PCB PIEZOTRONICS

UNDERSTANDING TORQUE-ANGLE SIGNATURES OF BOLTED JOINTS

THREADED FASTENER TORQUE-ANGLE CURVE ANALYSIS

Understanding Torque-Angle Signatures of Bolted Joints
Threaded Fastener Torque-Angle Curve Analysis

Torque-angle curve analysis is known to be one of the most basic and practical methods of determining not only what the fastener went through during the tightening process, but also the integrity of the joint itself. The ability to interpret the resulting signature of the tightening path gives an understanding of the installation, and in some cases the failure characteristics of a bolted joint.

The following sections will describe the various tightening zones of the torque-angle signature, analysis of the curve, tightening strategies using torque and angle specifications, and joint auditing methods utilizing torque-angle analysis.

Tightening Basics

Torque is applied to a threaded fastener in order to stretch the bolt while compressing the clamped parts. This compression of the clamped is known as the preload or clamp load. Prior to the assembly going into service the bolt stretch (tension) is equal to the clamp load.
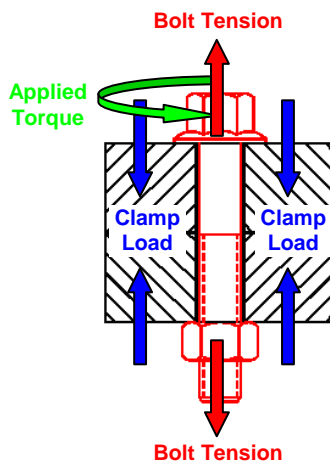

Figure 1: *Fastener Loads During Tightening*

Note: A properly designed joint will attain enough clamp load with the specified installation torque to overcome any projected working loads the joint will see in service and thus keep the assembly together

When applying torque to a fastener there will obviously be some resistance due to the friction effects in the bearing and threaded regions. If the resistance is great enough the bolt (or nut) will not turn and either the proper preload will not be attained or a joint failure will occur (due to torsional stresses or a cross-

threading situation). To insure that fastener movement occurs both the input torque and angular displacement of the fastener are monitored. Plotting torque in terms of angle of turn results in the torque-angle curve.
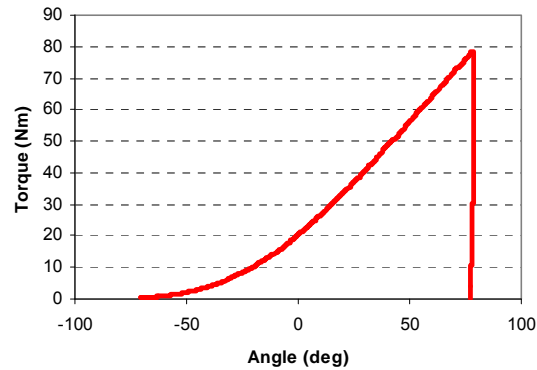

Figure 2: *Torque-Angle Curve*

Torque: The amount of energy applied to a bolt or nut.

Angle: The amount angular displacement of a bolt or nut.
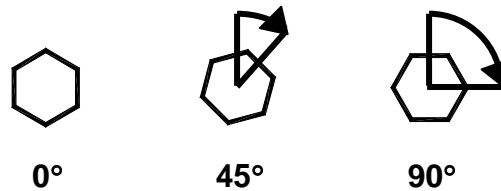

0°   45°   90°

Figure 3: *Angular Displacement*

Tightening Zones of the Torque-Angle Curve

When studying the torque-angle signature there are four distinctive zones that need to be identified. The four zones are:

- Rundown/Prevailing
- Alignment
- Elastic Clamping
- Post Yield

Each zone has its own characteristics regarding the effects on the joint as well as the look of the curve.

Rundown/Prevailing Zone

The Rundown/Prevailing zone occurs at the beginning of the tightening process (assuming the assembly is loose prior to tightening). In this zone the clamp load is zero and the only resistance is due to friction in the threaded region. This zone is prior to the bolt/nut touching the bearing surface.

