Bolted Joints, Often Looser than Expected!

Q1

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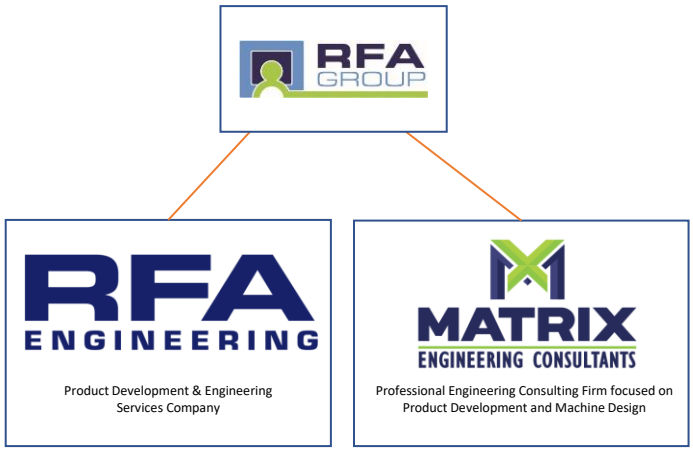

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Q2

2

Broad Product Development Experience

Industries and clients that embrace engineering rigor!

Q3

3

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Q4

4

Primary Bolted Joint Application Types

Structural Bolted Joints

Pressure Boundary Bolted Joints

Mechanical Bolted Joints

Its often said that ~90% of all fastener failures result from bad design or improper installation.

5

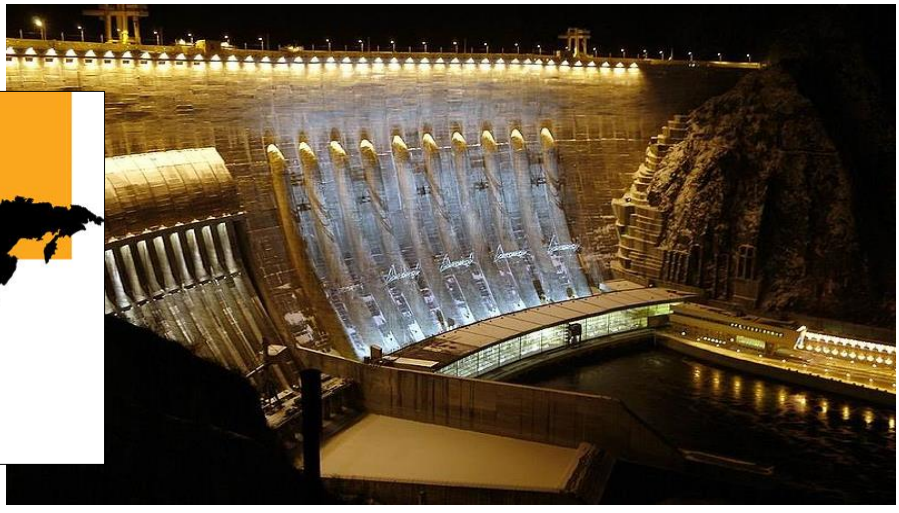
Bolted Joints, Often Looser than Expected

- **Tightening – Looser than Expected**
  - Torque Control Tightening
  - Torque Control plus Angle Monitoring
  - Common Issues During Tightening
    - Demonstration of Preload Scatter
- **Unintended Loosening**
  - Relaxation
  - Self-Loosening

6

Bolted Joint Failure

Sayano-Shushenskaya Hydroelectric
Power Station Accident
17 August 2009



BOLT

Q7G7

7

Bolted Joint Failures

Sayano-Shushenskaya Hydroelectric
Power Station Accident

BOLT SCIENCE

Q8G8

8

Bolted Joint Failures

Sayano-Shushenskaya Hydroelectric Power Station Accident

The bolts securing turbine 2 failed resulting in the turbine being lifted up.

BOLT

Q9

9

Bolted Joint Failures

Sayano-Shushenskaya Hydroelectric Power Station Accident

According to an eye witness: ‘The unit of 1650 tons flew up like a champagne cork’.

BOLT

Q10

10

Bolted Joint Failures

Sayano-Shushenskaya Hydroelectric Power Station Accident

75 people died as a result of the accident.

Q11

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Bolted Joint Failures

Sayano-Shushenskaya Hydroelectric Power Station Accident

The official report states that the accident was primarily caused;

- Excessive vibration of turbine 2 led to fatigue damage of the mountings of turbine 2, including the turbine cover.
- It was also found that at the moment of the accident, at least six nuts were missing from the bolts securing the turbine cover.
  - **Unofficial reports also pointed to improper tools and training.**

The official report about Sayano-Shushenskaya hydro accident was published by the Federal Environmental, Technological and Atomic Supervisory Service on 4 October 2009. However, later the report and the press release on the report were removed from the website.

Q12

12

Bolted Joint Failures

Electrical Arcing and Fire
South West Trains - Carriage

- A 10-carriage train had just left a station when a small explosion under the sixth carriage occurred.
- This was followed by about 22 seconds of severe electrical arcing under the train.
- Shortly afterward, circuit breakers operated, immobilizing the train.

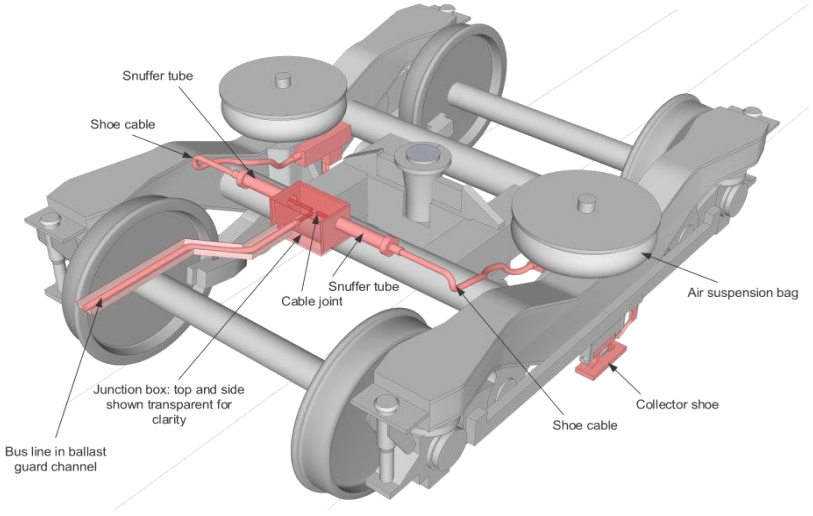
Electrical arcing and fire under a Train
Windsor & Eton Riverside
30 January 2015

13

Bolted Joint Failures

Electrical Arcing and Fire
South West Trains - Carriage

Electricity is picked up from the rail to drive the train.

