

An update on fatigue testing, modeling and damage accumulation



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Outline



- Description of HS-90 fatigue test program
- Significance of D/t ratio
- Fatigue life
- Ballooning
- Crack width
- Fatigue damage accumulation

Flexor Fatigue Test Machine





Fatigue Test Parameters

- Test parameters: Tube diameter (D), Tube wall thickness (t), internal pressure (p), and bend radius (R)
- Non-dimensional test parameters:

$$\varepsilon = \frac{D}{2R}$$

$$\frac{D}{t}$$

$$\frac{\sigma_h}{\sigma_y} = \frac{P(D_i - 2t)}{2t\sigma_y}$$

Fatigue Test Plan



- Introduce idea of test parameter bins

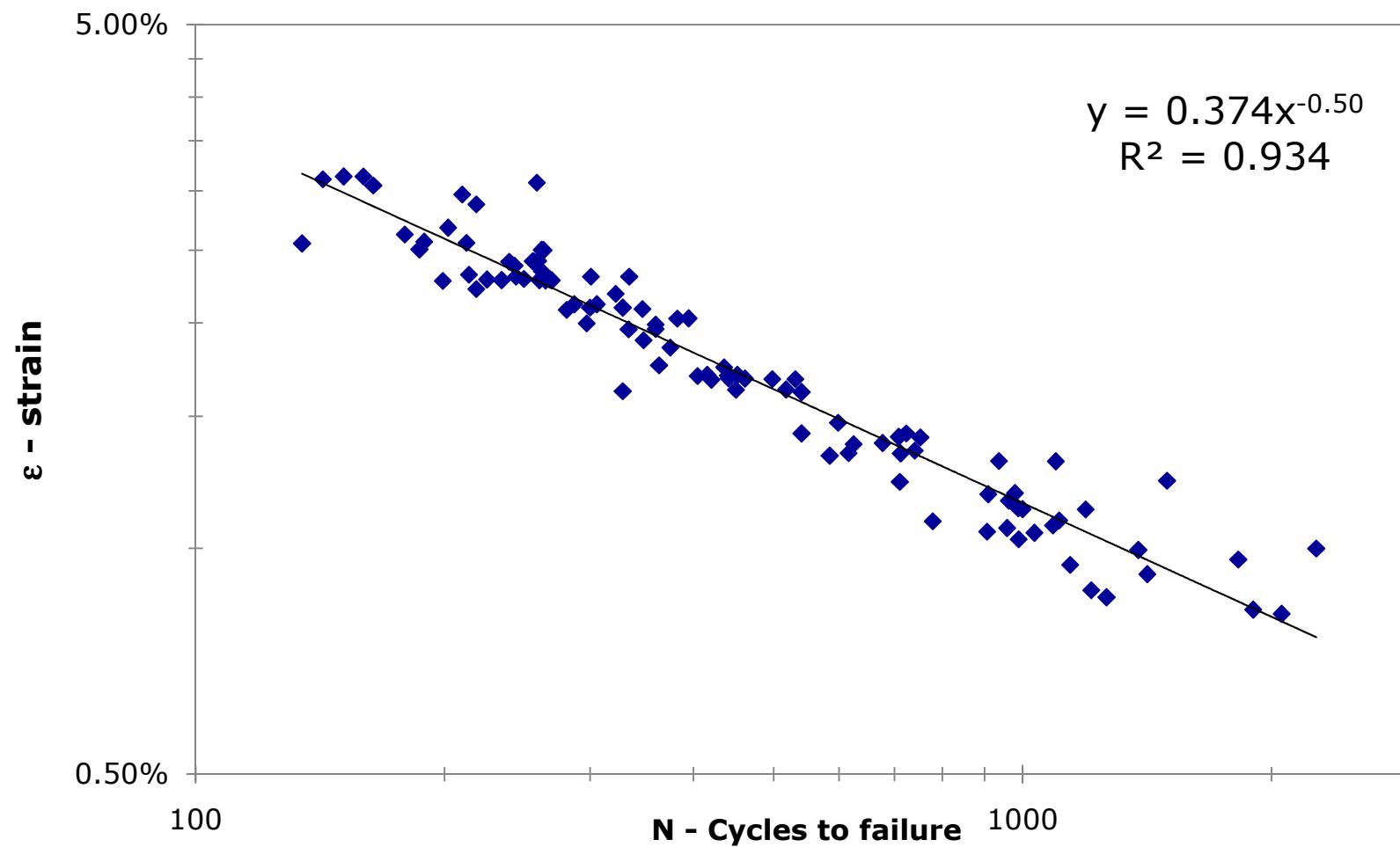
$\frac{D}{t}$ 8-10, 10-12, 12-14, 14-16, 16-18

ε_x 1.0-1.5, 1.5-2.0, 2.0-2.5, 2.5-3.0, 3.0-3.5 (%)

$\frac{\sigma_h}{\sigma_{ys}}$ low, 7%, 25%, 40%, 50%

- 3 parameters x 5 bins each = $5 \times 5 \times 5$ test matrix.
125 tests
- Repeat each condition 4 times = $4 \times 125 = 500$ tests

