

Fatigue Analysis Basics

Fatigue stress, S-N curves, HCF vs LCF, loading histories and durability testing

Core Concepts

Fatigue	Progressive weakening under cyclic loading, even when every cycle is within design limits. The most common source of mechanical failures.
Fatigue vs static failure	Static: one load event exceeds strength. Fatigue: many cycles, none near static strength.
S-N curve	Stress amplitude (S) vs cycles to failure (N), usually log scale. Estimates life at a given stress.
Endurance limit	Stress below which many steels survive theoretically infinite cycles. Most aluminum alloys have none.
Beach marks	Ripple pattern on the fracture surface left by crack growth.

Stages of Fatigue Failure

Stage	What happens
1. Crack initiation	Microscopic crack forms at a stress concentration: surface flaw, notch or inclusion.
2. Crack propagation	Crack grows a little each cycle, leaving beach marks.
3. Final fracture	Remaining section can't carry the load and fails suddenly, below static strength.

HCF vs LCF and the Analysis Method

	High-cycle fatigue (HCF)	Low-cycle fatigue (LCF)
Cycles	Typically > 10,000	Often < 10,000
Stress level	Below yield (elastic)	Above yield (plastic strain each cycle)
Method	Stress-life (S-N)	Strain-life (ϵ -N)
Test control	Load control, $R = 0.1$	Strain control, $R = -1$
Example	Suspension part cracking after years of driving	Severe overloads

Using stress-life on a low-cycle problem can significantly overestimate fatigue life.

Standard Cyclic-Stress Relations

Stress amplitude	$\sigma_a = (\sigma_{\max} - \sigma_{\min}) / 2$	Half the stress range.
Mean stress	$\sigma_m = (\sigma_{\max} + \sigma_{\min}) / 2$	
Stress ratio	$R = \sigma_{\min} / \sigma_{\max}$	$R = -1$ fully reversed; $R = 0.1$ tension-tension.
Basquin (S-N)	$\sigma_a = \sigma'_f (2N)^b$	Power-law fit to the HCF region.
Miner's rule	$D = \sum n_i / N_i$; failure at $D \approx 1$	Damage summation for variable-amplitude loading.

Loading Histories

Type	Description	Automotive examples
Constant amplitude	Every cycle the same over time	Body-in-white roof headers carrying a sunroof module; steady-state braking
Variable amplitude	Cycles fluctuate in magnitude	Suspension over potholes and bumps; engine vibration
Uniaxial / multiaxial	One direction vs several (vertical, fore-aft, lateral)	Multiaxial chassis load cases

How Engineers Test for Fatigue

Method	Purpose
Proving grounds	Controlled road surfaces, curves and grades that mimic real conditions
Accelerated testing	Higher-than-real stress to reveal failures in days or weeks (e.g. cycling ignition 20,000 times)
FEA	Apply load histories to virtual models; cheaper than physical testing
Test machines	Servo-hydraulic, electro-mechanical, all-electric dynamic and resonant machines

Factors that accelerate fatigue: corrosion, residual stresses, temperature.