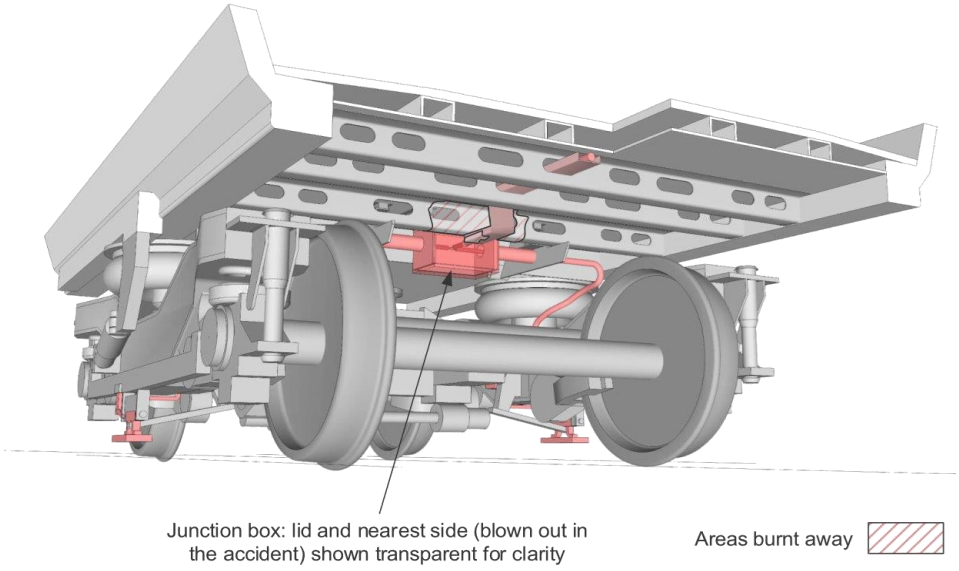


A subsequent investigation showed that the arcing had come from a junction box under the train. (It is shown here undamaged.)

14

Bolted Joint Failures

Electrical Arcing and Fire
South West Trains - Carriage



Q15

15

Bolted Joint Failures

Electrical Arcing and Fire
South West Trains - Carriage

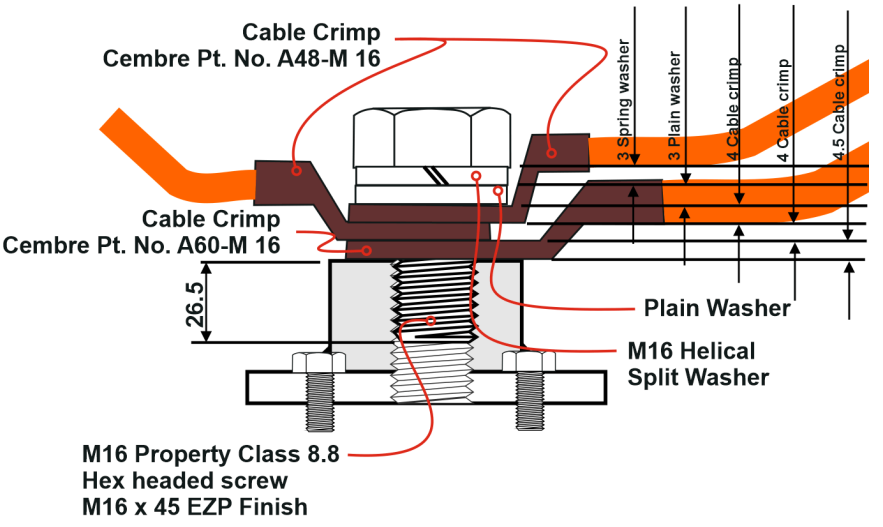
It was estimated that the arcing resulted in heat being released in the order of 32 megajoules, this is equivalent to the energy released from an explosion of 8 kilos of TNT.

Q16

16

Bolted Joint Failures

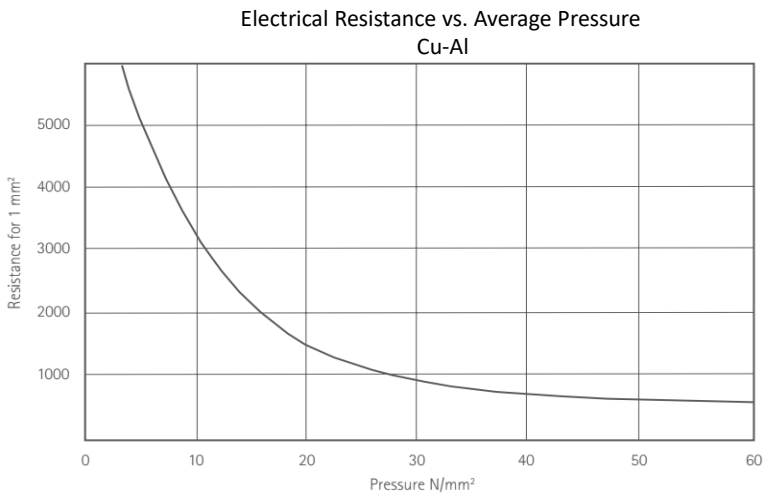
Electrical Arcing and Fire
South West Trains - Carriage

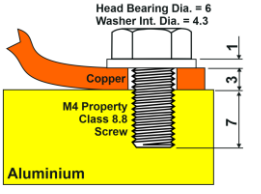


Q17

17

Electrical Resistance and Surface Pressure





- The electrical resistance across an electrical joint is dependent on the average surface pressure at the joint interface.
- If the bolt is loose or not tightened, the resistance increases.

Q18

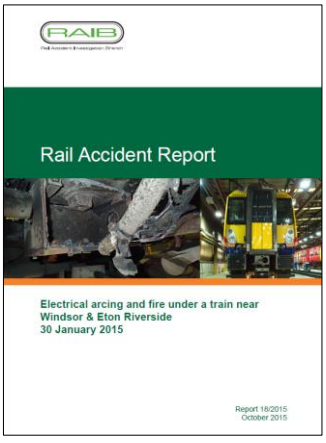
18

Bolted Joint Failures

Electrical Arcing and Fire
South West Trains - Carriage

The report states that the primary causes of the failure.

- Low clamp load resulted in a ‘hot-joint’
  - **Large amount of relaxation in the joint.**
  - **Lack of proper preventative maintenance.**



Q19

19

Bolted Joint Failures

Wheel Detachment – Chatsworth Freeway

Q20

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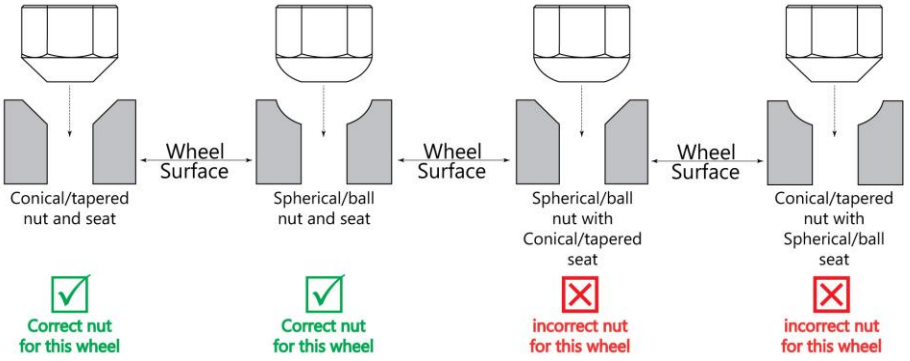
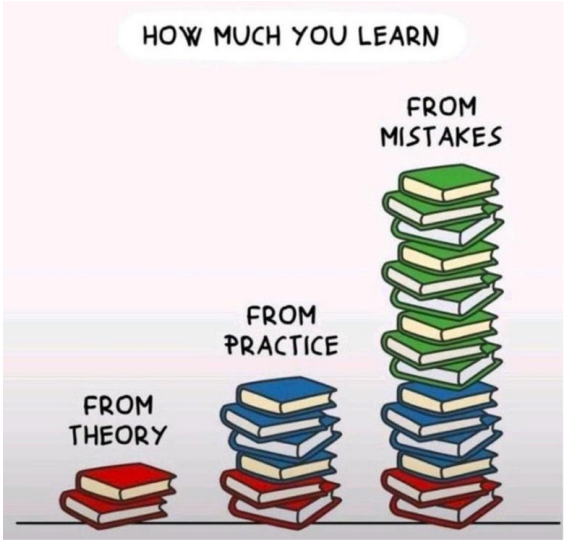
Detachments Cause – Incorrect Lug Nut Used

The suspected cause of the failure was the lug nut not matched to the rim.