Fatigue prediction-Manson Coffin





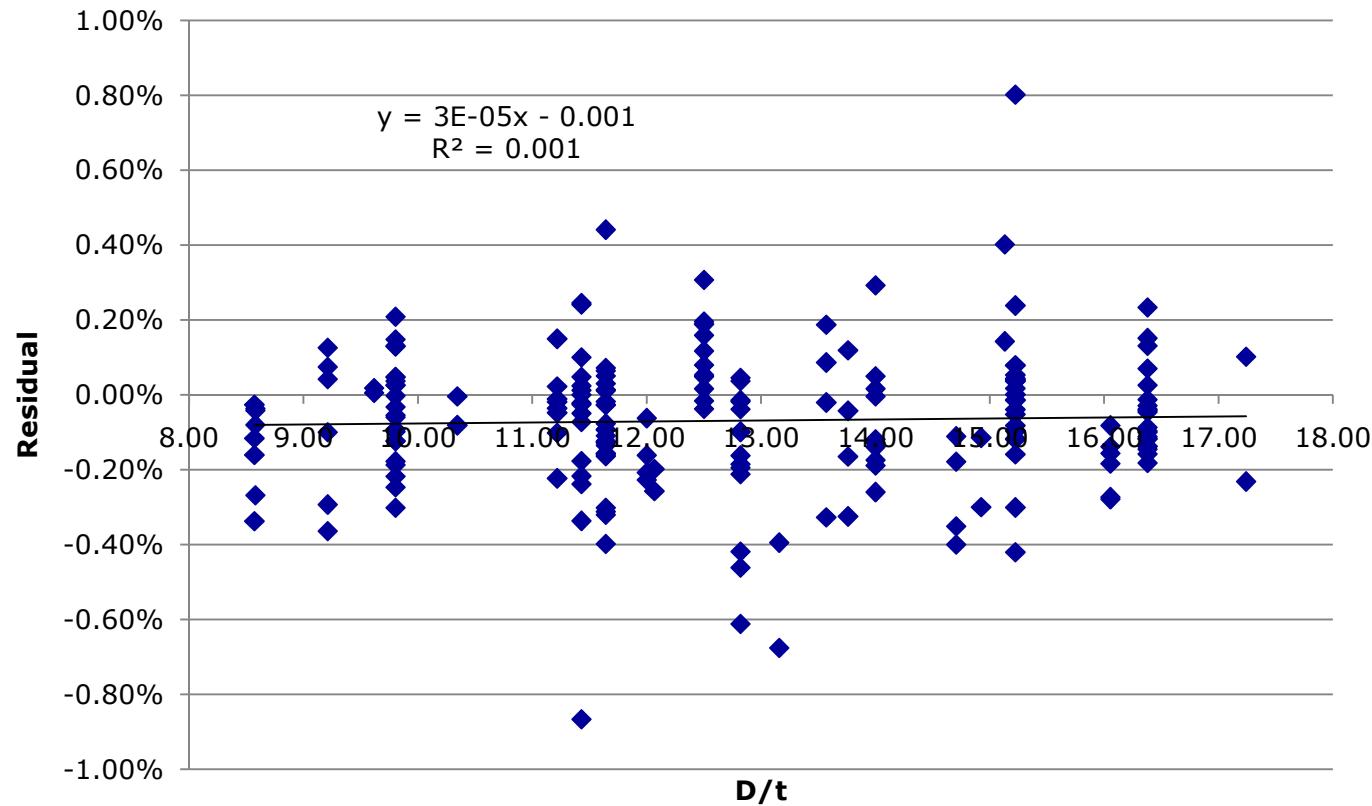
Parameter sensitivity

- Manson-Coffin equation has no “thickness” dependence
- Combine D/t and strain into a single parameter by considering strain **at the ID surface**— reducing independent parameters from 3 to 2
- Follow up testing of regression residual value dependence on D/t

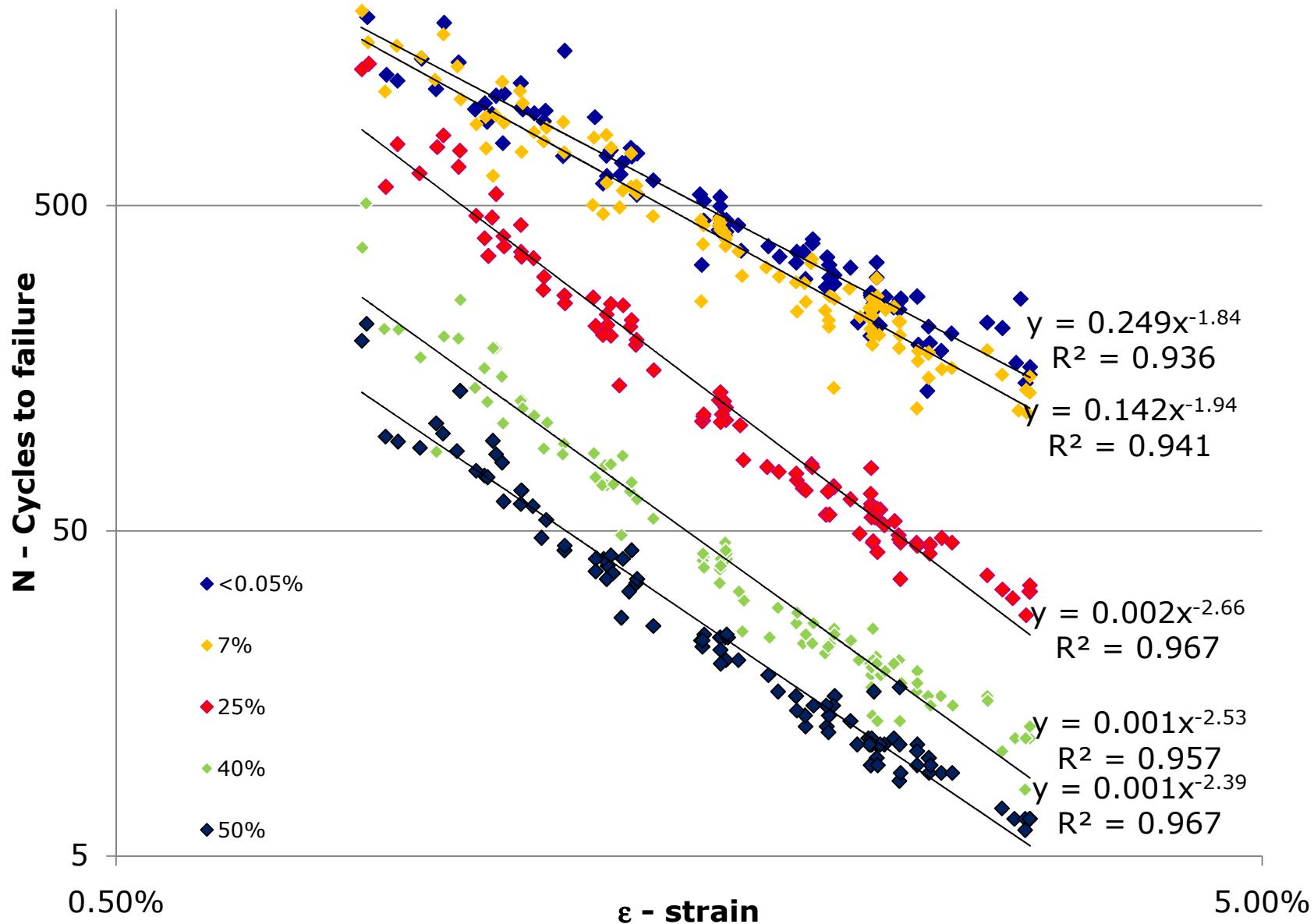
$$\varepsilon_i = \frac{D-2t}{2R+D} = \frac{\varepsilon \left(1 - \frac{2}{D/t} \right)}{\varepsilon + 1}$$



