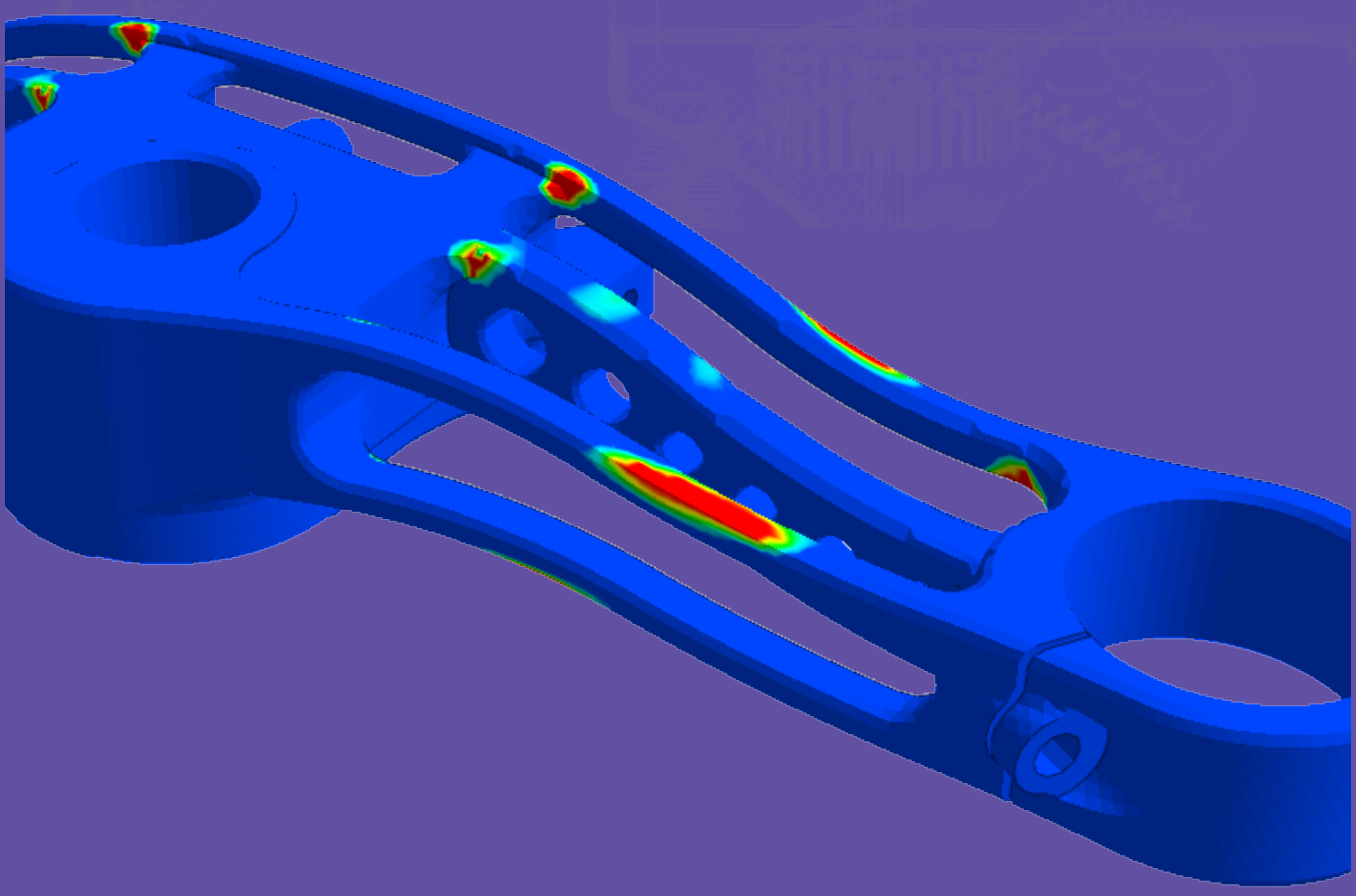
FEA forAll
From basics to Advanced

A Guide to Fatigue Analysis

This guide starts from the applications of fatigue analysis and its role in FEA simulation. Fundamental concepts and principles will be introduced such as what is fatigue, fatigue design philosophy, life estimation methods, stress life approach, etc...



About the Author:

My name is Cyprien Rusu, I am a French CAE engineer who wants to teach the right bases of FEA Simulation to designers, engineers and everyone aspiring to get it right!
Hundreds of FEA students followed my free FEA webinars on Youtube, read my blog articles on feaforall.com and joined my FEA courses to learn more and improve their understanding of FEA and become better engineers!