21

Bolted Joints – More to it Than You May Have Thought!



22

Bolted Joints, Often Looser than Expected!

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23

Tightening - Looser than Expected

Topics to be Covered:

- Explain Why Threaded Fasteners are Tightened?
- Tightening Methods
  - Torque Control Tightening
  - Torque Control and Angle Monitoring during Tightening
- Common Issues During Tightening
  - Hands-On Learning - Preload Scatter

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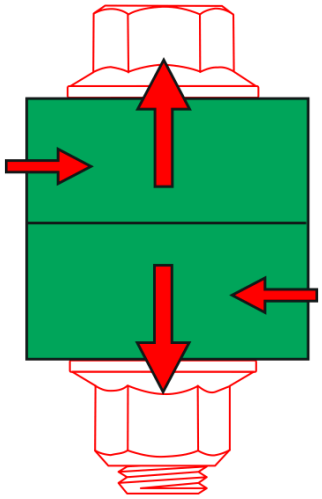
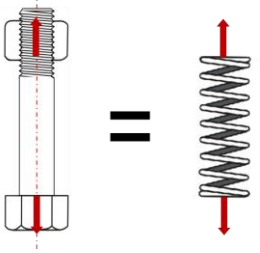
Why Threaded Fasteners Are Tightened

- The reason for tightening the bolt is to develop preload in the bolt and clamp load in the joint interface so that the joint is able to resist the applied loads without the joint plates moving relative to each other.
  - The preload in the bolt prevents resists joint opening.
  - The clamp load and friction in the joint interface resists joint slip.

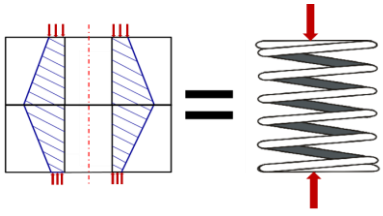


25

The Bolt and Joint Behave as Springs



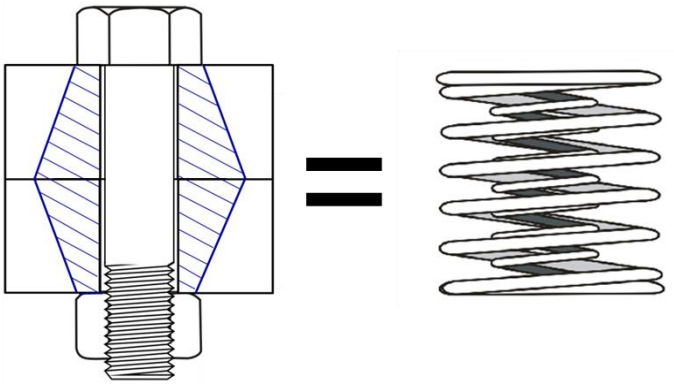
A bolt acts like a **tension** spring when it is tensioned.



The joint acts like a **compression** spring when it is compressed.

26

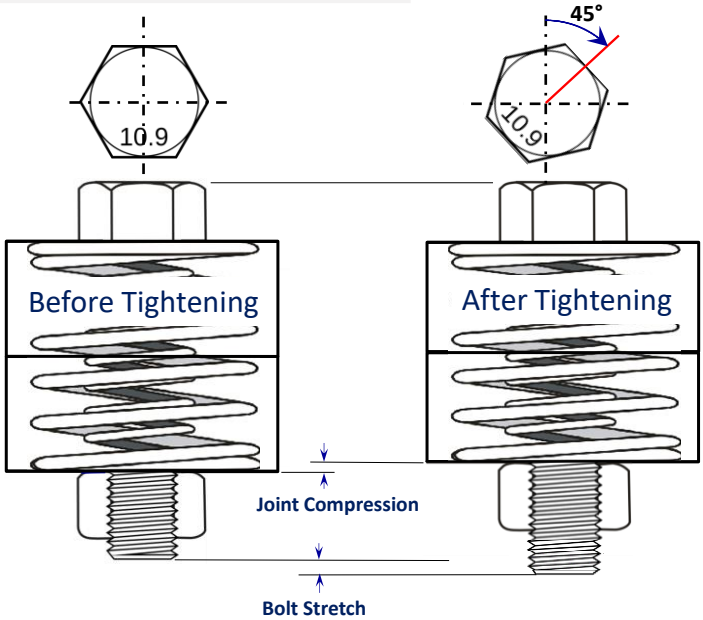
The Bolted Joint Acts Like a Spring



A bolted joint consists of these two springs.

27

The Bolted Joint Acts Like a Spring



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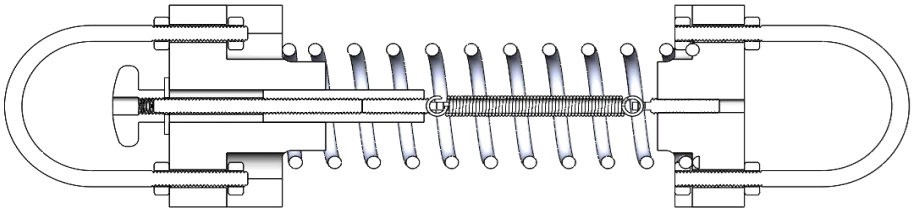

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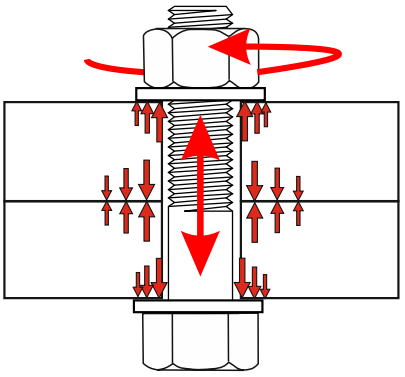
Torque Control Tightening

Q30

30

Basics of Tightening Threaded Fasteners



- When a nut is rotated on the thread of the bolt, the bolt is stretched.
- As a result, a force is generated in the bolt resisting this stretching action.
- This force is called the bolt preload.
- The preload is reacted by the joint resulting in a clamp force at the joint interface.