Baseline residual value analysis



Fatigue prediction

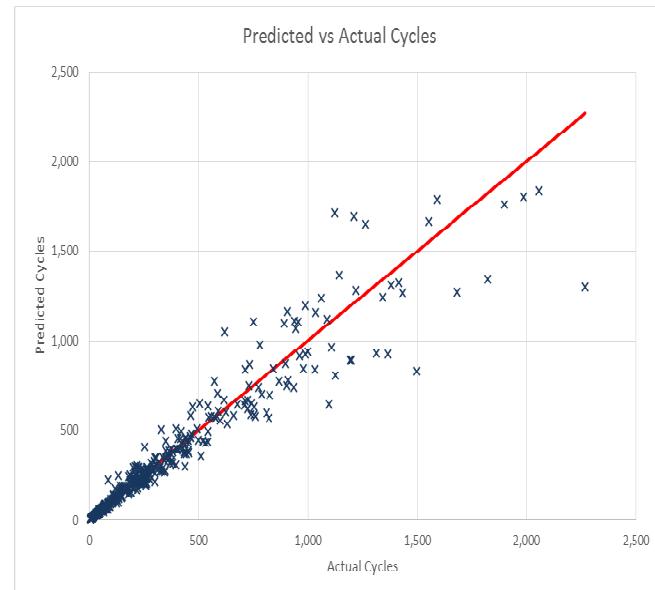
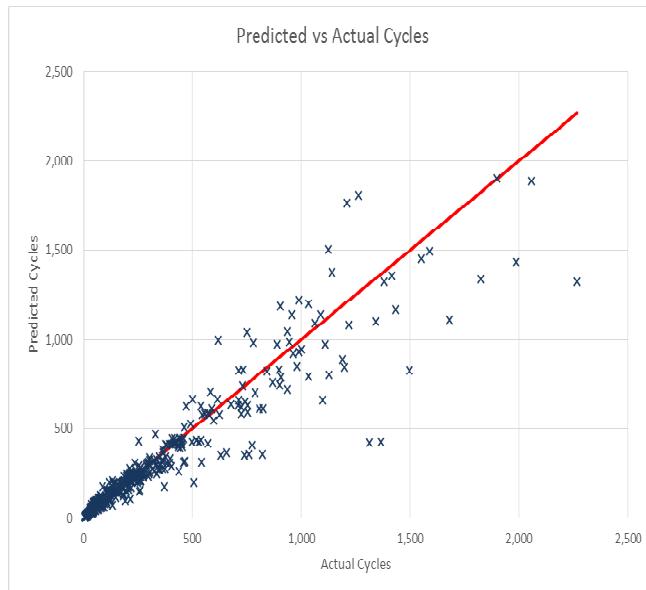




Comparison Old and New Approach

Old
(Flexor/Achilles)
HS90 model $R^2 =$
88.84%

New KNE
model
 $R^2 = 92.32\%$





Tube diameter growth

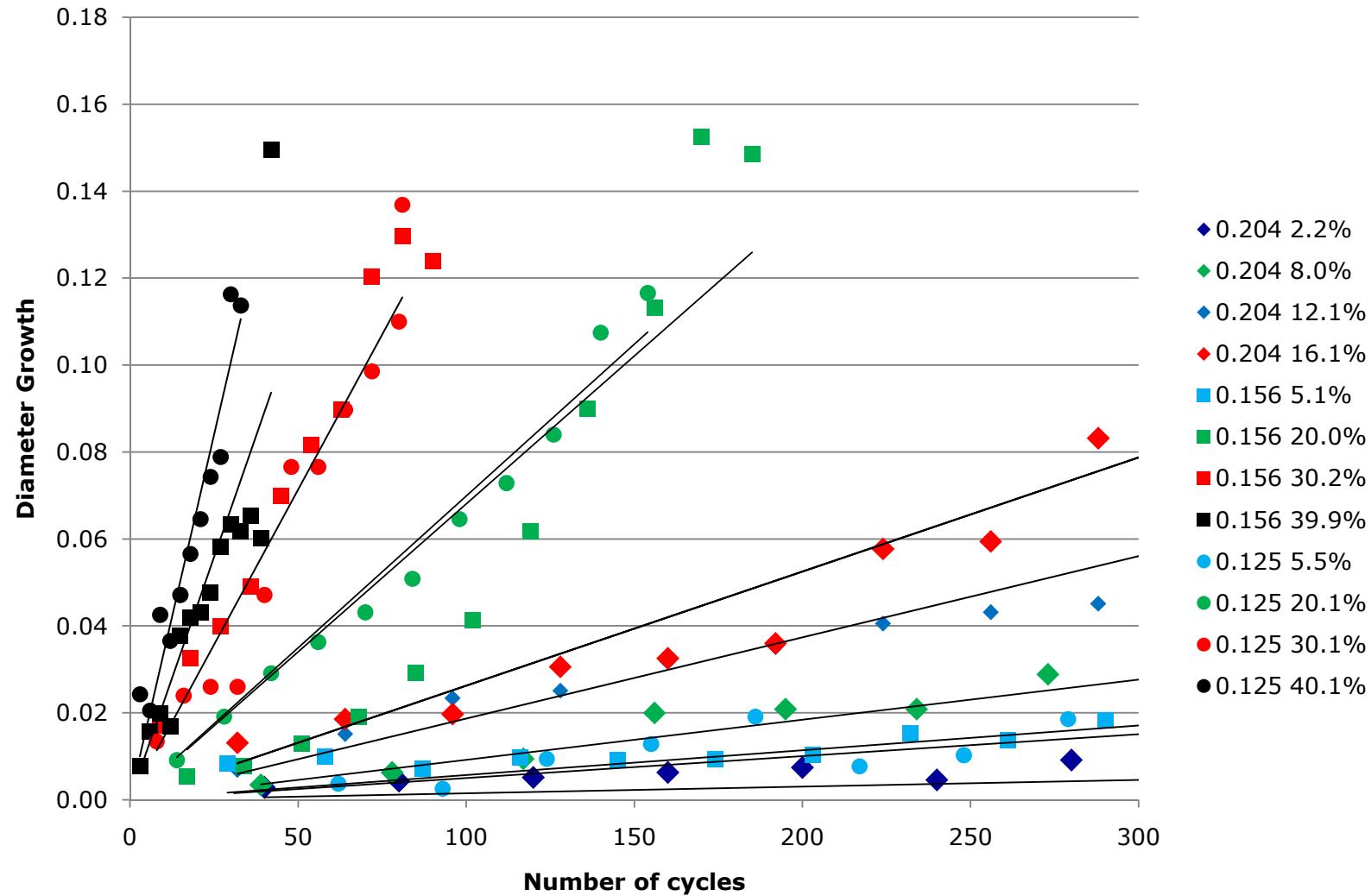
$$\varepsilon_D = \frac{D_f - D_i}{D_i} = f(\varepsilon, \frac{\sigma_h}{\sigma_y}, N)$$

$$DSPC = \frac{D_f - D_i}{D_i N} = f(\varepsilon, \frac{\sigma_h}{\sigma_y}) = f(\frac{\varepsilon \sigma_h}{\sigma_y})$$