The Rundown/Prevailing zone features any of the thread forming or thread locking processes that occur during the rundown. For non-prevailing nuts or assemblies with clean and tapped threads this zone will appear as a line overlapping the angle axis at a zero torque level.
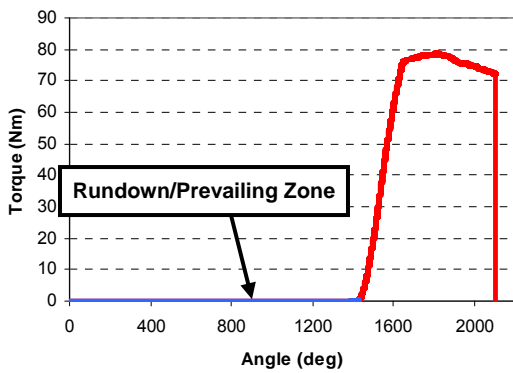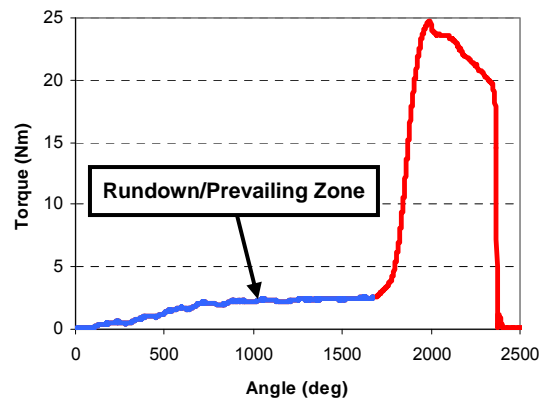
Figure 4: *Rundown with No Prevailing Torque*
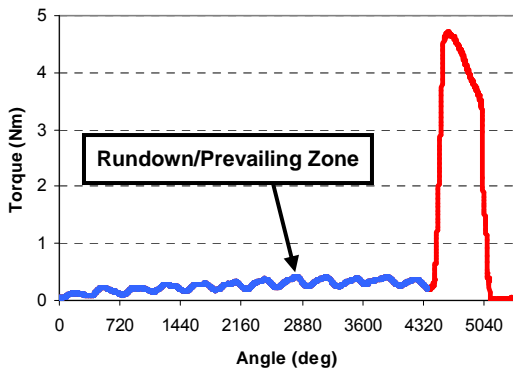
Figure 5: *Rundown with Locking Feature*

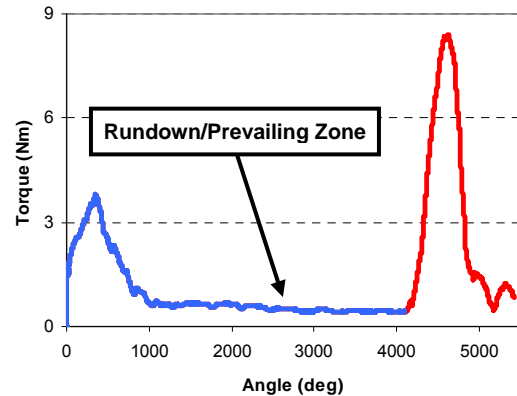**Figure 6**: *Rundown with Thread Forming*

Figure 7: *Rundown with Break Through Torque*

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Alignment Zone

The Alignment zone occurs at the end of the Rundown/Prevailing zone. In this zone the clamp load begins to increase but not at the same rate as the bolt tension. This causes the zone to appear nonlinear on the curve and makes this zone undesirable for any reference points such as a threshold for angle or especially a final installation torque.