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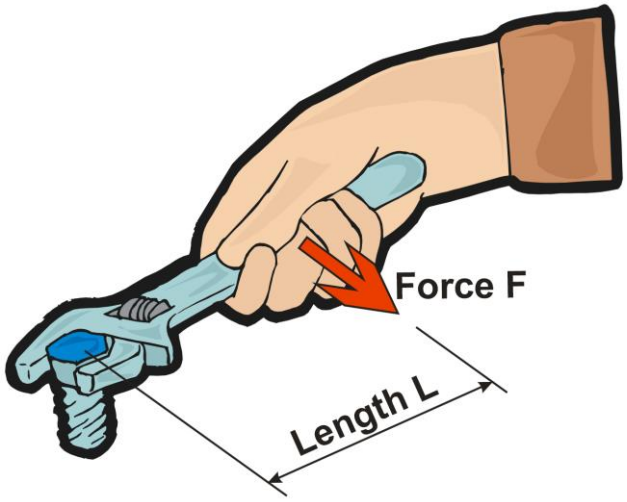
Tightening Threaded Fasteners: Torque



Torque = Force x Length

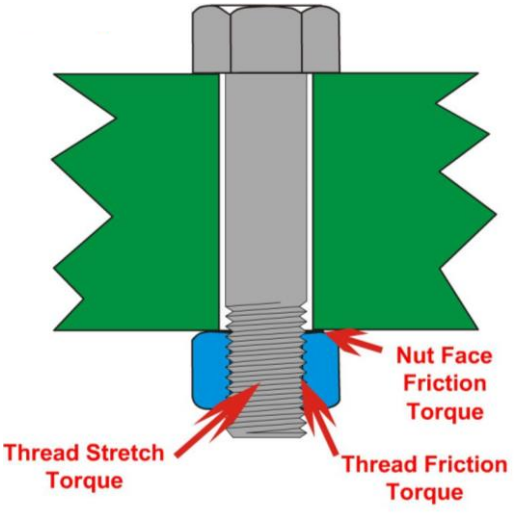
Typical Units

- Newton-meters (Nm)
- Foot-pound (ft-lbf)

32

Torque is Absorbed by the Bolt-Nut Assembly

- The torque needed to stretch the bolt by forcing the nut up the bolt thread.
- The torque needed to overcome the friction in the threads.
- The torque needed to overcome the friction under the hex being turned.



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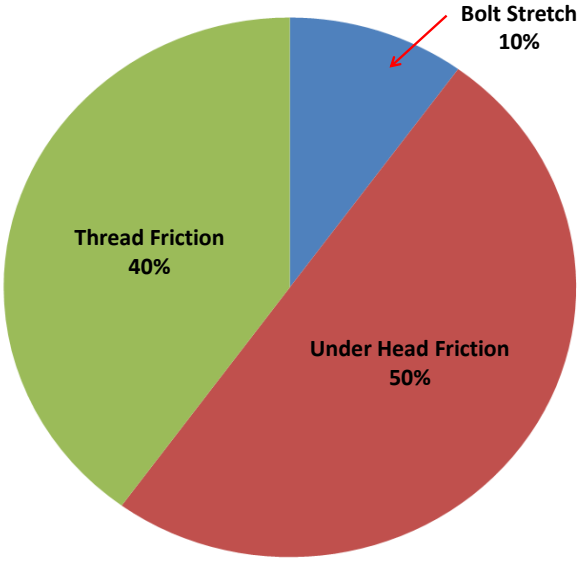
Torque is Absorbed by the Bolt-Nut Assembly



Q34

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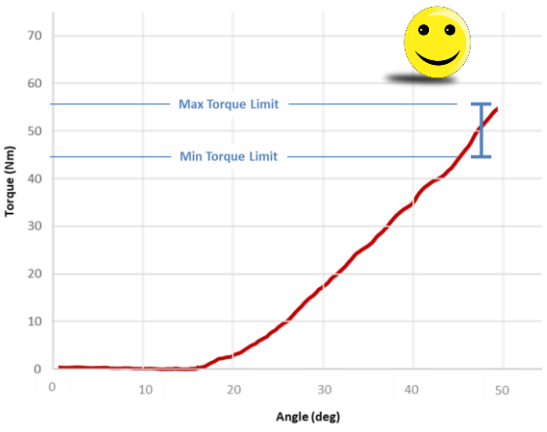
Torque Control Tightening

- The release engineer specifies target dynamic torque, including the min and max limits.
    - Tool must be set to dynamic nominal torque, not a range within the min/max limits.
- The predominant production method.
- The tool selection is based on the precision required to hit the dynamic torque limits.



Q35

35

Torque Control Tightening

Advantages

- Torque is a readily understood concept.
- Relatively easy to implement.
- May be achieved using relatively simple tools which are inexpensive.
- Very friendly to field and service environments (who have less sophisticated tools)

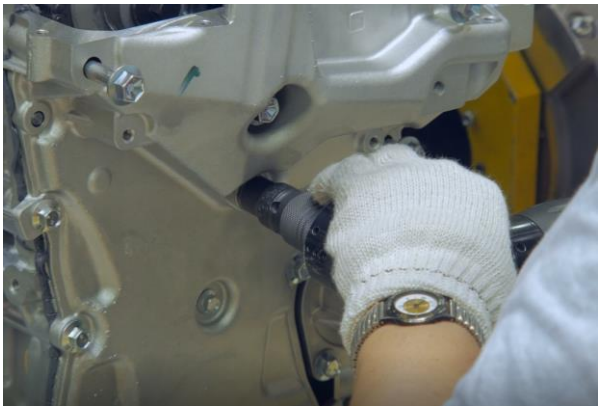
Limitations

- Torque is only an indicator of bolt tension.

Q36

36

Torque Control Tightening Plus Angle Monitoring

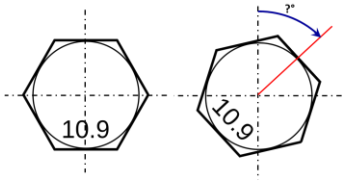


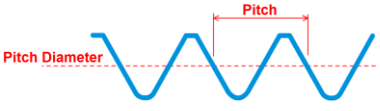
Q37

37

Torque Control and Angle Monitoring

- Controlling torque is an important **first** step in controlling the assembly quality of a bolted joint but it is not a guarantee that that the actual target preload was achieved and ensure that the bolt was assembled correctly.
- Measuring both torque AND angle of rotation during tightening provides a more robust quality control of the assembly process compared to simply measuring torque.
- The angle of rotation between the external and the internal thread defines the distance the bolt advances. In other words, rotating a bolt 1 turn (360°) causes it to advance by the pitch distance.





Q38

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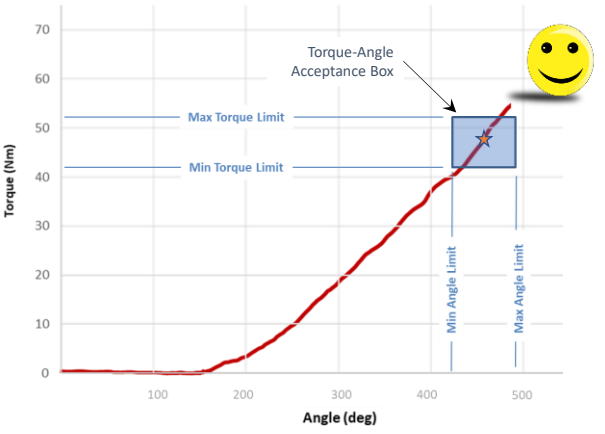
Torque Control and Angle Monitoring

- Measuring the angle of rotation during tightening enables the ME to compare the actual angle of rotation with the minimum and maximum angle limits.
- The torque-angle curve contains valuable information about the tightening process and can reveal potential quality issues.
- A deep dive into torque and angle curves are outside of this training module.