Tube diameter growth

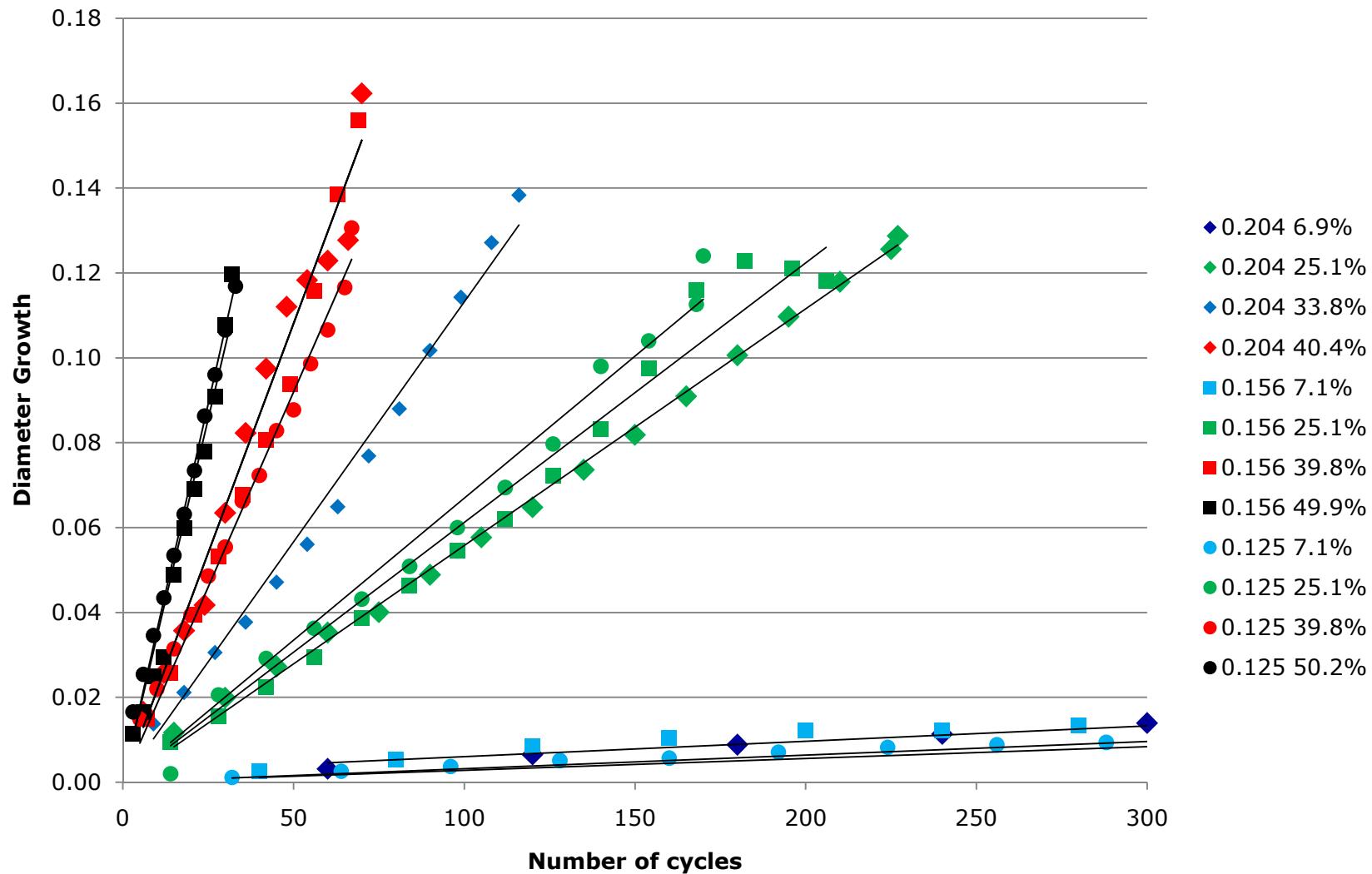
HS-90 Ballooning



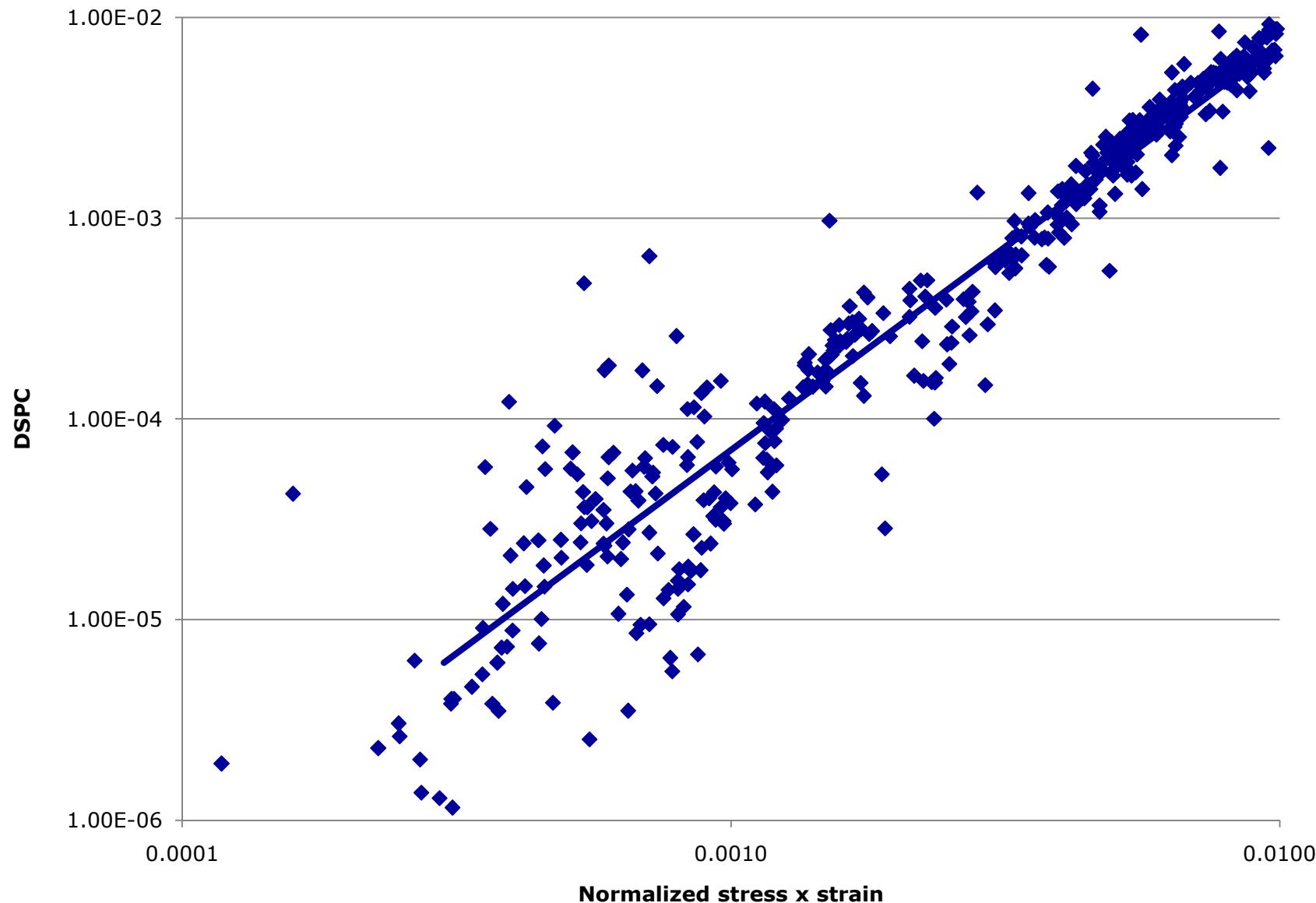


Tube ballooning

HS-110 Ballooning

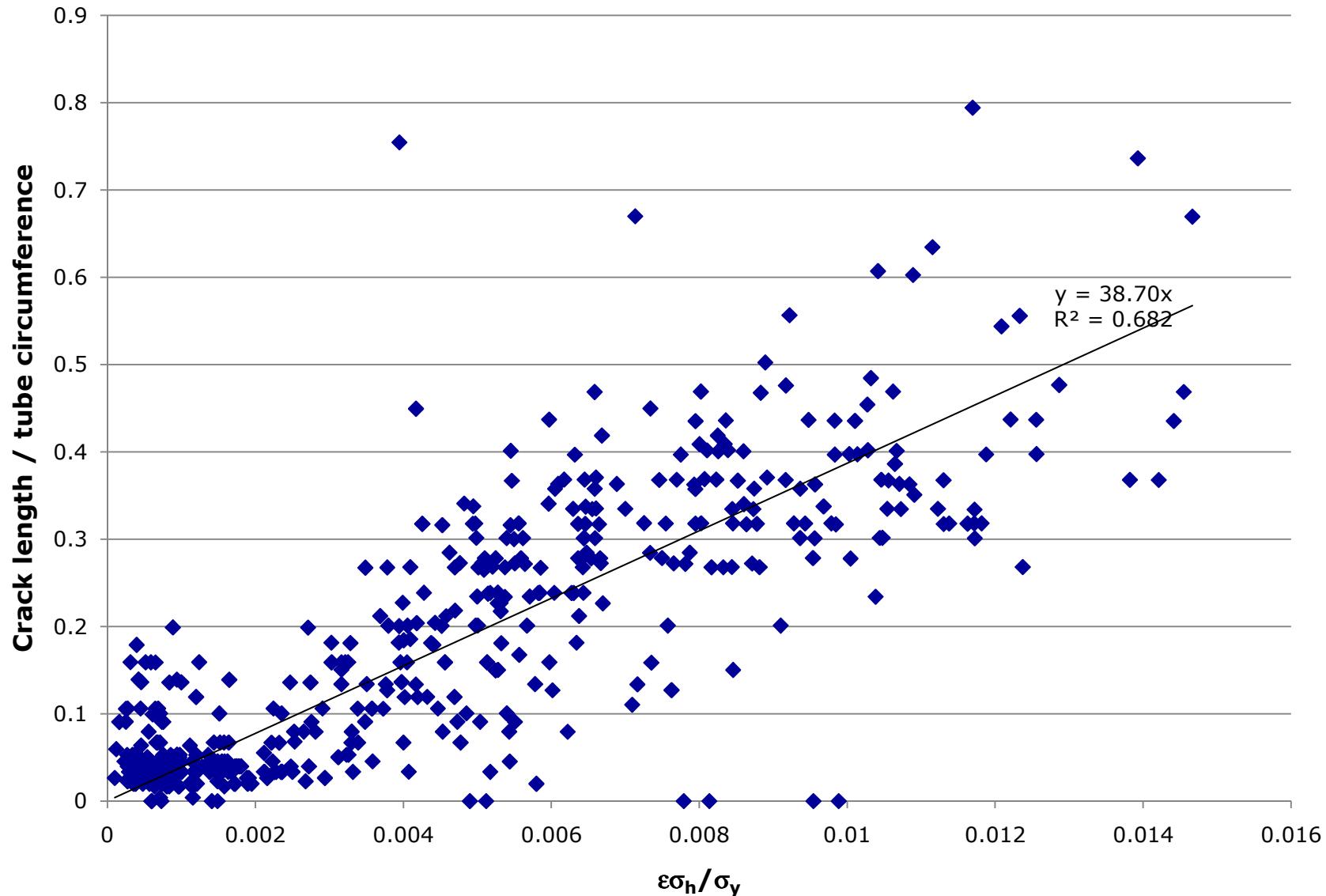


Tube diameter growth





Fracture Length



Fatigue damage accumulation



