Testing

Forensic Testing Methodologies to Determine the Root Causes of Fastener Failure

When a fastener or bolted joint fails, the results can be catastrophic and also sometimes tragic. The impact of the failure might be an isolated component malfunction, or an aircraft dropping from the sky. Whatever the impact, any fastener or bolted joint failure puts the pressure on the fastener manufacturer, the original equipment manufacturer (OEM), the operator and their insurers to determine the root cause and, ultimately, liability. Underpinning this process is the work of forensic engineers who apply fastener and bolted joint tests to find out what went wrong, so a solution can be developed to ensure it never happens again. Vibrationmaster's ***Morten Schiff*** *and Bolt Science's* ***Bill Eccles*** *explain how forensic fastener and bolted joint testing methodologies can be used to determine failure modes.*

"Fasteners can fail due to simple metallurgical defects. It is also common for failures to arise as a result of bolted joint issues and the root cause is typically a design or installation fault," explains Dr. Bill Eccles, who provides expert witness and forensic engineering services to leading OEMs across sectors such as automotive, aerospace, energy and construction.

"Therefore the process of identifying the root causes of fastener and bolted joint failures involves a broad range of evidence gathering. The forensic engineer will apply a combination of calculations and tests specific to the fastener, bolted joint and application to identify why the failure occurred."

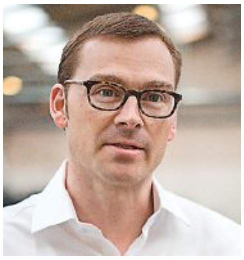
Morten Schiff notes that when failures occur, the blame typically falls on the fastener manufacturer first, but it is the forensic examination that can reveal that the fastener is not at fault. According to Schiff, "Although the costs of the fasteners supplied to the OEM may be in the tens of thousands of dollars, product recalls to fix the problem may cost millions. Determining the reason for failure is driven by financial as well as design imperatives. The impact on reputations can also be considerable, so many failures and resulting forensic examinations never make it into the public domain."

Fastener & Bolted Joint Failure Modes

According to Eccles, for a fastener manufacturer to understand why its fastener or bolted joint failed and to devise a solution, an understanding of fastener and bolted joint failure modes is required. Eccles says, "Failure modes fall into two broad categories—manufacturing quality defects and design quality defects. In my experience, most failures occur as a result of deficiencies in designing and assembling the bolted joint." He explains further:

Manufacturing Quality Defects.

—The fastener is made incorrectly. This may be a metallurgical fault that results in the fastener not performing according to its specifications.



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—The fastener itself has not been manufactured correctly. For example, the thread angle may be incorrect, altering the fastener's performance characteristics.

—Hydrogen embrittlement, where hydrogen is introduced into the fastener during the manufacturing electroplating phase.

Design Quality Defects.

—These include insufficient preload. Either the bolted joint has not been tightened sufficiently or the design of the joint is such that it is unable to sustain the load applied when tightened. The root cause of insufficient preload leads to four failure sub-groups:

- ***Self-loosening.*** If not clamped sufficient transverse movement will occur. An effective locking method can prevent self-loosening, but this in turn may lead to the fastener subsequently failing by fatigue.
- ***Fatigue*** (see **Figure 1** and **Figure 2**). Joint separation occurs when the applied axial load overcomes the bolt's preload. In such circumstances, fatigue failures are likely to occur. They can also occur if transverse joint movement occurs as a result of bending stresses induced by the movement.
- ***Wear*** (see **Figure 3**). The joint may not come loose, but because it is moving back and forth it causes elongated holes and the joint fails due to wear.
- ***Gasket leakage.*** Insufficient preload may not seal a gasket joint, which leaks as a result, and is itself a failure of the joint.

Eccles highlights that this insufficient preload is the predominant source of fastener and bolted joint failure.