This zone is very dependent on the stiffness of the joint. Typically hard joints will have a smaller alignment zone than softer joints.
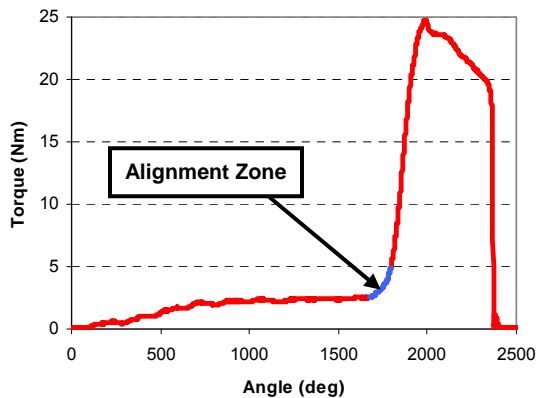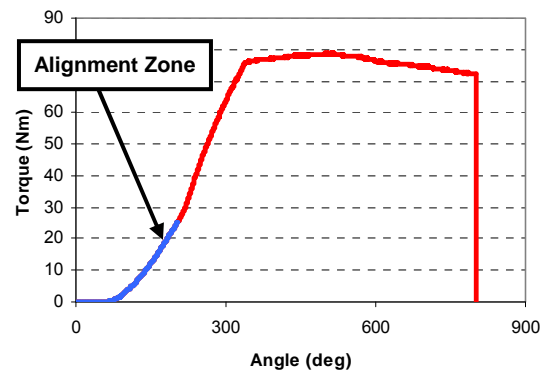
Figure 8: *Small Alignment Zone*   **Figure 9**: *Large Alignment Zone*

The Alignment zone represents the portion of the curve where the mating parts and the fastener come together and start to deform. This zone is a complex mixture of both macro and micro effect including:

Macro Effects
- Drawing Together of Mating Threads
- Bending Together of Mating Parts
- Fastener Bending as a Result of Non-Parallelism of the Bearing Surfaces

Micro Effects
- Contact Stress Deflections of Plating
- Surface Roughness
- Thread Deformations

The further the fastener is tightened through the Alignment zone the closer the assembly gets to deforming as a single entity with the fastener.

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Elastic Clamping Zone

The Elastic Clamping zone occurs at the end of the Alignment zone. In this zone the clamp load increases at the same rate as the bolt tension. This causes the zone to appear linear on the curve. In this zone the most consistent relationship can be found between torque, clamp load, and angular displacement.
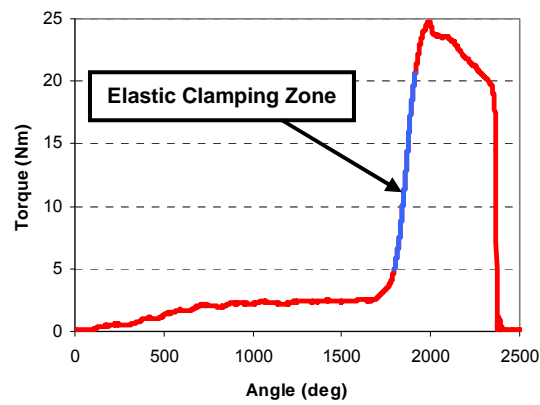

Figure 10: *Elastic Clamping Zone*

<u>Note</u>: Due to the linearity of this zone it is the only zone on the torque-angle curve where the basic tightening (K-Factor) and friction calculations are valid.

Any angle reference points should be made in this region, and angle measurements will be most consistent in this zone.
Most torque specifications are made in this region in order to prevent any permanent deformation of either the clamping parts or the fastener.

The slope of the Elastic Clamping zone is a function of the stiffness of the assembly (combination of fastener and clamped parts) and the friction in the thread and bearing areas. A change in either of these will affect the slope of this zone.

Harder joints will typically have a steeper slope than softer joints, and joints with higher friction will have steeper slopes than those with lower friction.
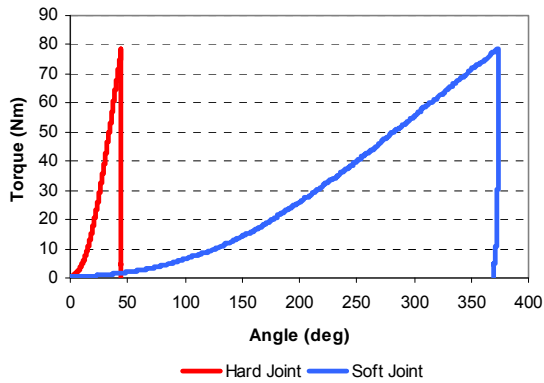