Question – Suppose the fatigue life of a tube with specified pressure and bend radius is 100 cycles. How much fatigue life is used after 50 cycles?

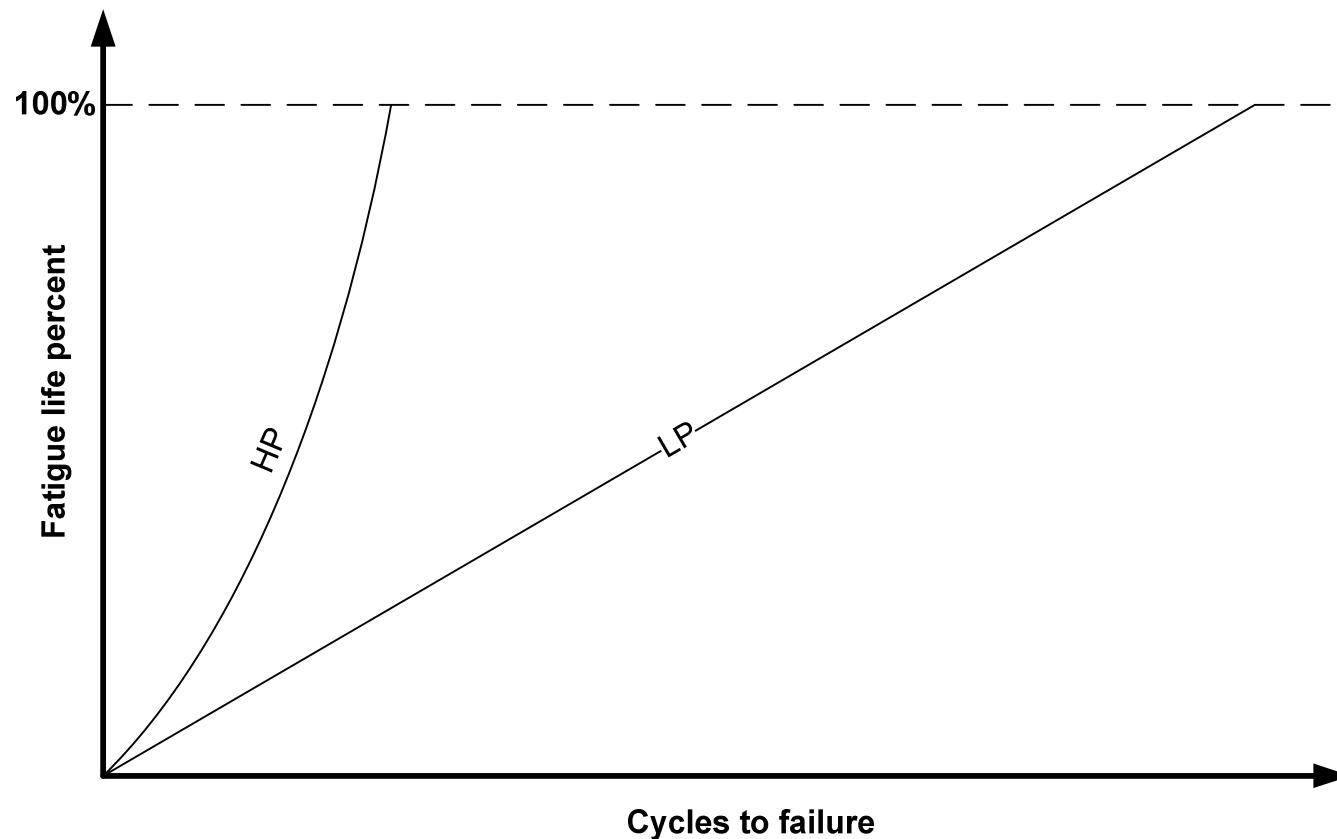
- (a) 50% of fatigue life**
- (b) More than 50%**
- (c) Less than 50%**