—Overload in service (see **Figure 4**). This failure mode results in the bolt breaking as a result of overload. Although overload is often the initial reason suspected when a fastener or joint fails, Eccles says it is rare in practice. The excessive load in service usually results in joint separation as the joint materials are pulled apart. The bolt may experience some plastic deformation, but often does not immediately fail. This will result in the preload reducing and the subsequent risk of fatigue failure. A catastrophic load such as an impact can deliver massive overload, causing breakages.

—Fatigue. Even though it may have sufficient clamp force, certain types of joint geometry are prone to fatigue. This failure mode is largely overcome through joint design, and the choice of fastener can mitigate impact of fatigue. Rolling a bolt after heat treatment induces compressive stresses in the thread, which delivers improved performance under fatigue conditions. Fastener makers can supply this type of product when high fatigue resistance is required.

Fig. 1 — Bending fatigue failure (source: Bolt Science).

Fig. 2 — Bending fatigue failure (source: Bolt Science).

Fig. 3 — Worn bolt as a result of transverse joint movement (source: Bolt Science).

Principal fastener and bolted joint failure modes (source: Bolt Science):

1. Manufacturing quality defects
   a. Incorrect manufacture
   b. Hydrogen embrittlement
   c. Incorrect tightening/assembly

2. Design quality defects and assembly issues
   a. Insufficient preload
   b. Overload in service
   c. Fatigue
   d. Thread stripping
   e. Excessive bearing stress

Principal tests for Forensic examination of fastener and bolted joint failures (source: Bolt Science):

- **Design verification calculations**
- **Torque tension test**
- **Hardness test**
- **Proof load test**
- **Tensile test**
- **Hydrogen embrittlement tests**

Fig. 4 — Bolt overload failure (source: Bolt Science).

—Thread stripping (see **Figure 5**). This occurs when the shear strength of the fastener thread is insufficient, and less than that of the bolt. Thread can be partially stripped at the point of assembly and the installer tightening the bolt may not be aware. As a result, the product goes into service with a partially stripped thread. When the joint sustains an external load, the thread is stripped, or literally pulled off and the nut comes away from the bolt, and catastrophic failure occurs. Matching the same class of fastener with the same class of bolt reduces the chances of thread stripping. Eccles notes that this failure mode is common with galvanized fasteners. "The tolerance must be modified to accommodate the thickness of the coating, usually compromising the strength of the assembled product," he says.

—Excessive bearing stress. It is quite common for the bolt strength to be significantly stronger than the material it is clamping. This can cause surface stress on the clamped surface underneath the bolt head and can in turn cause partial collapse. The phenomenon can occur during tightening and normal operation. The result is a loss of the bolt extension, which can lead to self-loosening and fatigue issues. The joint starts to move, eventually resulting in the

Fig. 5 — Thread stripping of a galvanized bolt (source: Bolt Science).

nut loosening or fatigue failure. The root cause is that the surface stress is too high for the clamped material.

Forensic Testing to Determine the Root Cause of Failure

"The first step towards understanding how and why a fastener or bolted joint has failed involves calculations and joint investigations," explains Eccles. "The tests used to investigate further will depend on the nature of the joint and the product."

Schiff provides an example: "Say a car has a problem with its wheel nuts coming off. The root cause could be due to the finish or torque tension relationship. The initial test may be on a wheel and fastener to establish the torque tension relationship, make design changes and then to validate the design in the laboratory.

"If the problem was serious enough, the next stage may be to test a subassembly to examine the wheel and axle and simulate loadings. Finally, a product test on an entire vehicle could be used to test the wheel fastener performance under road conditions."