I have also taught FEA seminars to FEA engineers from all over the world…

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1- What is Fatigue Failure?

Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking under repeated alternating or cyclic stresses of an intensity considerably below the normal strength.

Although the fracture is of a brittle type, it may take some time to propagate, depending on both the intensity and frequency of the stress cycles.

Examples of fatigue failure

All structures and mechanical components that are cyclically loaded can fail by fatigue.

Fundamental requirements during design and manufacturing to avoid fatigue failure are different for each different case and should be considered during the design phase.

2- Fatigue Design Philosophy

Before attempting to carry out a fatigue calculation, or even choosing a way of calculating, it is necessary in critical situations to decide on a design philosophy.

The three main approaches are Safe-Life, Fail-Safe and Damage-Tolerant.

Safe-Life

Products are designed to survive a specific design life. Full scale tests are usually carried out with margins of safety applied. Fairly optimized structures.

A “safe-life” stool.
Any less than three legs and it would fall over!

Fail-Safe

Products are designed to avoid any failure regardless of costs. If the structure were to fail in some part, it would capable to working properly, until necessary repairs could be made.

A “Fail-Safe” stool.
Failure of one leg would not result in overall failure.

Damage-Tolerant

Products are design to take into account inspection criterion to investigate the structure periodically to see whether or not crack have started.

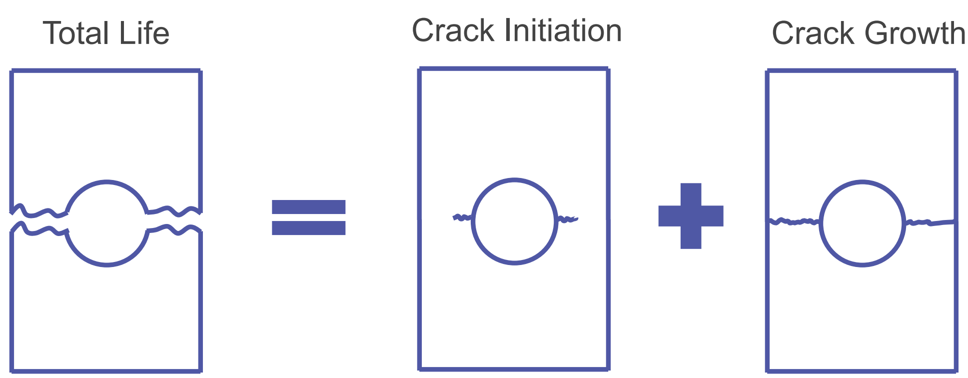
A “damage-tolerant” stool.
The stool has some built in redundancy and is inspected regularly.

3- Life Estimation Methods

Fatigue analysis itself usually refers to one of two methodologies.

The stress-life (or S-N method), is commonly referred to as the total life method since it makes no distinction between initiating or growing a crack. This was the first fatigue analysis method to be developed over 100 years ago.

The local-strain or strain-life (E-N) method, commonly referred to as the crack initiation method, was more recently developed and is intended to describe only the 'initiation' of a crack.



An idealization of the fatigue design process

Fracture specifically describe the growth or propagation of a crack once it has been initiated and has given rise to many so-called crack growth methodologies.

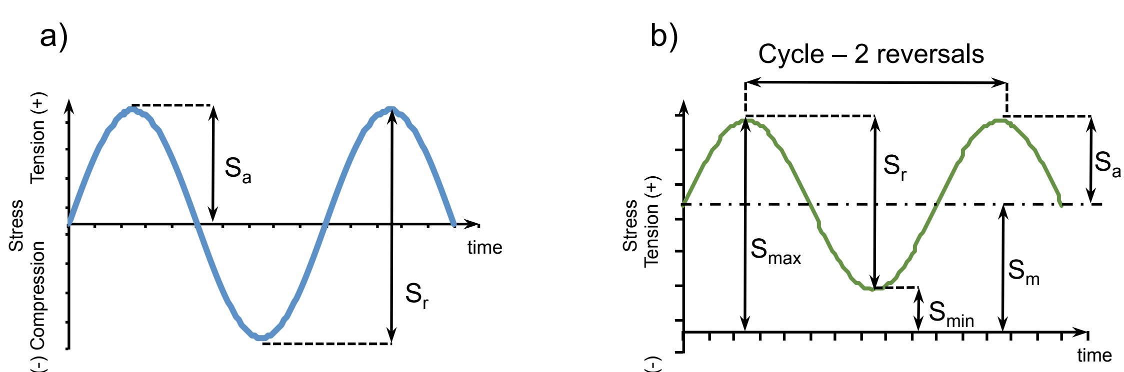
4- Fatigue Loading

Some load histories may be simple and repetitive, while in other cases they may be completely random. They can also have constant or variable amplitudes.