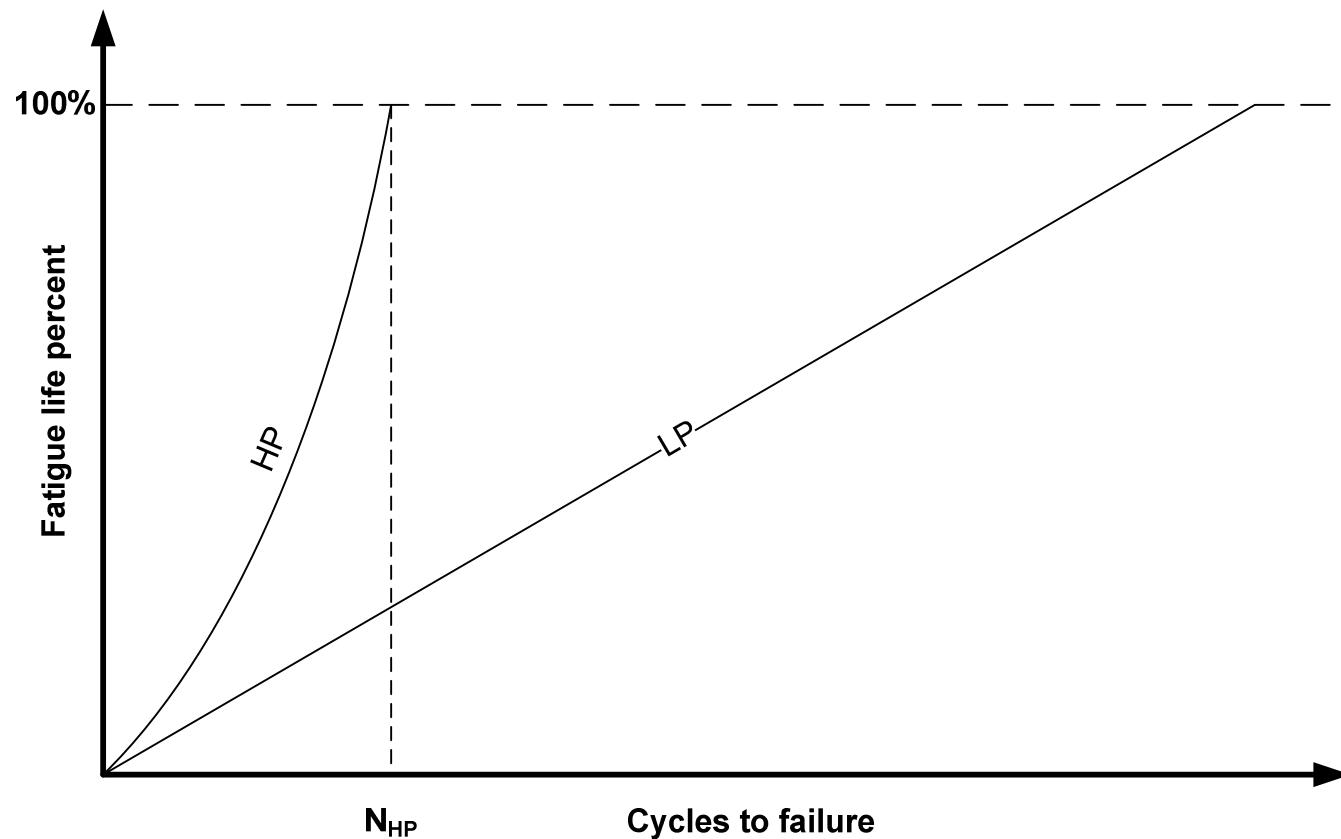
Hi-Lo fatigue testing

- Tube samples were 2" OD x 0.204" WT HS-90
- Bend radius 42"
- 5 tube samples cycled to failure at 8,000 psi – Average cycles to failure N_{HP}
- 5 tube samples cycled to failure at 2,000 psi – Average cycles to failure N_{LP}
- 5 tube samples cycled $N_{HP} / 2$ times at 8,000 psi and then cycled to failure at 2,000 psi
- 5 tube samples cycled $N_{LP} / 2$ times at 2,000 psi and then cycled to failure at 8,000 psi

