Some Basics About Fatigue

Fatec Engineering

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Fatigue failure occurs when a material is subjected to repeated loading and unloading cycles. The stress levels that cause fatigue failure are well below values that are considered safe for static load cases. Fatigue initiation usually occurs very locally and is a result of factors such as stress concentration (high local stresses) due to component shape, surface conditions or corrosion pitting.

Fatigue is one of the major causes of in-service failure throughout engineering history. During the industrial revolution (18th & 19th century), fatigue failures were documented for the first time. The early railway axle failures and mining equipment failures prompted fundamental testing and research. The theories on which much of modern fatigue analysis is based on were developed in that period by people like August Wöhler.

The nature and prediction of fatigue is much better understood nowadays. But still, designing against fatigue failures and the application of fatigue analysis is not easy. A good understanding of the background is essential to be able to design and analyse you structure.

In this document I will discuss a few basic topics about fatigue.

1. What is Fatigue

Metal fatigue is about the predominant cause of failure of structures. But what is fatigue? Fatigue occurs when a structure is subjected to cyclic loading. If the stress amplitude exceeds a threshold value, microscopic cracks will initiate at locations with high stresses (stress concentrations). At first, the cracks propagate very slowly and remain undetectable for the bare eye for most of the fatigue life. Gradually the crack propagation rate increases and the cracks will become visible. Eventually the crack will reach a critical size and the structure will fail. Due to the nature of the fatigue process, fatigue failure can lead to safety issues.

The stress levels that cause fatigue damage are much lower than the static strength of the material, i.e. ultimate tensile strength and yield strength. Decisive for fatigue damage propagation are stress amplitudes; it is cyclic loading that determines fatigue.

Many factors play a role in fatigue, such as incorrect choice of material, rough finish or damaged metal surface, poor maintenance, including failure to timely replace a part. The shape of the structure will significantly affect the fatigue life; square holes or sharp corners will lead to high local stresses where fatigue cracks easily can initiate. Round holes and smooth transitions or fillets will increase the fatigue strength of the structure.

Some fatigue characteristics

- Fatigue is a structures issue, not just a material issue.
- Stress concentrations (holes, keyways, fillets) and locations with secondary bending are common locations at which fatigue cracks initiate.
- Fatigue often shows significant scatter.
- The larger the stress amplitude, the shorter the fatigue life.
- No large scale plastic deformation.

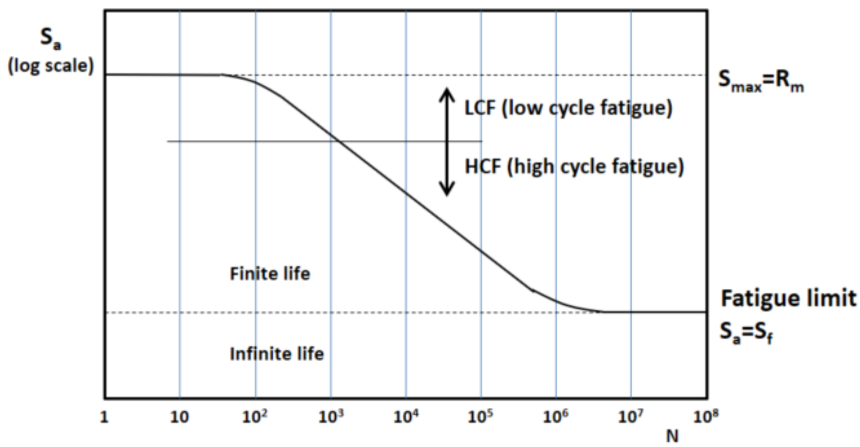
- Damage is cumulative. Unlike humans, materials do not recuperate from fatigue.

2. Description of a S-N Curve

Fatigue properties of materials are often described using the fatigue limit or the S-N curve (fatigue curve, Wöhler curve). The S-N curve describes the relation between cyclic stress amplitude and number of cycles to failure. The figure below shows a typical S-N curve. On the horizontal axis the number of cycles to failure is given on logarithmic scale. On the vertical axis (either linear or logarithmic) the stress amplitude (sometimes the maximum stress) of the cycle is given.