Q39

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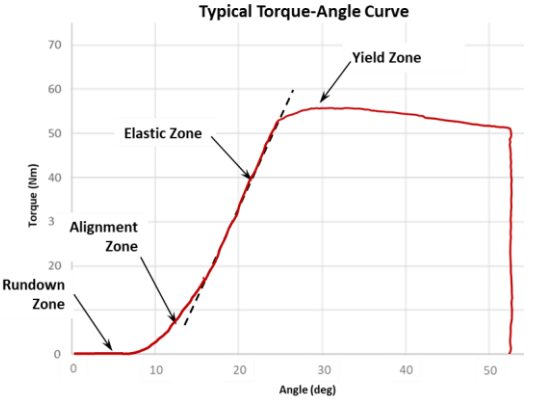
Torque Control and Angle Monitoring

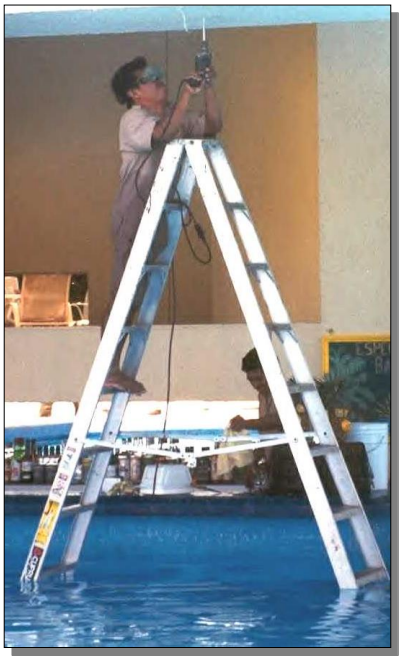
- A lot can be learned about the installation of a bolted joint by observing its torque-angle curve.
  - The stiffness of the joint
  - Friction of the threads and rotating load bearing surfaces
  - Whether embedment occurred during tightening
  - Whether the bolt broke or the threads stripped
  - If the bolted assembly was tightened beyond yield
- The review of a torque-angle curve is an inexpensive yet effective method to understand bolted joint issues before the assembled product leaves the plant.



Q40

40

Common Issues During Tightening



Q41

41

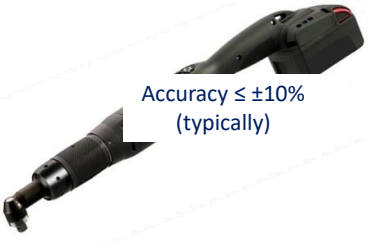
Accuracy of Tightening Torque

Accuracy = ??

Un-controlled Impact Driver

Accuracy = ±10% (typically)

Clicker-type torque wrench



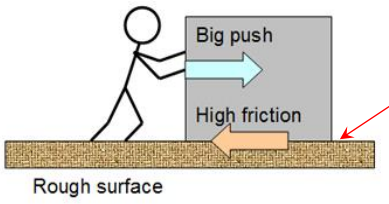
Accuracy ≤ ±10% (typically)

Controlled Nut-Runner

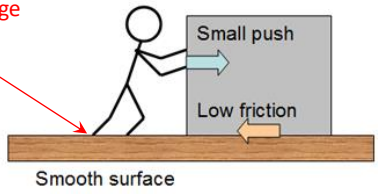
Q42

42

Basics of Tightening Threaded Fasteners: Friction



Placing contaminants (like dirt) or oil on the surface will change the friction!



Plain Steel

Al-ZN Flake Coating

Q43

43

Typical Preload Scatter

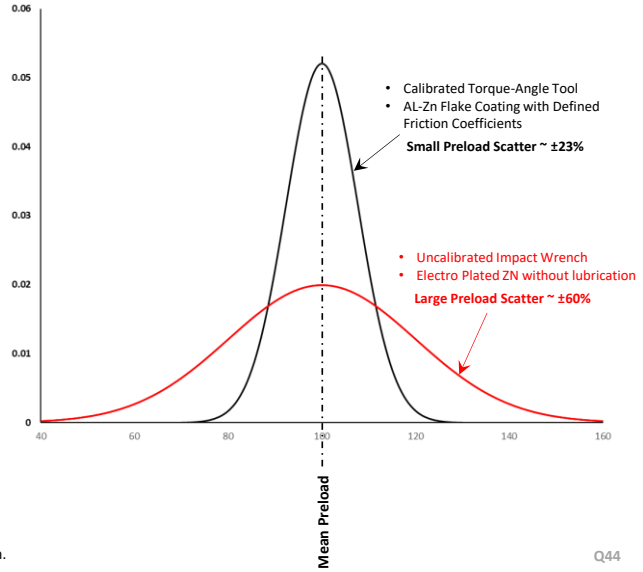
Impact Driver

Electroplated Zinc Fasteners

Precision Torque-Angle Tool

Al-Zn Flake Coated Fasteners

Distribution of Preload for a Sample of Torque Tightened Bolts



Q44

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Demonstration of Preload Scatter Using Torque Control Tightening
(~25 minutes)

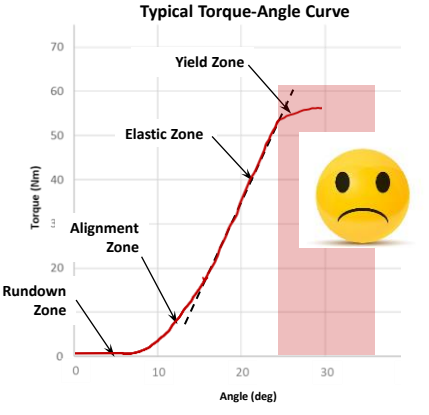
- M10 X 1.5 - Electroplated Zn – Yellow tri-chromate
  - Tightened using an uncontrolled impact driver
- M10 X 1.5 – Zn Flake Coating
  - Tightened using controlled nut-runner

Q45

45

Yield During Tightening

- The yield point of a bolt can be seen in the Torque-Angle Curve as a change in slope.
- Yield of the bolt is not always a failure. Sometimes, the tightening process is intended to yield the bolt slightly.
- The **cause** of the yield or tensile fracture can be:
  - The bolt was over-torqued.
  - The friction coefficients are significantly lower than what was expected. (oil contaminants)
  - The bolt material has a lower strength than what was expected.
  - Defect in the metallurgy or bolt geometry.



Q46

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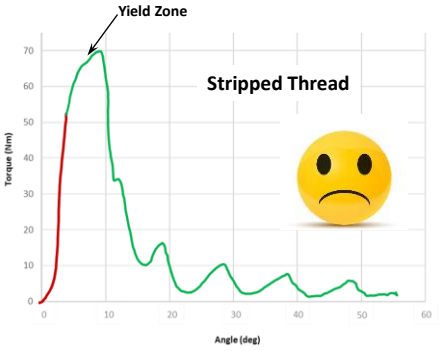
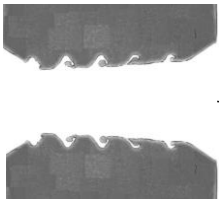
Thread Stripping During Tightening

- The torque-angle curve shown at the right is for a stripped thread.
- The torque value typically **does not** drop all the way to zero.
- The **cause** of thread stripping can be;
  - Improper torque specification released.
  - Internal or external threads out of specification.
  - Material properties of internal or external thread out of specification.
  - Use of lubricant when not intended.



