Fatigue in Materials

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Fatigue

- Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses.
- It is observed that materials subjected to dynamic/repetitive/fluctuating load (stress) fail at a stress much lower than that required to cause fracture in a single application of load.
- When a material is subjected to a force acting in different directions at different times it can cause cracking.
- In time this causes the material to fail at a load that is much less than its tensile strength, this is fatigue failure.
- Vibration for example is a serious cause of fatigue failure.
- The term fatigue is borrowed from human reaction of ‘tiredness’ due to repetitive work!

Cyclic Stresses

The applied stress may be generally of three types

1) Axial (tension-compression),
2) Flexural (bending), or
3) Torsional (twisting) in nature.

Three factors play an important role in fatigue failure

1) Value of tensile stress (maximum),
2) Magnitude of variation in stress,
3) Number of stress cycles.

In general, three different fluctuating stress–time modes are possible

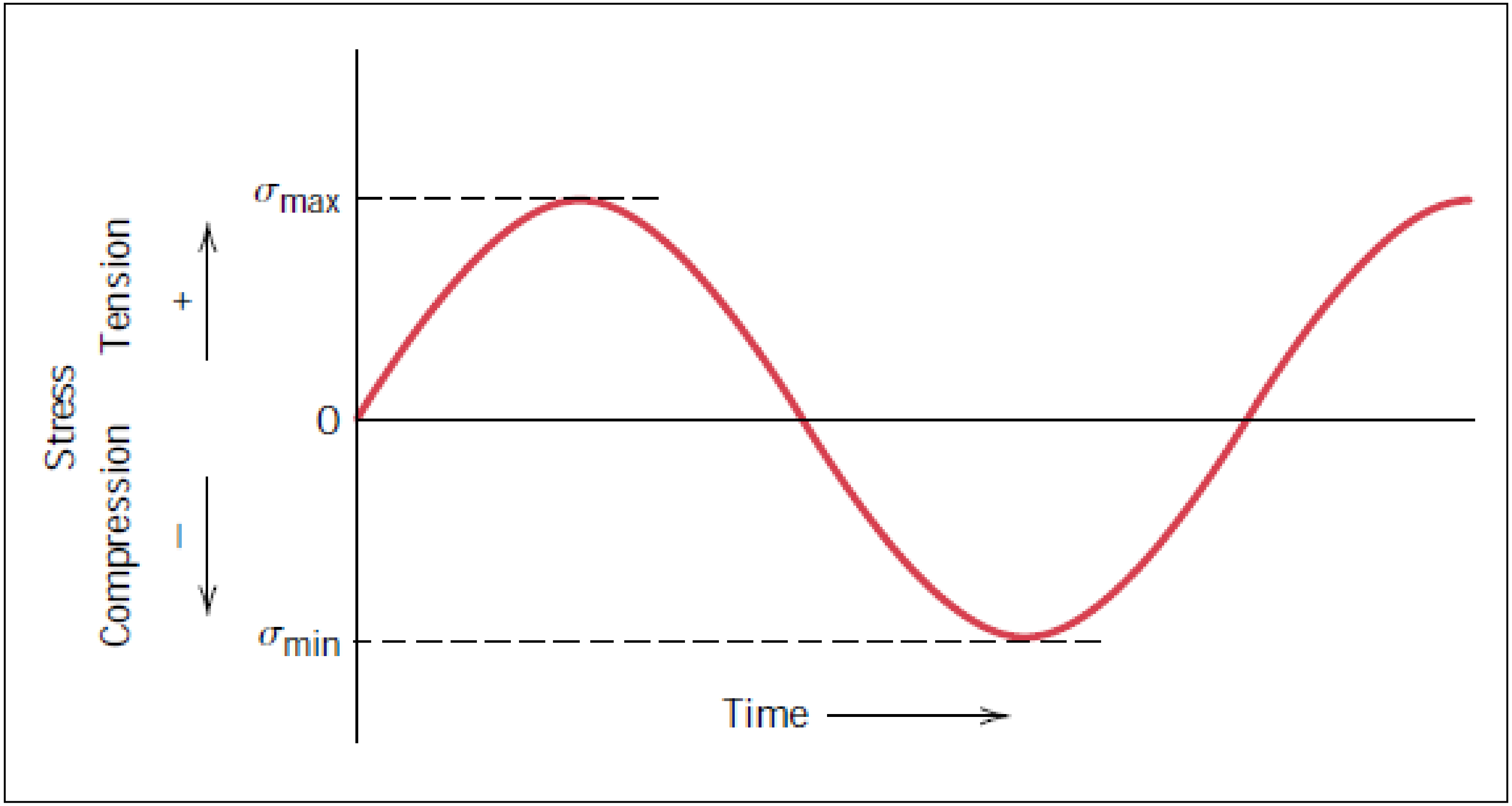


Fig. 1: Variation of stress with time that accounts for fatigue failures.

A regular and sinusoidal time dependence of stress, wherein the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress (σ_{max}) to a minimum compressive stress (σ_{min}) of equal magnitude; this is referred to as a *Reversed Stress Cycle*.

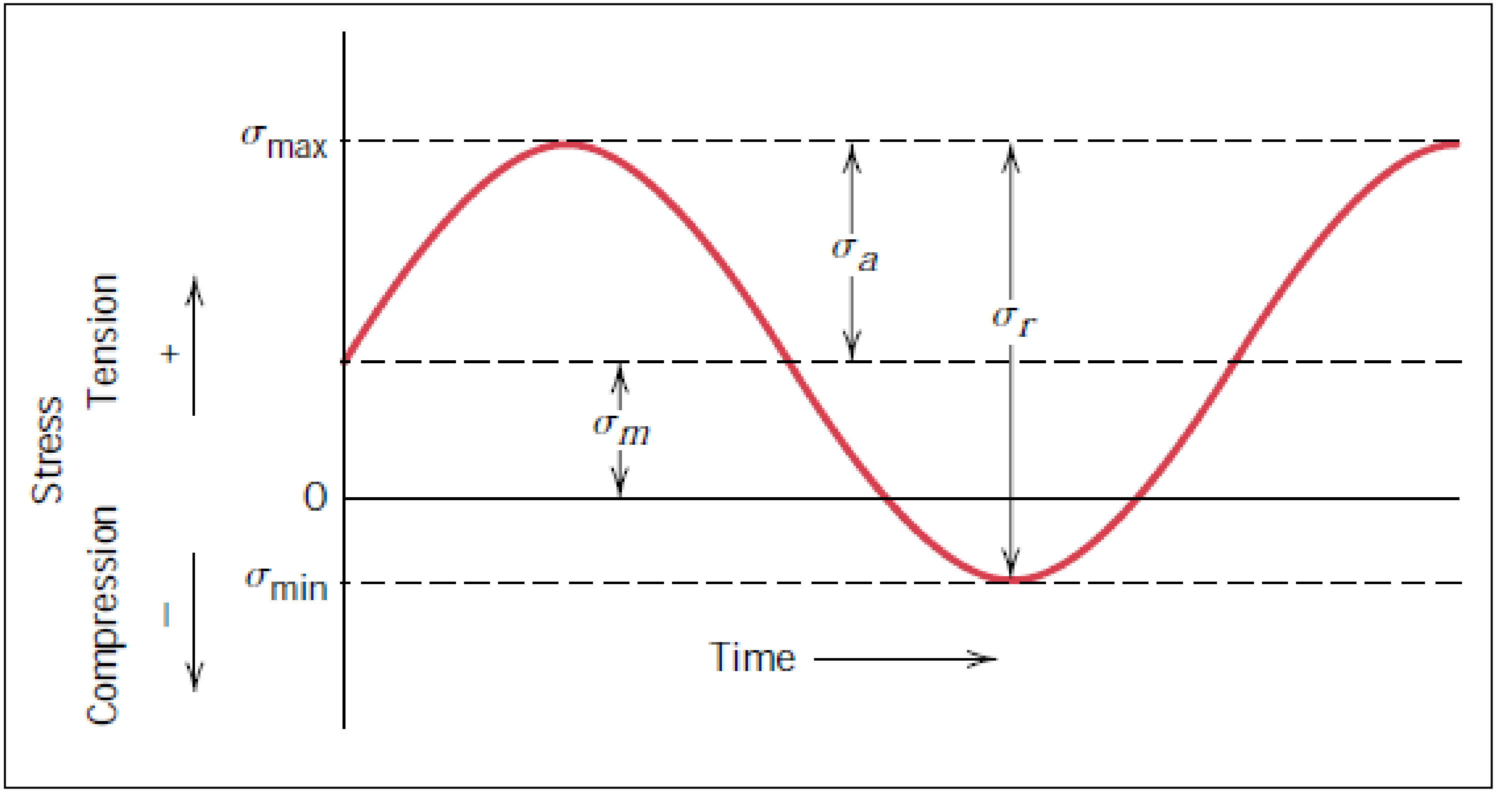


Fig. 2: Variation of stress with time that accounts for fatigue failures.

Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero stress level; mean stress (σ_m), range of stress (σ_r) and stress amplitude (σ_a) are indicated.

Mean Stress (σ_m)	Range of Stress (σ_r)	Stress Amplitude (σ_a)
$\sigma_m = \dfrac{\sigma_{max} + \sigma_{min}}{2}$	$\sigma_r = \sigma_{max} - \sigma_{min}$	$\sigma_a = \dfrac{\sigma_r}{2} = \dfrac{\sigma_{max} - \sigma_{min}}{2}$

$$Stress\ ratio \rightarrow R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

$$Amplitude\ ratio \rightarrow A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R}$$

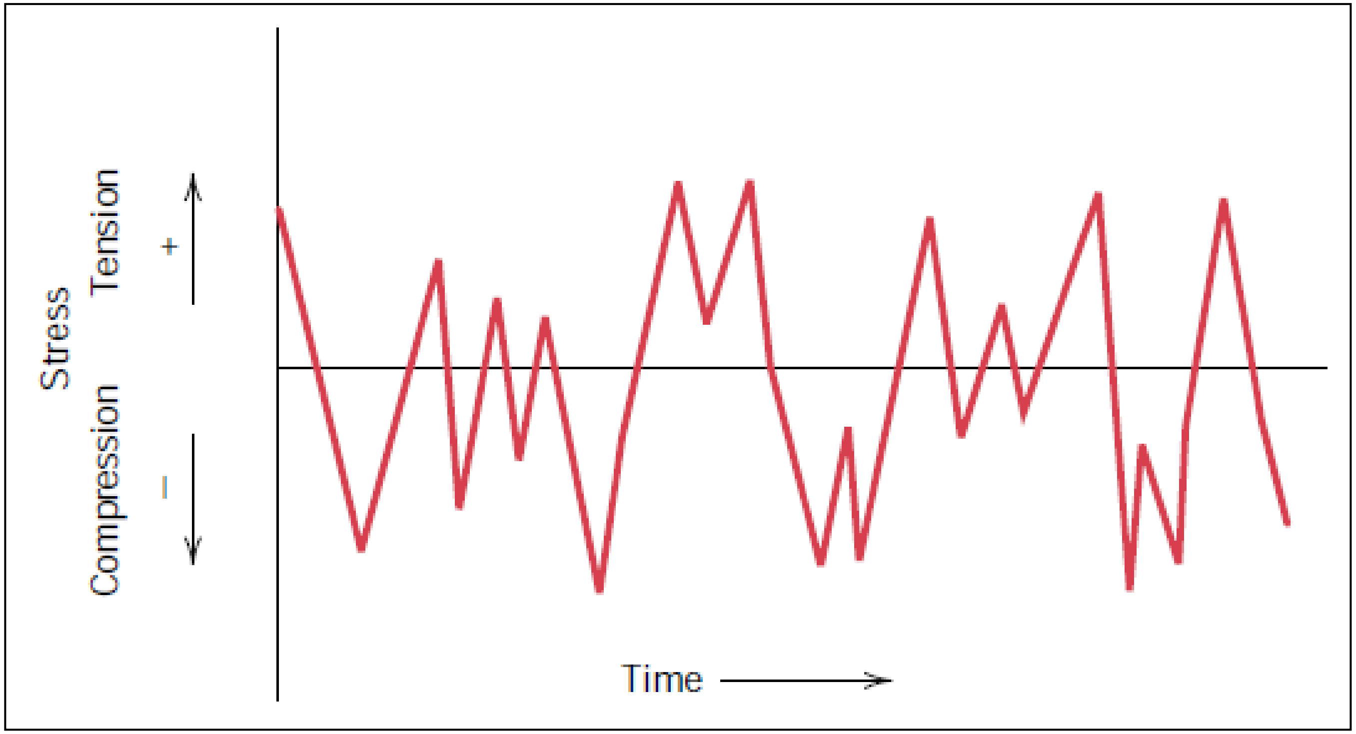


Fig. 3: Variation of stress with time that accounts for fatigue failures.