In practice, Eccles will secure detailed engineering specifications of the fastener and bolted joint, and perform his own calculations to determine whether the joint was designed correctly. This process can identify the root cause of the failure from the outset. Then Eccles will confirm his calculations in the laboratory by running a range of standard and bespoke tests. His basic checklist of fastener and bolted joint failure investigation tests are as follows:

- ***Torque tension test:*** This can assist to establish from the outset whether the most common form of fastener and bolted joint failure—insufficient clamp force—is to blame. Eccles will simulate the joint in a test rig to determine the clamp force.
- ***Hardness test:*** The root cause could be as simple as delivering a fastener with insufficient strength. A basic hardness test can be used to check the fastener's actual hardness against specifications. If there is a mismatch, it may have led to failure. The hardness value can be related to the steel's tensile strength by reference to standards.
- ***Proof load test:*** bolt/nut are put in a tensile test machine to check that the fastener will achieve specified proof load.
- ***Tensile test:*** A tensile test machine will determine the fastener's tensile properties.
- ***Bespoke joint test:*** A rig test can be performed on the bolted joint, which typically involves subjecting it to a simulated service loading to allow a comparison to be made between an existing and proposed design.

Failure Due to Hydrogen Embrittlement

A range of metallurgical and mechanical tests exist to determine whether a fastener failed due to hydrogen embrittlement. Eccles points out that it is also important to distinguish between hydrogen embrittlement caused during manufacturing and electroplating, and stress corrosion cracking during operation. The former is down to the fastener manufacturer, but liability for failure caused by the latter could be due to engineering design, operation and maintenance.

"Hydrogen is released as a corrosion byproduct, so embrittlement of the fastener can occur during operation causing stress corrosion cracking," notes Eccles. "The downstream user may have caused the failure by not adhering to the fastener manufacturer's coating requirements. The designer may have some responsibility for the failure by specifying fasteners inappropriate for the application.

He continues, "The surface characteristics of hydrogen embrittlement from manufacturing and stress corrosion cracking look similar, so it is usually necessary to consider additional factors and conduct further tests."

Eccles would normally investigate whether the fastener had been in service for a significant period prior to failure, which would be a strong indicator that the failure was due to stress corrosion cracking. Conducting destructive tests on fasteners from the same batch will also help identify the root cause. A fastener from the same batch, which has absorbed hydrogen during manufacturing and is then subjected to a load test, is likely to fail within 24 hours. That would suggest the root cause is the manufacturing process and not the operating environment.

Understanding Why Failure Occurred to Then Devise a Solution

"The purpose of a forensic examination into why a fastener or bolted joint has failed is not just to establish whether it is the fastener manufacturer, OEM or operator who is liable for any losses," suggests Schiff. "The key purpose of testing is also to understand what measures to take to ensure the failure won't occur again."

Eccles agrees, and adds that this is why it is so important to understand the root cause of failure: "If you get the diagnosis wrong, you then run the risk of delivering the wrong solution and the same problem could recur. In critical applications, this could lead to further loss of life."

Eccles concludes, "By systematically testing fasteners and bolted joints, and making detailed observations/calculations, it is possible to identify the root cause of failure and design a solution so the failure does not reoccur." FTI

About the contributors...

Bolt Science provides independent technical expertise in bolted joint technology. Software products include bolted joint analysis, torque tightening and fastener failure programs. Bolt Science delivers a range of training courses to fastener manufacturers and downstream OEMs on bolting technology and analysis. Consultancy services include creating analytical solutions to bolting problems, joint and fastener testing and expert witness services. Based in the UK, the firm operates globally, with clients from the fastener sector and across all major industrial and engineering areas. ***www.boltscience.com***

Vibrationmaster designs/manufactures advanced testing technology and delivers specialized test services. Products include Junker Test machines to analyze/demonstrate self-loosening behavior of fasteners and bolted joints to *DIN 65151* and the new *DIN 25201*. With a head office and R&D function in Luxembourg and advanced manufacturing facilities in Denmark and India, the firm operates globally. Customers span the commercial, academic, research, public, government and not-for-profit sectors. We offer highly reliable test solutions to organizations seeking market-proven and cost-effective technology to test and prove reliability, consistency and safety of their products.
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