External Thread Strip



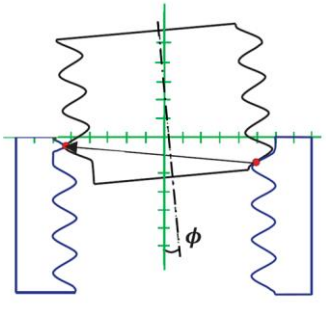
Internal Thread Strip

Q47

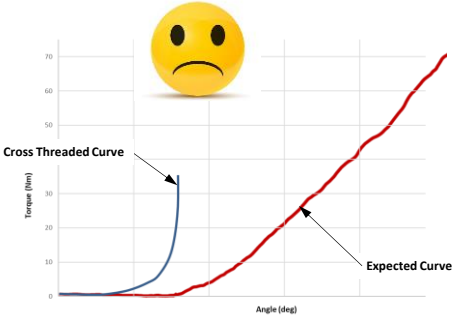
47

Cross Threading During Tightening

- Cross threading occurs when the bolt thread and internal thread are engaged on different revolutions (mis-matched).
- The **cause** of cross threading is an angular misalignment of the bolt with the internal thread.



Cross Threaded

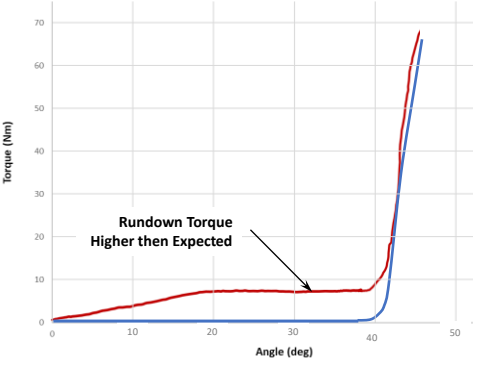


Q48

48

Coating Thickness Issues on Threads

- It is common for dip-spin coatings to be applied too thick.
- Thick coatings results in an interference fit between the internal and external threads.
- The interference results in high run-down torques.

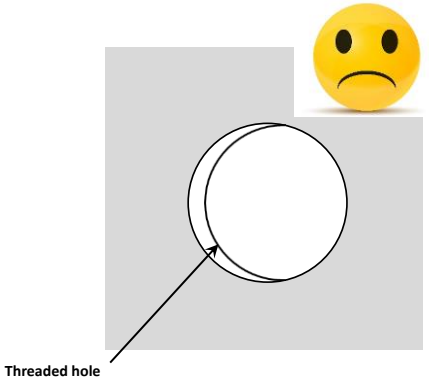


Weld Spatter

- Weld spatter can land and stick to the threads if the threads are not properly masked.
- Although it may be possible to start the bolt in the hole, the nut-runner may hit a torque limit before the target clamp load is achieved.

‘Winking’ of Holes

- Winking of holes occurs when there is mis-alignment between holes on different layers in the assembly.
- Cross Thread
- Although it may be possible to start the bolt in the hole, the nut-runner may hit a torque limit before the target clamp load is achieved.



Q51

51

52

Tightening - Looser than Expected

53

Unintended Loosening of Threaded Fasteners

Topics to be Covered:

- Relaxation
  - Embedment Relaxation
  - Compressive Yield
  - The Effect of a Washer
  - Effect of Paint
  - Demonstrations
- Self-Loosening
  - History and Modern Solutions
  - Loosening Curves
  - Demonstrations

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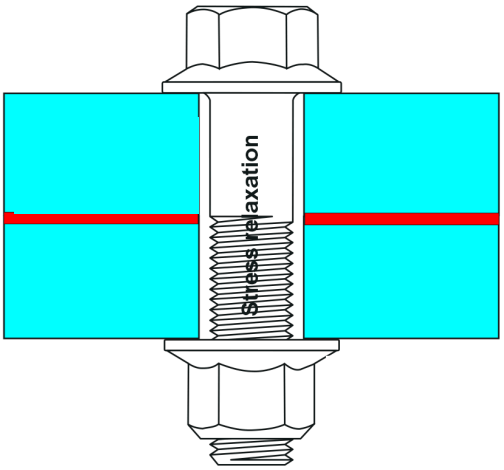
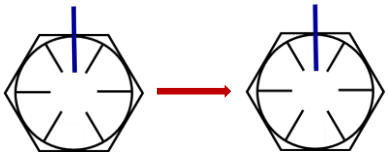
Loosening Processes - Relaxation



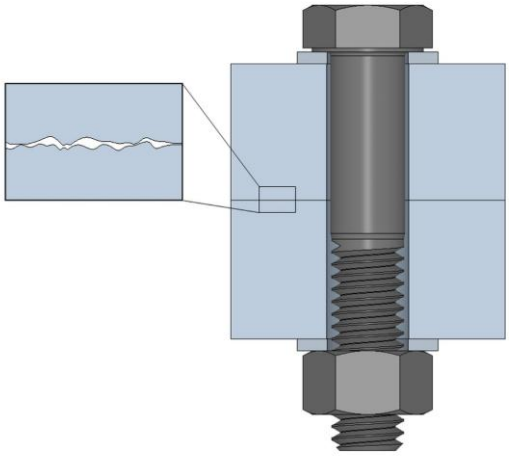
Relaxation



The bolt does not rotate relative to the nut, but the joint loosens over time!

55

Relaxation Due to Embedment



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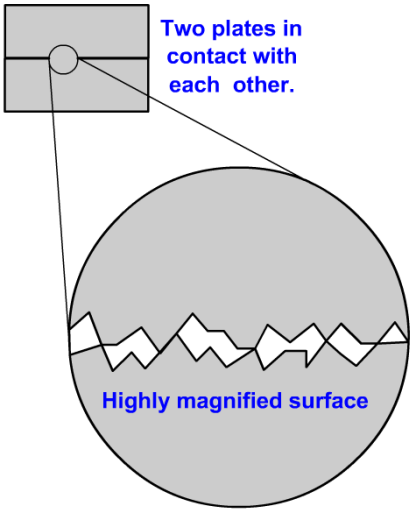
Loosening Processes - Relaxation - Embedment

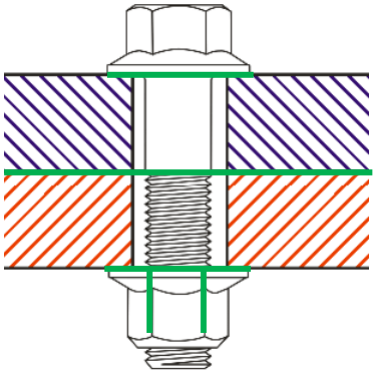
- If you magnified the surface of the joint and threads, what appears to be a smooth surface actually consists of ridges (or asperities) and valleys.
- The interfaces within the joint compress a distance called f_z



57

Loosening Processes - Relaxation - Embedment

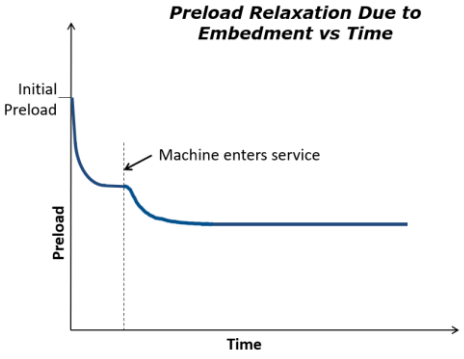
- Embedment is the localized plastic deformation occurring in the mating surfaces within a joint during and after assembly.
- Embedment causes 'plastic flattening' of load-bearing surfaces.
  - Between the bolt head and plate
  - Between the nut head and plate
  - Between the bolt and nut thread
  - Between the plates
- Embedment even occurs when bolted joints are tightened below the yield point and surface pressures are less than the limiting surface pressure.