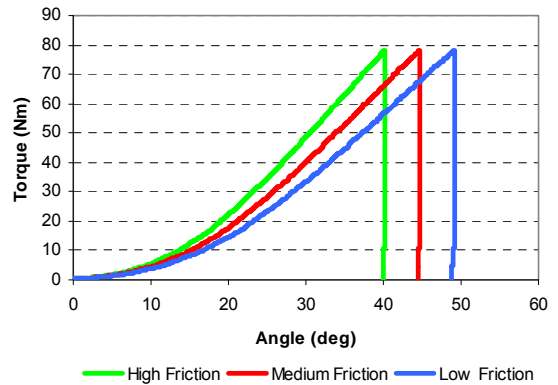**Figure 11**: *Hard and Soft Joint Curves*

Figure 12: *Frictional Effects*

Stiffness changes will have a larger effect on the slope than the frictional changes.

Note: Frictional changes will alter the slope only when joint stiffness remains constant.

The following figure shows how change in both the stiffness and underhead friction coefficient can alter the slope of the linear portion of the curve.
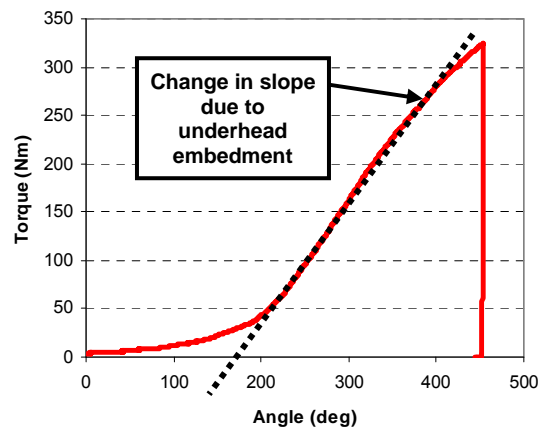

Figure 13: *Underhead Embedment*

Underhead embedment is a slight crushing of the bearing surface in the clamped parts. This is not a yielding of the bolt, and thus it is important to understand the service loading of the joint. Often embedment is a desired effect in order to help prevent slipping due to transverse loading.

Post Yield Zone

The Post Yield zone occurs at the end of the Elastic Clamping zone. In this zone permanent deformation has occurred in either the fastener or clamped parts causing a change of slope of the torque-angle curve. Depending on the elasticity of the joint this zone will vary in size prior to ultimate failure (bolt breaking, thread strip, or parts crushing).
This zone begins when the slope of the curve decreases from the Elastic Clamping zone. If tightened far enough into this zone a peak torque will be reached and additional loading will cause the joint to fail.

It is possible to determine the failure mode of the bolted joint by studying the Post Yield zone of the torque-angle curve.

The failure mode of the fastener breaking is evident by the curve demonstrating a vertical drop after the peak torque value followed by a flat line along the zero torque axis.
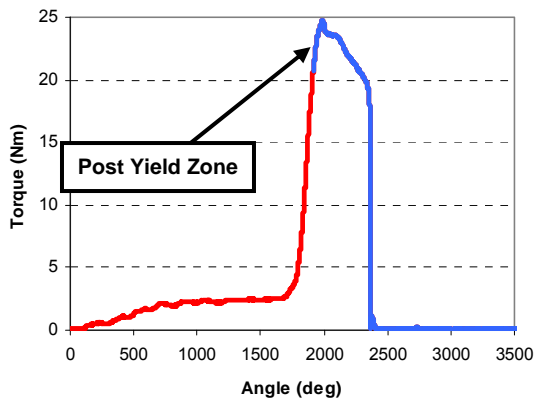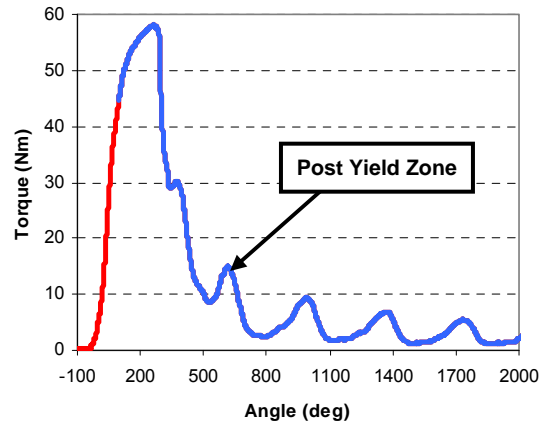
Figure 14: *Bolt Breaking Failure*

