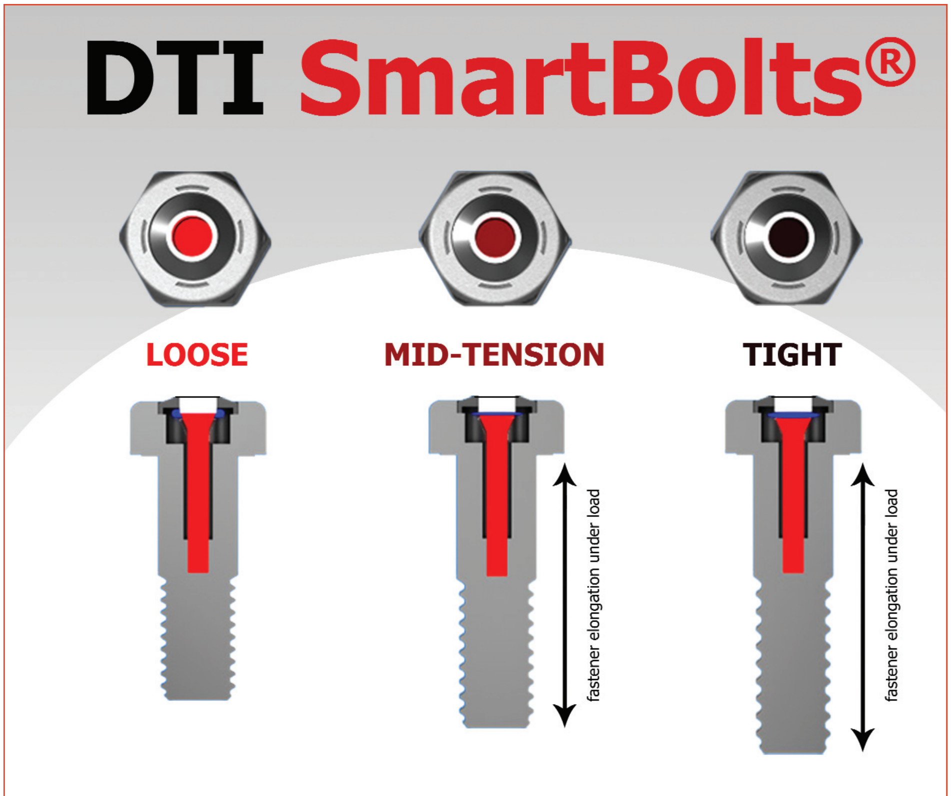


**Figure 3.** SmartBolts® provide visual indication of tension.

## SMARTBOLTS® PROVIDE VISUAL INDICATION OF TENSION

Direct Tension Indicating (DTI) SmartBolts®, manufactured by Stress Indicators, Inc., are specialty fasteners with a built-in visual indicator that shows the developed tension as the bolt is installed. The indicator gradually darkens from bright red to black as the fastener is properly tightened (see Figure 3).

SmartBolts®' unique microindicator technology utilizes the most accurate principle for tension measurement—actual fastener elongation under load. As the bolt is stretched elastically, the minute displacement of the gage pin allows the microindicator to create the completely reversible color change. The indicator system continuously monitors bolt tension and ensures proper preload at installation as well as in service.

Visit www.SmartBolts.com to learn more about Stress Indicators, Inc.'s products. If you currently have a specific application in mind for DTI SmartBolts®, there is an Application Qualifier Form at www.smartbolts.com/aq. ■

## REFERENCES

Bickford, J.H. (1995). *An introduction to the design and behavior of bolted joints* (3rd ed.). New York, NY: Taylor & Francis Group

## CHRIS BUNAI

Chris Bunai is chief engineer at Stress Indicators, Inc., a privately owned engineering and manufacturing company based in Gaithersburg, Maryland. He holds a degree in Mechanical Engineering from the University of Maryland College Park and is a member of ASME.