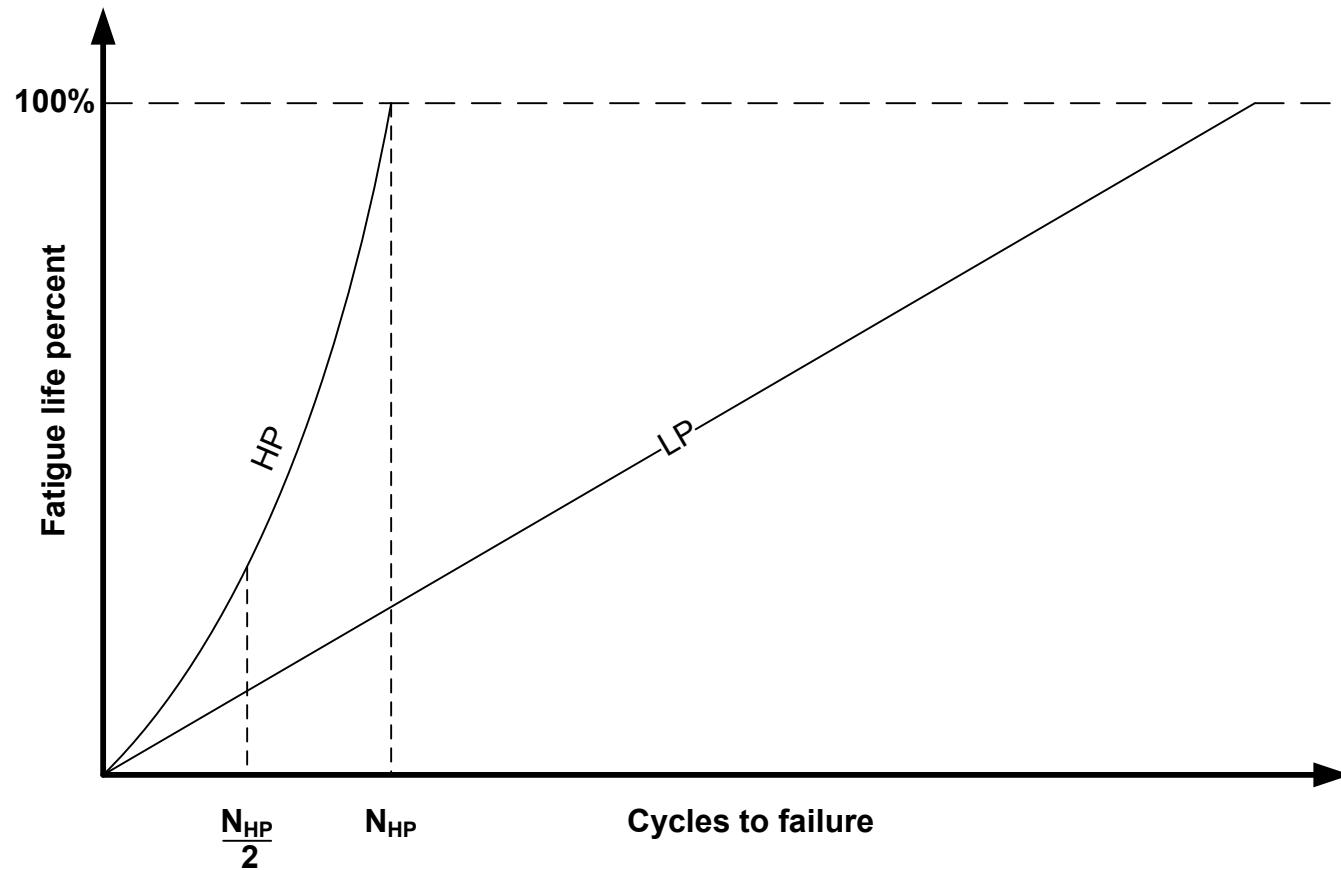
Fatigue damage accumulation



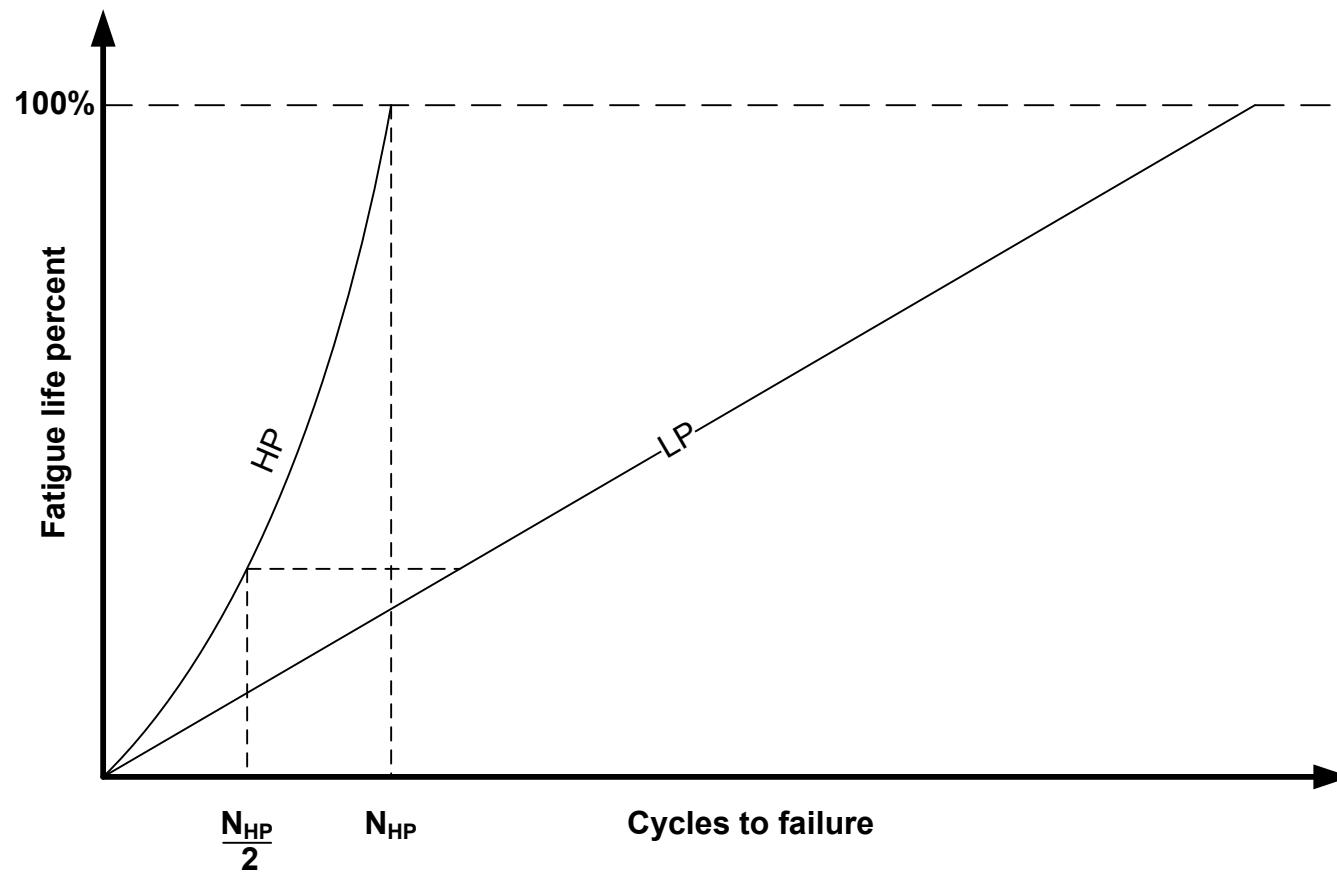
Fatigue damage accumulation