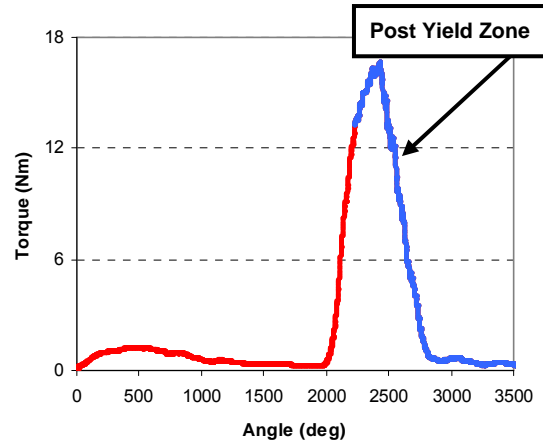**Figure 15**: *Thread Strip Failure*

Figure 16: *Thread Strip Failure*

On a thread strip failure the decrease in torque will not typically be a vertical drop after the peak torque. A steep downward slope can occur along with the torque value not going to zero. Often times a cyclical wavelike form will be present as in Figure 15.
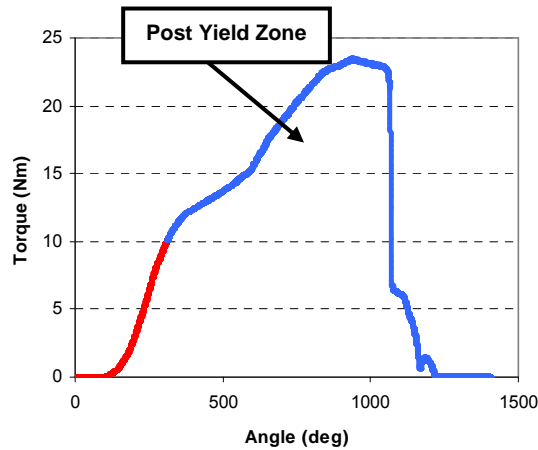

Figure 17: *Clamp Parts Crushed w/ Bolt Breaking Failure*

Figure 17 shows the curve increasing in slope after the initial yielding. This represents that the clamped parts crushed but eventually stabilized to have another elastic clamping range with a new joint stiffness (different slopes in the two elastic zones). Eventually the bolt yields and breaks.

Note: Depending on the joint, even entering this region will consider the joint failed.

Analysis of the Torque-Angle Curve

Within the four tightening zones there are four critical points that need to be identified. These points include:

- Max Drive/Prevailing Torque
- Seating Torque
- Yield Torque
- Ultimate Torque

These torque points are used to determine if the installation torque is at a desired location on the curve. These points are typically found by torque to failure testing on actual assemblies.

Max Drive/Prevailing Torque

The Max Drive/Prevailing torque value represents the maximum torque value located within the Rundown/Prevailing zone of the torque-angle curve.
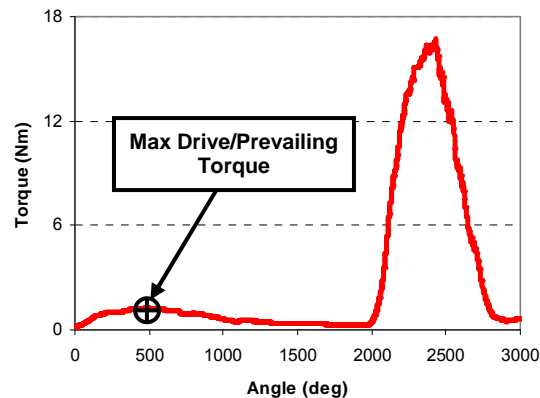

Figure 18: *Max Drive/Prevailing Torque*

This torque value represents the maximum torque effects of any thread forming or thread locking process. The occurrence of the max drive torque can happen anywhere within the Rundown/Alignment zone depending on the joint being analyzed.