For simple cases constant amplitude loading is used to obtain material fatigue behavior/properties for fatigue design.

Some real life load histories can occasionally be modeled with constant amplitude as well.

Constant amplitude loading has been introduced below:



S_{min} – minimum stress
S_{max} – maximum stress
S_a – alternating stress (stress amplitude)
S_m – mean stress
S_r – stress range

R – stress ratio

R = -1 fully reversed cycle
R = 0 pulsating tension

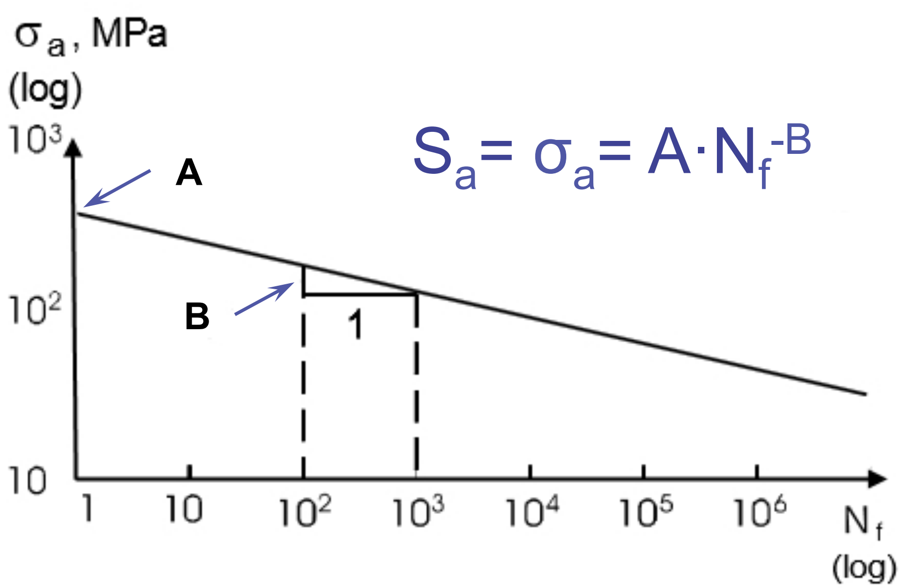
Examples of stress cycles, (a) fully reversed, and (b) offset.
Stresses can be replaced with load, moment, torque, strain, deflection or stress intensity factors.

5 - Wőhler's Curve, S-N Curve

This curve has been developed by German August Wőhler for his systematic fatigue tests done in the 1870's.

S-N Curve plots the diagram of **amplitude of nominal stress** as a function of number of cycles to failure for **un-notched** (smooth) specimens.

Mathematical description of the material S-N curve:



$$S_a = \sigma_a = A \cdot N_f^{-B}$$

σ_a – applied alternating stress
A – constant, value of σ_a at one cycle
B – Basquin's exponent, slope of the log-log curve
N_f - the number of cycles of stress that a specimen sustains before failure occurs

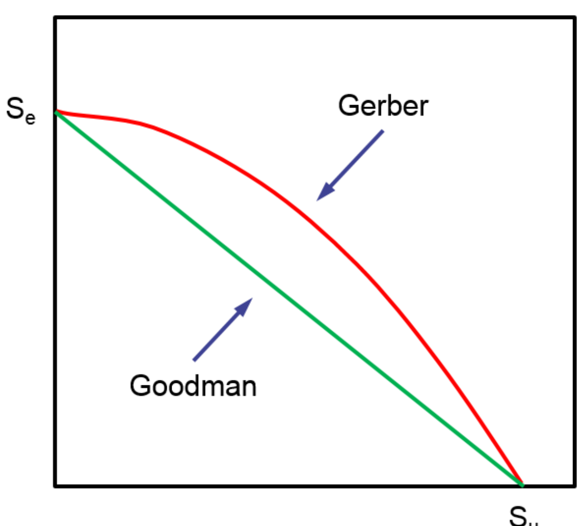
6 - Stress Life Approach

Stress life method, more commonly known as the S-N or Nominal Stress method is used for total life calculation.