The stress level may vary randomly in amplitude and frequency (*Random Stress Cycle*)

S – N Curve

- Engineering fatigue data is usually plotted as a S-N curve.
- Here S is the stress and N the number of cycles to failure (usually fracture).
- The x-axis is plotted as log(N).

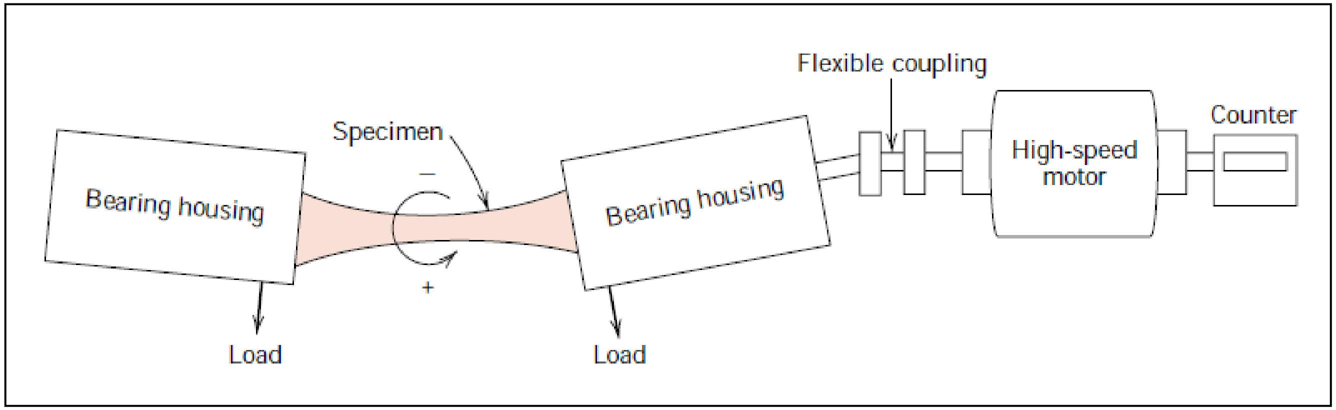
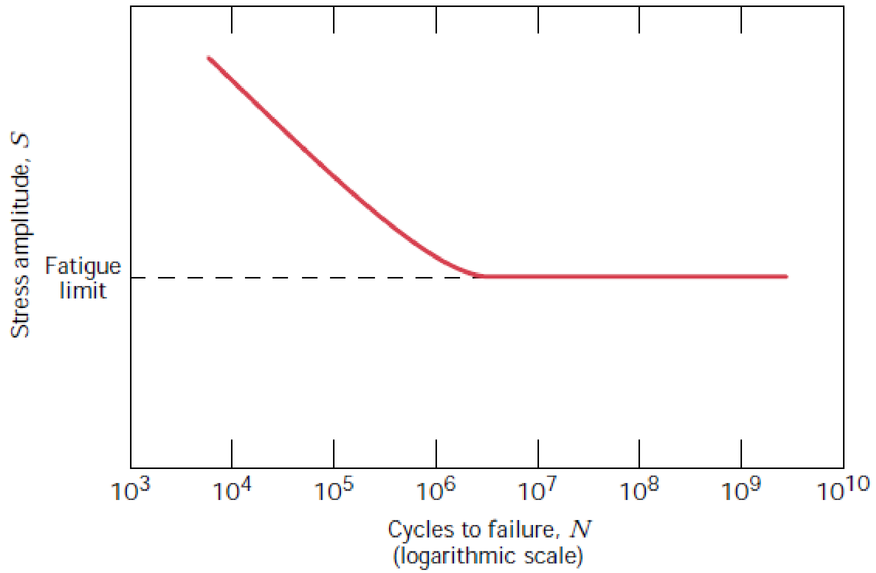


Figure: A schematic diagram of a rotating-bending test apparatus, commonly used for fatigue testing,