58

Loosening Processes - Relaxation - Embedment

- The greatest amount of embedment occurs during the assembly tightening process.
  - This embedment is compensated for by further tightening.
- Additional embedment occurs after assembly during the initial loading cycles.
  - Since most joints are not re-tightened after the initial assembly, embedment occurs when the product is in the field, resulting in a loss of preload.
- Assuming the joint was designed correctly, the preload losses due to embedment eventually diminish to zero.



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Demonstration of Relaxation Due to Embedment

60

Relaxation Due to Compressive Yield

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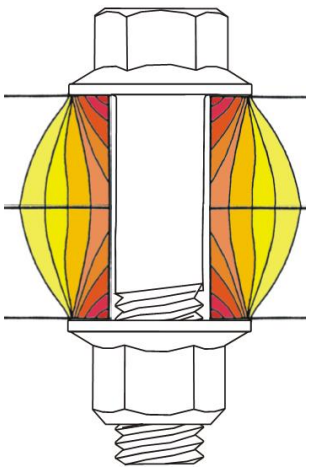
Relaxation - Compressive Yield

- If the average compressive stress in the joint plate is higher than the limiting surface pressure for that plate, then the plastic collapse will occur during and after the bolt is tightened, and a significant loss of clamp load will occur.



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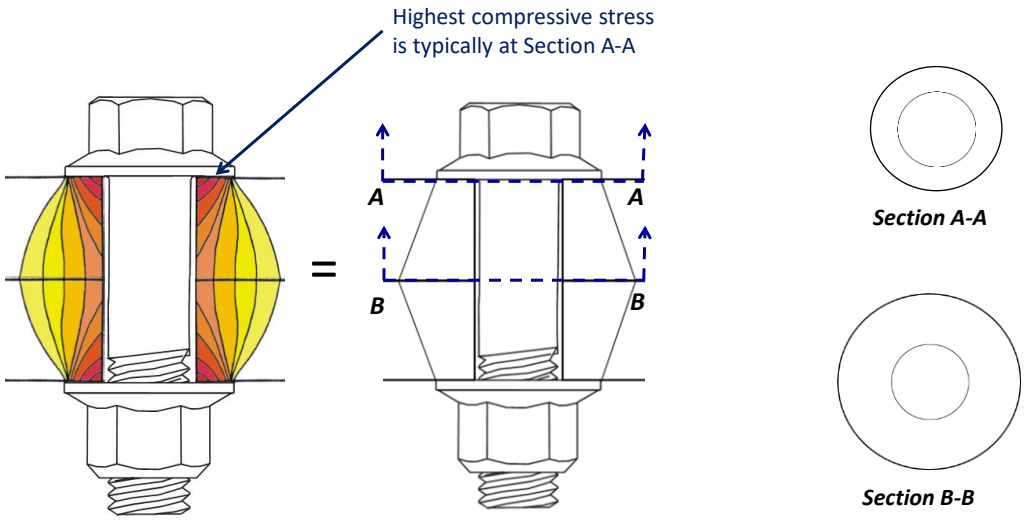
The Bolted Joint Stress Cone

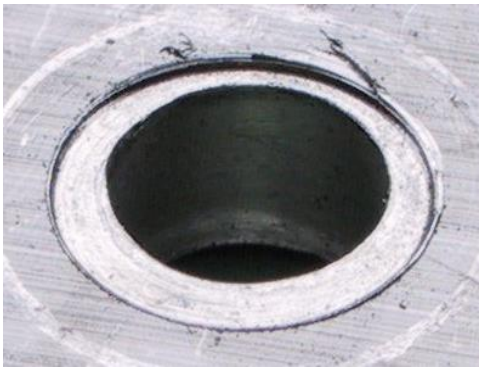


Q63

63

Compressive Stress in Bolted Joint

- Joint materials are often substantially weaker than the bolts that clamp them together.
- When fully tightened, the stress under the bolt head or nut face can be higher than some types of joint materials can resist, causing compressive yield of the joint plate.



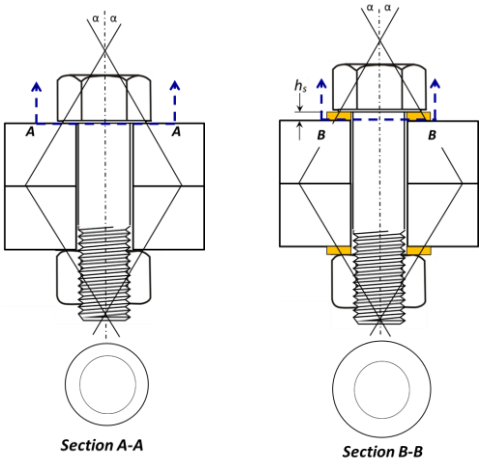
Evidence of compressive yield

Q64

64

Compressive Stress under Bolt or Nut Bearing Face

- The addition of a washer increases the effective contact area, reducing the compressive stress.
- Choosing a washer with an OD that is larger than the stress cone does not increase the effective contact area.
- Instead, the thickness of the washer has the most effect.



No Washer Under Bolt Head ***Washer Under Bolt Head***

Q65

65

Reducing Compressive Stress under Bolt or Nut Head

- To reduce the compressive stress under the bolt or nut head to acceptable limits, consider using the following:
  - Flanged-headed hardware

    - OR -
  - A through-hardened washer or spacer

Q66

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Demonstrate the Effect of Washer

Q67

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Effects of Paint in the Joint

- It is considered good practice to avoid the presence of ‘top-coat’ paint in the joint interface in critical joints
- The paint film can result in a preload loss from creep, and/or break down in film.
- Studies have found that the creep loss is not significant on thin films (for example the presence of a e-coat primer on a car body).
- It is highly likely that top-coat paint in the joint interface affects the coefficient of friction.

Fatigue failure of the bolt after the breakdown of the paint film at the joint interface

Q68

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The Presence of Paint in the Joint

Top coat paint breakdown - Vibratory pod attachment joint

Top coat paint breakdown - Engine mount joint

69

Demonstrate Compressive Yield/Creep in Joint
(~10 minutes)

70

Methods of Reducing Preload Relaxation

- Use a thru-hardened washer on weak joint materials.
- Reduce the joint-bolt stiffness, specifically…
  - ‘Soft bolts’ are less sensitive to embedment.
    - Target long bolts (i.e. Effective Length $\geq 4d$)
- Reduce the number of embedding surfaces in the joint.
- Avoid ‘thick’ layers of top coat paint in critical structural joints, ideally, paint should be removed from structural joints.
- Reduce fastener tightening speed.
- Re-tighten bolts early in service life (generally not a practical option).