S-N curves are derived from fatigue tests. Tests are performed by applying a cyclic stress with constant amplitude (CA) on specimens until failure of the specimen. In some cases the test is stopped after a very large number of cycles ($N>10^6$). The results is then interpreted as infinite life.

Fatigue curves are often given for $K_t=1$ (unnotched specimens). Those curves describe the fatigue properties of a material. Actual structures are better described with S-N curves for $K_t>1$ (notched specimens).



The S-N curve above has some characteristic features which are discussed below.

Fatigue Limit: For some materials (steel and titanium) there is a stress level (lower asymptote in the S-N curve) below which the material will not fail. This stress level is known as the fatigue limit, endurance limit or fatigue strength. For materials like aluminium, magnesium, austenitic steel, etc. the fatigue limit is not very distinct.

The level of the fatigue limit depends on many factors, such as geometry (stress concentration factor K_t), mean stress (stress ratio), surface conditions, corrosion, temperature, and residual stresses.

High Cycle Fatigue (HCF): In this region the material behaviour is fully elastic. On log-log scale the S-N curve can be considered to be linear.

Low Cycle Fatigue (LCF): If the maximum stress level in a cycle is exceeding the yield strength, the material behaviour in the net section will be predominantly plastic. Number of cycles to failure will be very small, hence the term LCF. Usually a strain-life curve instead of the S-N curve is used to described fatigue behaviour.

Note that the actual distinction between HCF and LCF is not defined by a certain number of cycles but by the amount of plasticity in the net section, i.e. the stress level.

3. What is the Difference between Low & High Cycle Fatigue?

The difference between low cycle fatigue (LCF) and high cycle fatigue (HCF) has to do with the deformations. LCF is characterized by repeated plastic deformation (i.e. in each cycle), whereas HCF is characterized by elastic deformation. The number of cycles to failure is low for LCF and high for HCF, hence the terms low and high cycle fatigue.

Transition between LCF and HCF is determined by the stress level, i.e. transition between plastic and elastic deformations. That implies that there is no fixed transition life, e.g. 10^3, but that transition life depends on the ductility of the material.

Large numbers of small cycles

Small cycles (i.e. cycles with a small amplitude) lead to longer fatigue lives than large cycles (i.e. cycles with a large amplitude). This fact may lead to the incorrect conclusion that small cycles can be neglected in a fatigue life analysis. However, in a spectrum the number of small cycles is often much larger than the number of large cycles. If so, the small cycles do give a significant contribution to the damage accumulation.

It is sometimes even thought that small cycles can be neglected, resulting in a small number of large cycles, which situation then erroneously is interpreted as LCF. Note that LCF corresponds with cyclic plastic deformations, not with small number of occurrences of large (elastic) cycles.

Stress peaks exceeding the yield limit

In some stress spectra a peak stress may incidentally exceed the yield limit. Does that make the fatigue process LCF? As long as the cycles are dominated by elastic strains, the fatigue mechanism will be typical for the HCF process. An incidental cycle with increased contribution of plastic strain does not change this.

If stresses close to a notch exceed the yield limit, some local plastic deformation will occur. Subsequent elastic unloading leads to an inhomogeneous stress distribution. At the edge of the notch there will be compressive stresses, which are in fact favourable for fatigue.

Damage Mechanism

The HCF mechanism is determined by cyclic elastic strains. Important parameters are the stress concentration factor (presence of a stress gradient), surface roughness and conditions and mean stress levels. The LCF mechanism is determined by cyclic plastic deformations. The parameters that are important for HCF have no impact on LCF.

Since the mechanisms are so different, different methods should be used for fatigue life estimation for HCF (using S-N data) and LCF (using e-N data). However, despite of the difference, it happens often that LCF methods are used for HCF analysis using local stresses (or strains).

10 Tips for Designing Against Fatigue

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About Johannes Homan

Johannes has a background in aerospace engineering and has specialized himself in fatigue and damage tolerance. After his graduation at Delft University of Technology (faculty of Aerospace Engineering) Johannes started working at Fokker Aircraft as Fatigue & Damage Tolerance specialist.

In 1996 Johannes started his own firm: Fatec Engineering and works in this firm since then. During that period, Johannes was also active as researcher and assistant professor at Delft University of Technology (faculty of Aerospace Engineering) and as researcher at GTM Advanced Structures.

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