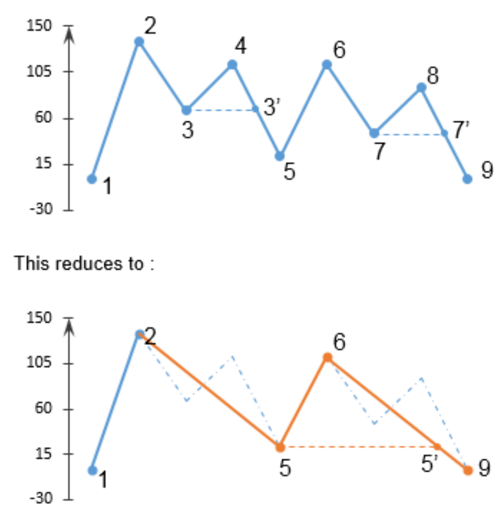
It assumes the structure to be fully elastic (even in local fatigue related details like notches). Initiation or growing phase of a crack is not considered. Applicable to **high cycle fatigue** problems (low load-long life). This approach should not be used to estimate fatigue lives below 10,000 cycles.

Some basic features related to Stress-Life approach:

- Material and component S-N curves
- Stress concentration factors,
- Miner’s cumulative damage theory
- Goodman or Gerber mean stress correction
- Rainflow Cycles Counting



Gerber-Goodman diagram



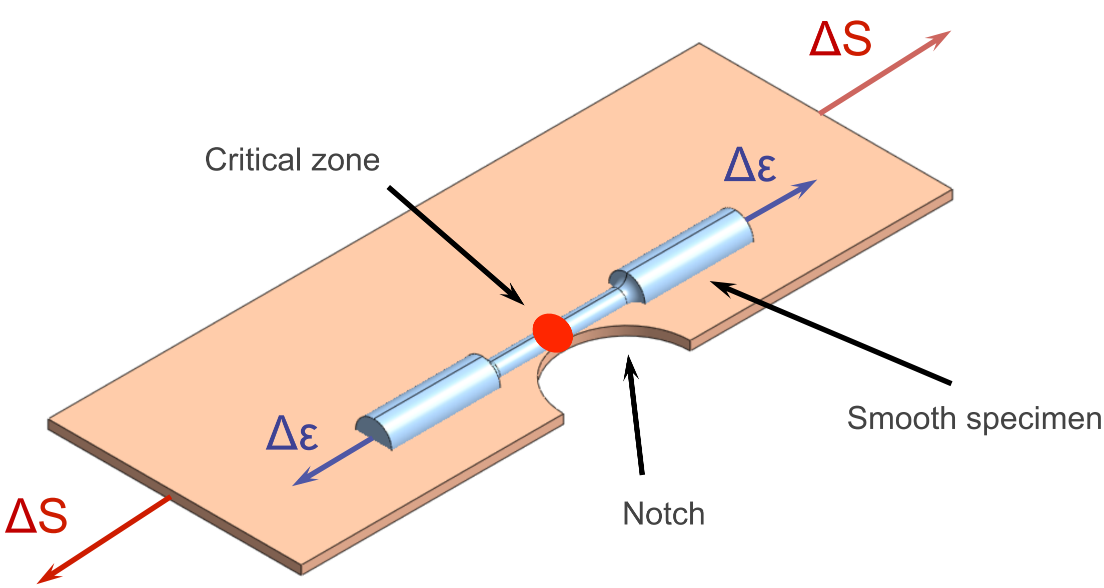
Rainflow cycles counting example

7 - Strain Life Approach

This method is also called Critical Location (CLA) approach, Local Stress-Strain, E-N or Crack Initiation.

It applies when the structure durability depends on stress amplitude of local strain at the crack initiation place. Strain-life design method is based on relating the fatigue life of notched parts to the life of small unnotched specimens cycled to the same strains as the material at the notch root.

This approach is best suited for **low cycle fatigue** problems, where the applied stresses have a significant plastic component.