This torque value is necessary in establishing an acceptable installation torque window.

Note: An installation torque that is lower than the Max Drive/Prevailing torque value would result in zero clamp load in the bolted joint.

Seating Torque

The Seating torque value represents the beginning of the Elastic Clamping zone. It is the torque at which the fastener is fully seated and where the fastener and clamped parts are deforming as one.
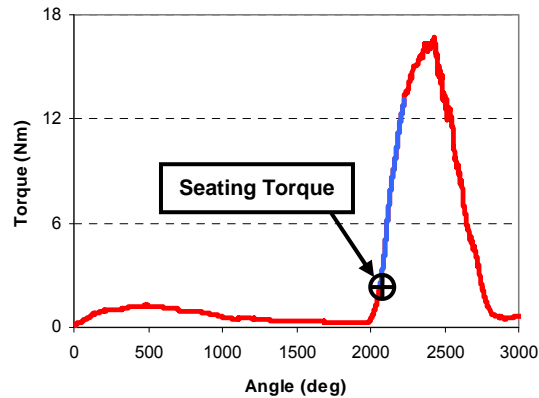

Figure 19: *Seating Torque*

If a line is drawn tangent to the linear portion of the curve, the Seating torque will be located at the point where the tangent and the curve first bisect.

Note: An installation torque that is lower than the Seating torque value would result in a low clamp load and inconsistent load from part to part.

Yield Torque

The Yield torque value represents the end of the Elastic Clamping zone. It is the torque at which the fastened assembly will stop returning to its original shape if loosened.
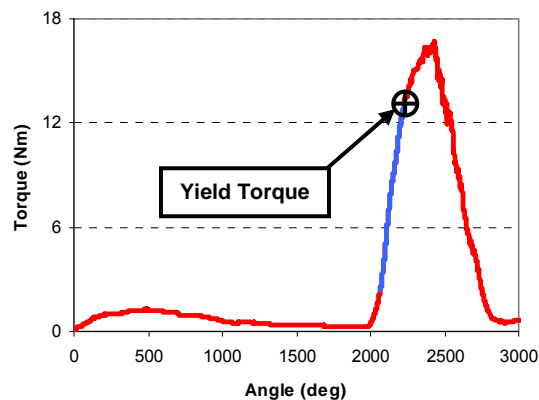

Figure 20: *Yield Torque*

This point represents the end of the consistent relationship between torque, clamp load and angle. The Yield torque represents the beginning of either the bolt yielding, parts permanently crushing, or the threads beginning to strip.

If a line is drawn tangent to the linear portion of the curve, the Yield torque will be located at the point where the slope of the curve becomes less than the tangent.

Note: An installation torque that is greater than the Yield torque value may result in the assembly failing when the joint is put into service.

Note: Some bolted joints are intentionally tightened past the Yield torque in order to insure a minimum clamping load is attained.

Ultimate Torque

The Ultimate torque value represents the maximum torque that the joint can handle prior to the bolt breaking, clamp parts crushing completely or cracking, or the threads stripping
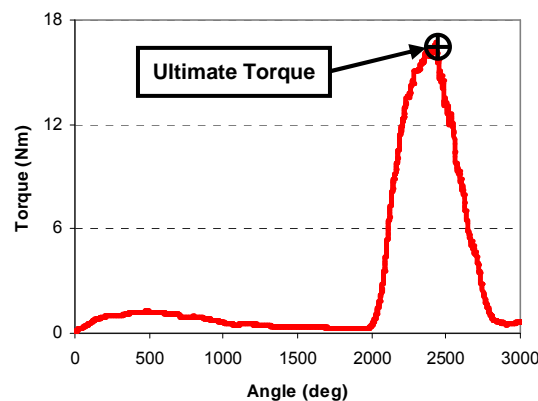

Figure 21: *Ultimate Torque*

The Ultimate torque value is located at the maximum torque value on the curve.

Note: An installation torque that is greater than the Ultimate torque value will result in the assembly failing during installation.