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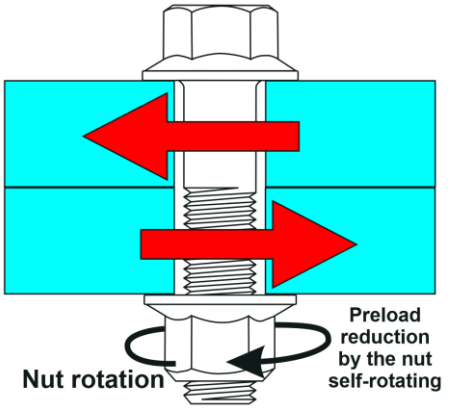
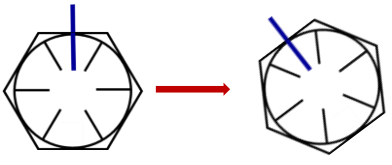
Loosening Processes - Self-Loosening



Self-Loosening



The bolt rotates relative to the nut, and the joint loosens over time!

72

Explanation of Junker Test & Self-Loosening

Double Click Image to Launch Video

73

Self Loosening in Slow Motion

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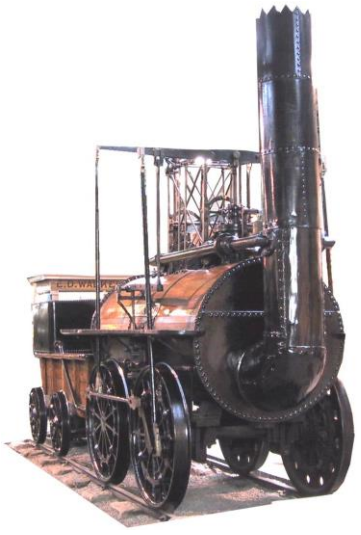
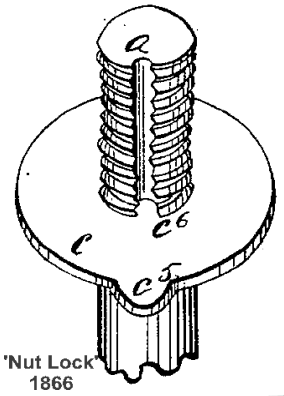
Early Problems with Self-Loosening



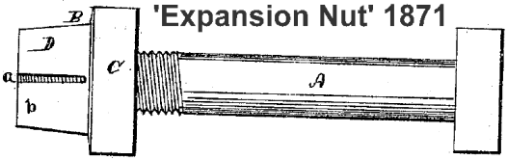
- The Industrial Revolution witnessed a dramatic increase in the usage of fasteners.
- Problems soon became apparent, especially on the railways.

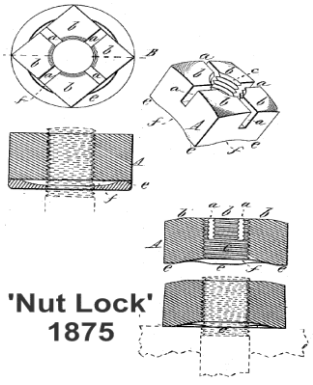
75

Early Problems with Self-Loosening



Over the last 200 years, thousands of patents have been relating to 'nut locks' or lock nuts as they became known.





76

Modern Solutions to Self-Loosening?

Hundreds of locking devices/approaches are available; some are more effective than others.

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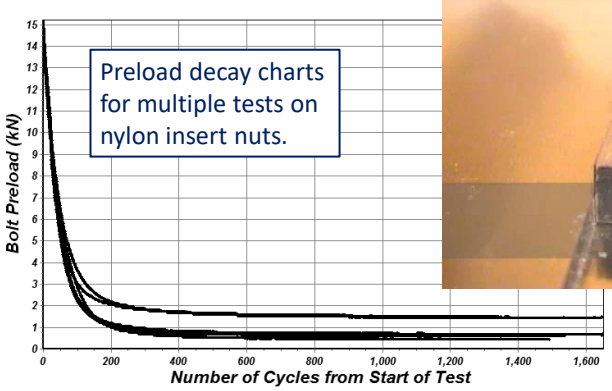
Nylon Insert Nut



Preload decay charts for multiple tests on nylon insert nuts.

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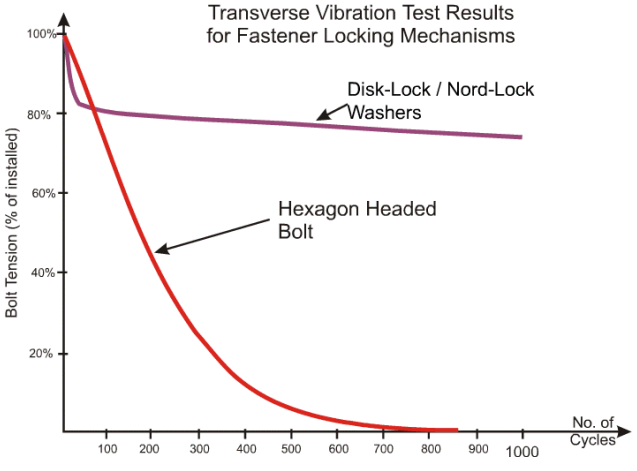
Thread Locker

- Assembler Applied
- Pre-Applied Thread Locker

Image courtesy of ANOCHROME-INLEX LOCKING

79

The Wedge Lock Type of Washer: Disc-Lock / Nord Lock Washers



- On one side of the discs, there are cams that have a greater angle than the pitch of the thread.
- The washers are installed in pairs, cam face to cam face.

80

Nord-Lock Promotional Video – Wedge Lock Washer

81

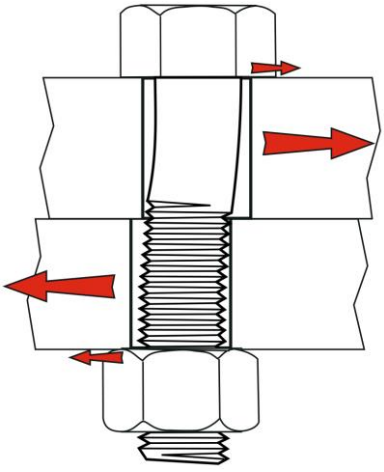
Demonstration of Self-Loosening
(~25 minutes)

82

Bolt Bending Due to Transverse Movement

- The bolt preload generating friction grip will result in some degree of bolt bending when transverse joint slip occurs.
- If this bending keeps occurring, fatigue failure of the bolt is likely.

Side: Fatigue failure of a locked bolt in a Junker test after approximately 3000 cycles.



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Key Conclusions

- The primary cause of the self-loosening of threaded fasteners is not vibration but repeated joint slip.
- The best way to ensure fasteners do not self-loosen is to prevent the joint from slipping repeatedly.
  - The friction grip capacity of the joint must be greater than the shear load applied to the joint to prevent slip.
- If it is not feasible to prevent repeated slip, then a thread-locking device of proven ability should be specified.
- Locking the threads does not address the root cause of the self-loosening, but it does lessen the loosening effects.
- Fasteners in joints that repeatedly slip are at increased risk of fatigue failure

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