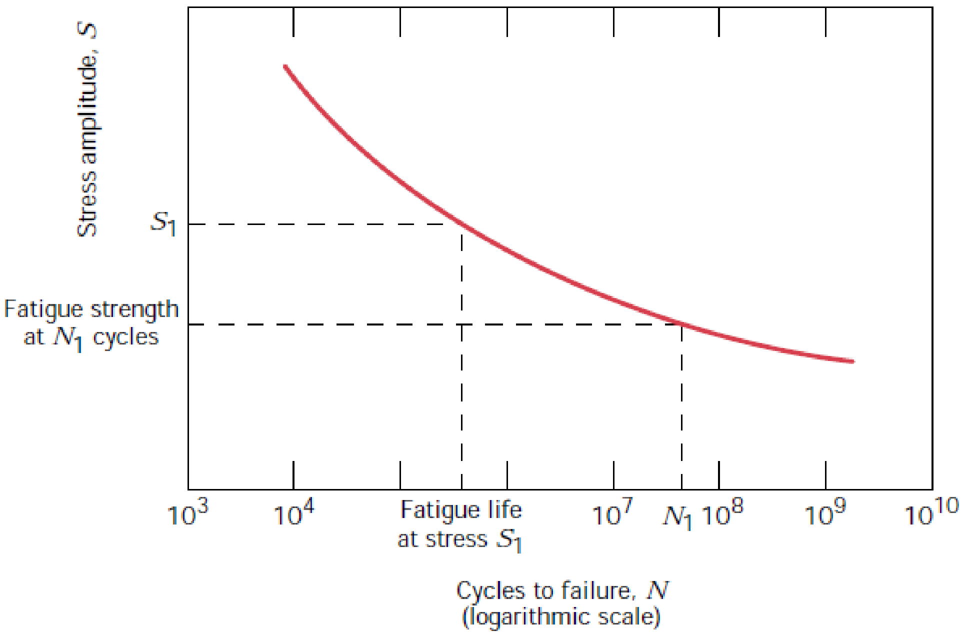
- A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude (σ_{max}), usually on the order of two thirds of the static tensile strength; the number of cycles to failure is counted.
- Data are plotted as stress *S* versus the logarithm of the number *N* of cycles to failure for each of the specimens.
- Values of *S* are normally taken as stress amplitudes (σ_a); on occasion, σ_{max} or σ_{min} values may be used.

Two types of Stress amplitude (*S*) versus logarithm of number of cycles to fatigue failure (*N*)



(*a*) a material that displays a fatigue limit

- The higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.
- For some ferrous (iron base) and titanium alloys, the *S*–*N* curve becomes horizontal at higher *N* values; or, there is a limiting stress level, called the **fatigue limit** (also sometimes the ***endurance limit***), below which fatigue failure will not occur.
- This fatigue limit represents the largest value of fluctuating stress that will *not* cause failure for essentially an infinite number of cycles.
- For many steels, fatigue limits range between 35 and 60% of the tensile strength.



(*b*) a material that does not display a fatigue limit.

- Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the *S*–*N* curve continues its downward trend at increasingly greater *N* values.
- Thus, fatigue will ultimately occur regardless of the magnitude of the stress.
- For these materials, the fatigue response is specified as fatigue strength, which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., 107 cycles).
- The determination of fatigue strength is also demonstrated in Figure.

"How does Fatigue Failure occur if the stress value used is below the yield stress?"

- Fatigue failure occurs because of microscopic plasticity (which can occur below the yield stress) and damage accumulation with time (i.e. number of cycles of loading).
- Four important stages of fatigue can be identified:

1) **Crack initiation**: This occurs mostly at surfaces or sometimes at internal interfaces.
2) **Stage-I crack growth**: Growth of crack along planes of high shear stress. This can be viewed as essentially extension of the slip process which lead to crack formation.
3) **Stage-II crack growth**: In this stage, the crack grows along directions of maximum tensile stress. Hence, crack propagation is trans-granular.
4) **Ductile failure**: Reduction in load bearing area (due to crack propagation) leads to ultimate failure.

- Crack which forms after stage-1 can be removed by annealing (damage is reversible at that stage).

Crack initiation → Crack deepening → Crack growth → Failure