Determining Tightening Specifications

The previously mentioned torque points are measured in order to determine a installation torque value that will insure that the joint is fully seated and not in a yielded state. Failure testing will be performed on actual assemblies (typically of lots of 6 to 30 samples) in order to obtain a distribution of each of the four points. The ±3 sigma values for each point will be calculated and compared to determine an acceptable torque window for the bolted assembly.

The following will describe the procedure.

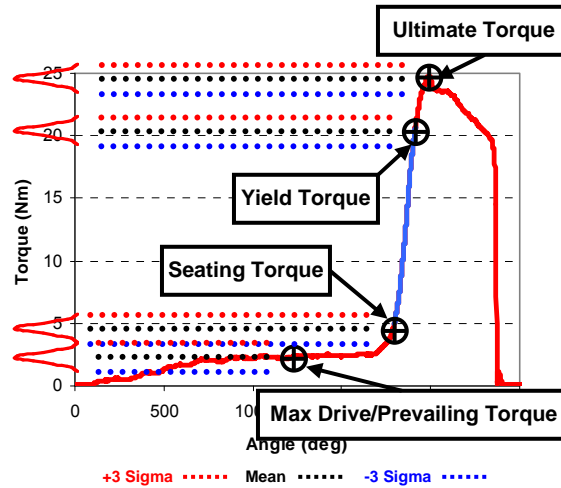1. Determine the ±3 sigma values of each of the four points.

Figure 22: *Measured Torque Values*

2. Establish a torque window between the –3 sigma yield torque value and +3 sigma max drive or seating torque. The larger of the two values should be picked.
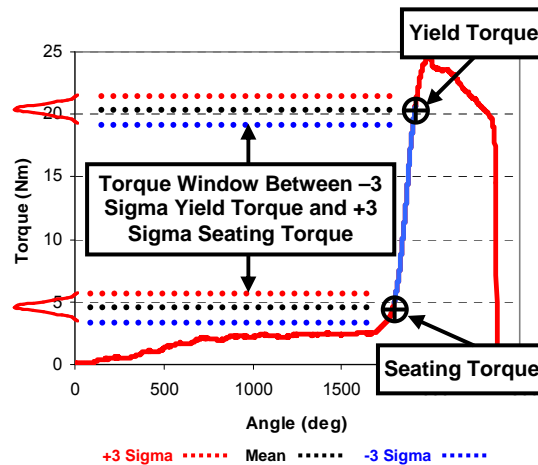

Figure 23: *Torque Window Using Seating Torque*

The following figure shows a torque window being made using the max drive/prevailing torque value as the minimum torque limit.
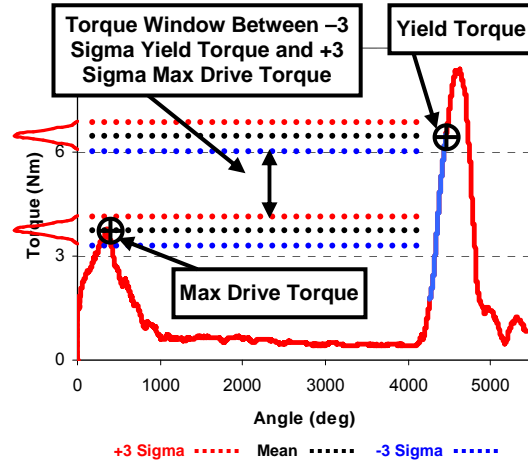

Figure 24: *Torque Window Using Max Drive Torque*

Once a torque window is established, select a torque value at the upper end of the range. The +3 sigma value should not be used because tools tend to overshoot the programmed or set torque shut-off due to momentum, signal response time, and/or tool capability. Typically 80-90% of the +3 sigma torque value will be set as the torque specification depending on tool capability.

Note: The method described above assumes that the proper bolt size is being used to keep the assembly together. Bolted joints should be designed with a minimum required clamp load in mind to prevent joint failure.

Conclusion

Quite a lot can be learned about the installation of a bolted joint by observing its torque-angle signature. An understanding of the type of joint, failure mode, or if the bolted assembly is in a yielded state can be determined. Torque-angle signature analysis proves to be an inexpensive yet very effective method to understand bolted joint issues and should always be considered for a preliminary study.

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