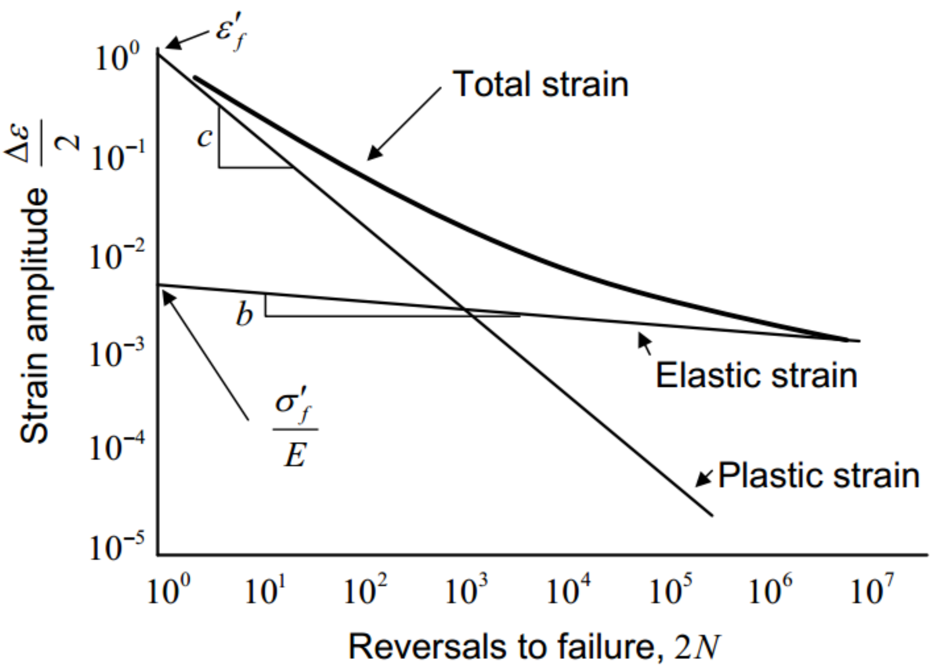
The concept of similitude between strain controlled test specimen and a component being designed

8 - Strain Life Curve

E-N curve shows the relationship between the strain and the number of cycles causing fatigue failure as expressed in equation below.

By applying a number of individual strain amplitudes to the E-N curve, which have been extracted through rainflow-counting, each number of cycles and the corresponding individual damage level are obtained.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} \cdot (2N_f)^b + \varepsilon'_f \cdot (2N_f)^c$$



$\Delta\varepsilon/2$ – total strain amplitude = ε_a
N_f - the number of cycles of stress that a specimen sustains before failure occurs
E – modulus of elasticity

σ_f' – fatigue strength coefficient
ε_f' – fatigue ductility coefficient
C – fatigue ductility exponent

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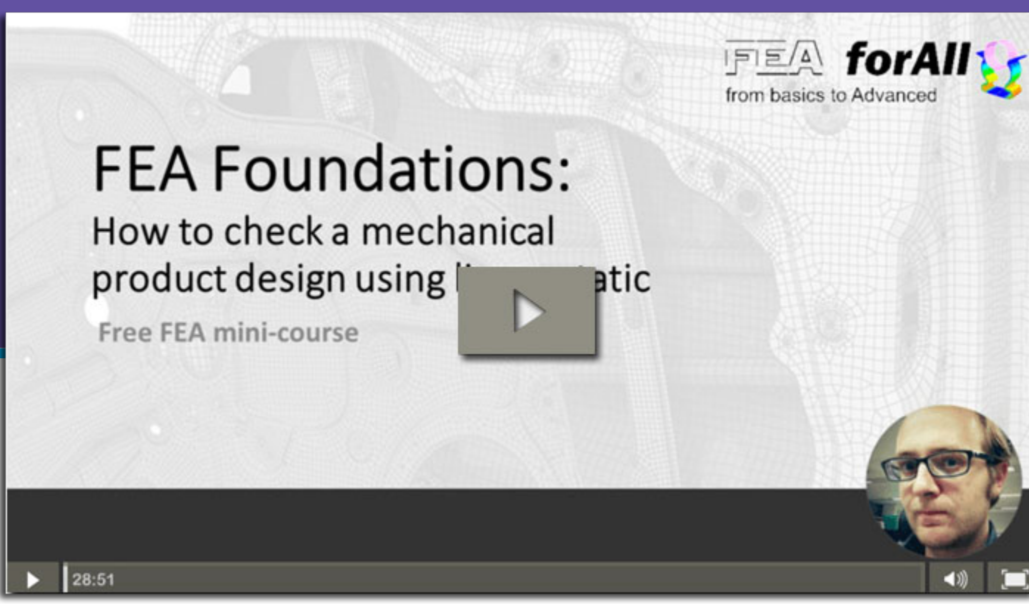

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