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How to detect and prevent metal fatigue

Imagine how shaken up the engineering world was when they began to experience the sudden failing of axles of post coaches, journals of railway carriage axles and other mechanisms made of highly reliable and durable metal in the mid-nineteenth century.

In 1842, near Versailles, an overcrowded passenger train carrying people coming back from celebrations at the palace derailed and caught fire because of a broken locomotive axle. After this accident, they abandoned the practice of locking passengers in their carriages in France and scientists embarked on an in-depth investigation of the problem. Engineers and metallurgists had yet to discover and formulate what the fatigue of metals and alloys was and what factors it was dependent upon.

Metal fatigue test

It was gradually noticed that failure occurs if metal is subjected either to multiple repeated stresses (combined with stress relieving) or stresses in opposite directions, e.g. alternating compression and tension, repeated bending in different directions, etc. To find out the causes of such disconcerting phenomena, it was decided to investigate the suitability of iron for

bridge-building

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The failures observed could be explained by two reasons: either the metal strength is prone to deteriorate, regardless of service conditions (if that were the case, this would have become a genuine catastrophe for the rapidly developing industrial production), or failure is caused by repeated alternating stresses. To find out which of the guesses was correct, scientists ran an experiment. Several iron rods were loaded to a stress level that would not yet cause failure but was very close to it (it should be noted that iron is quite brittle and fails without permanent deformation). Rods were kept in the loaded condition for four years, after which the specimens proved not to have failed. This meant that the first hypothesis of scientists was wrong.

Then they ran drop-weight experiments on iron beams to test for fractures. The deflection of a beam was measured after each impact. It transpired that with a deflection equal to half the deflection that caused the fracture of a beam after a one-time impact, a specimen would break after 4,000 impacts. With a deflection equal to one-third of the deflection at fracture, a beam could withstand far more than 4,000 impacts. This proved how harmful repeated stresses are when they reach half of the level that causes fracture of the metal after a one-time impact.

To rule out the critical role of vibrations, which inevitably originate from each impact, they ran experiments with a quiescent repeated load, which showed the same results. A whole range of subsequent systematic research provided an external mechanical picture of failure caused by repeated loads. Such failures had to be attributed to a new property of metals. Like any other living thing, metals get tired.

The term ‘metal fatigue’ was first used in 1854 by the English physicist and scientist Frederick Braithwaite in his paper, “On the fatigue and consequent fracture of metals”.

Metal fatigue in practice

Nowadays, fatigue stresses in structures and parts of machines are studied by a special branch of mechanics: metal fatigue. The modern definition of metal fatigue is the weakening of a material caused by cyclic loading. It results in progressive and localised structural damage and the growth of cracks. Once a fatigue crack has initiated, each loading cycle will further its growth, producing characteristic striations on some parts of the fracture surface. The crack will continue to grow until it reaches a critical size. Then it propagates rapidly, causing complete fracture of the structure. ‘Metal strength’, i.e. the ability of a material to withstand repeated loads without failure, is the opposite of fatigue.

To fully grasp what metal fatigue means and how critical this property of materials is, it helps to consider one characteristic of the progress in the machine-building industry. As machines become faster every year, the alternating stresses that they have to withstand in the course of their service life grow. In turn, as alternating stresses grow, the risk of structural failure by fatigue or negative implications of a potential failure increases rapidly.

Recall the accident at the Sayano-Shushenskaya Hydroelectric Plant, which has been compared with the disaster at the Chernobyl Nuclear Power Plant in terms of its socioeconomic impact. This man-made disaster on the Yenisei River occurred in 2009 and is still believed to be the worst emergency in the history of the hydraulic power industry, causing many deaths, damaging infrastructure and seriously polluting the river basin. The accident killed 75 people. The building and process equipment were flooded and practically destroyed, and the production of electricity was stopped. Connection problems and lack of information about the condition of the dam caused panic among the local population, who started to flee to upstream settlements. The normal life and energy safety of the region were seriously compromised. It took five years to restore the Sayano-Shushenskaya Hydroelectric Plant. In its conclusions, Russia’s Federal Service for Ecological, Technological, and Nuclear Supervision (Rostekhnadzor) mentions fatigue damage to the turbine cover fasteners.

How to identify metal fatigue?

Although fatigue is an inherent property of metals, nowadays, similar disasters caused by fatigue stresses happen rarely. This is because the laws of fatigue have been well studied. As such, we can deal with fatigue in an organised manner, structurally, technologically and metallurgically. There are several methods for determining that a metal is starting to become fatigued:

- Visual inspection. Detection of cracks or other deformations.
- Noise analysis. Damaged metal makes a specific rattling noise.
- Ultrasonic and X-ray inspection. Diagnostics of a human body and a steel structure have a lot in common in this regard.
- Fluorescent dyes. They make cracks visible.
- Magnetic powders. They are applied to iron parts.

Notably, when exposed to a corrosive environment, metal behaves in a completely different manner.

Corrosion

greatly facilitates the propagation of a fatigue crack and can cause the crack to initiate at lower stresses and make cracks deepen faster. This is called corrosion fatigue. Various surface coatings – from painting to galvanising – protect from corrosion fatigue.

How to reduce metal fatigue?

Structural measures against fatigue include giving parts shapes without sharp or little rounded reentrant comers, abrupt changes of section, boring of a small radius, etc. Otherwise, stress concentrations may occur abruptly. Often, structural errors can be eliminated merely by increasing the size of a part. This will relieve the stress and prevent from exceeding the fatigue limit.

Technological measures against fatigue often boil down to the proper processing of parts. For instance, when it comes to parts made of high-strength steel, attention is primarily paid to surface grinding. However, the wrong assembly of structures also can cause dangerous variable stresses.

Metallurgical measures to counter fatigue failure should also be borne in mind. Fatigue cracks can initiate from foreign inclusions in a metal resulting from its contamination during casting (e.g., slag inclusions). It should be pointed out, though, that given the current advancements in the industry, leading steel producers dedicate efforts to improve the metal purity and enhance the chemical composition and heat treatment of products.

As such, engineers and builders are now dealing with fundamentally different, stronger steel grades. While fatigue still occurs, critical failures of metal structures and parts caused by fatigue stresses have been minimised.