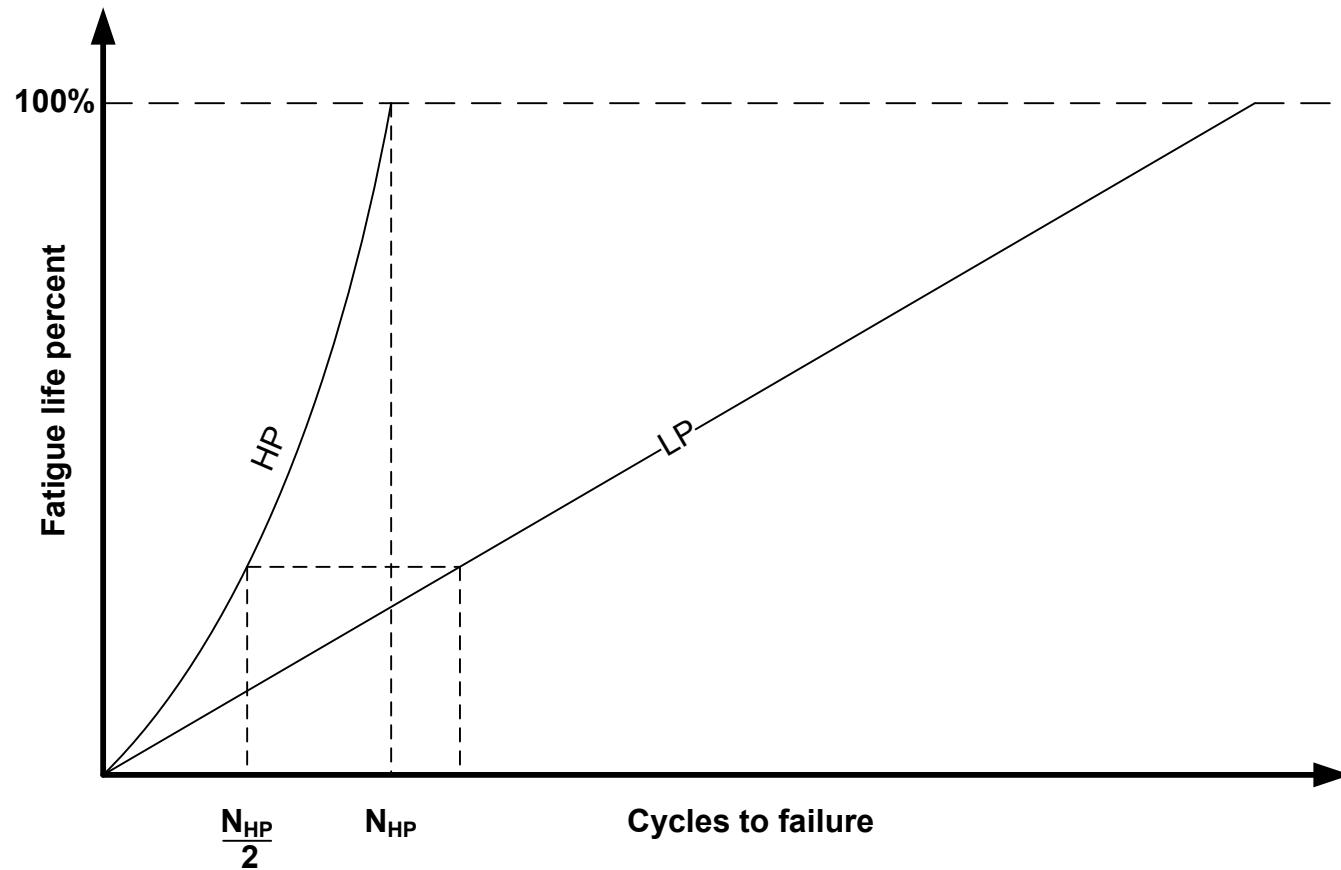
Fatigue damage accumulation



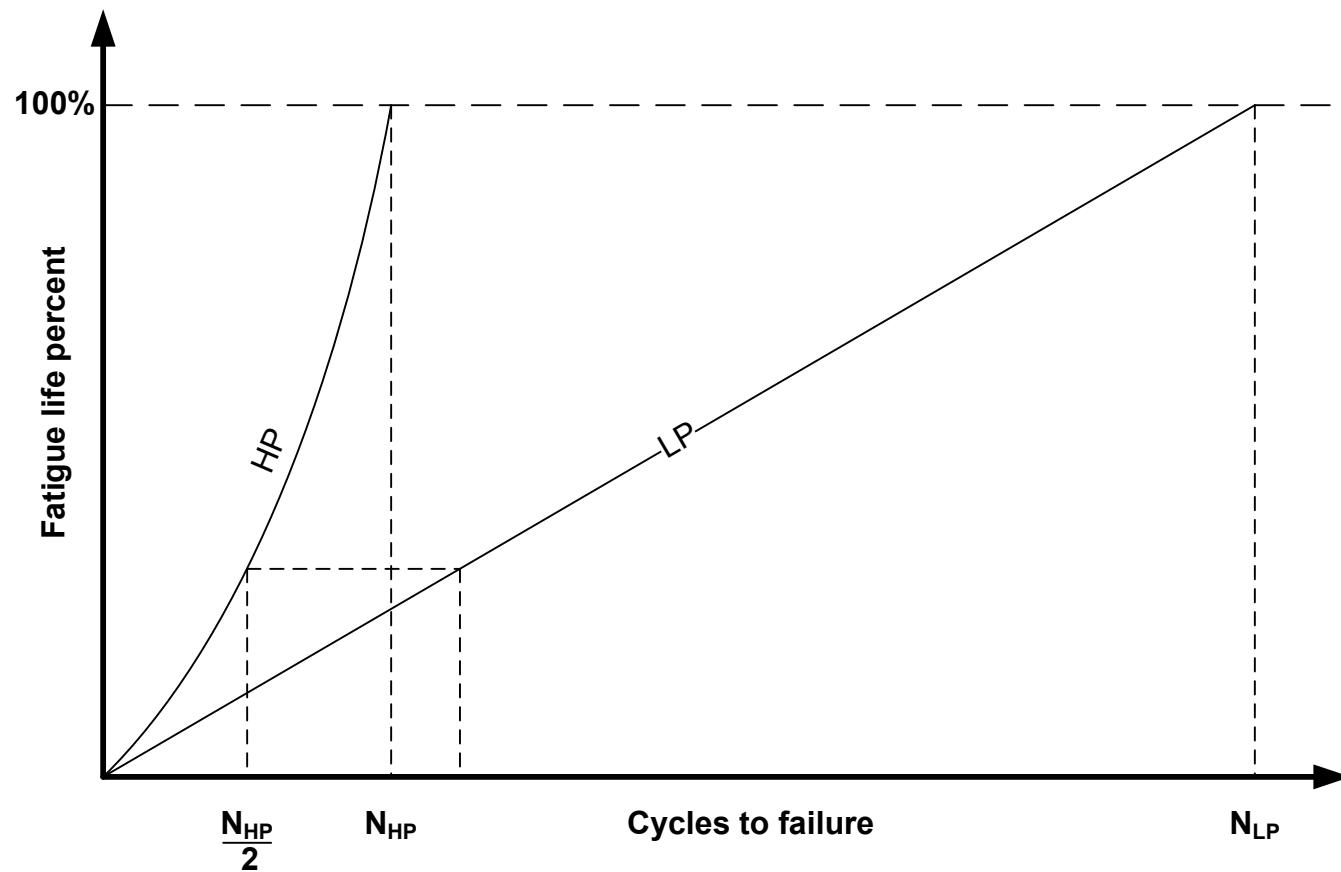
Fatigue damage accumulation



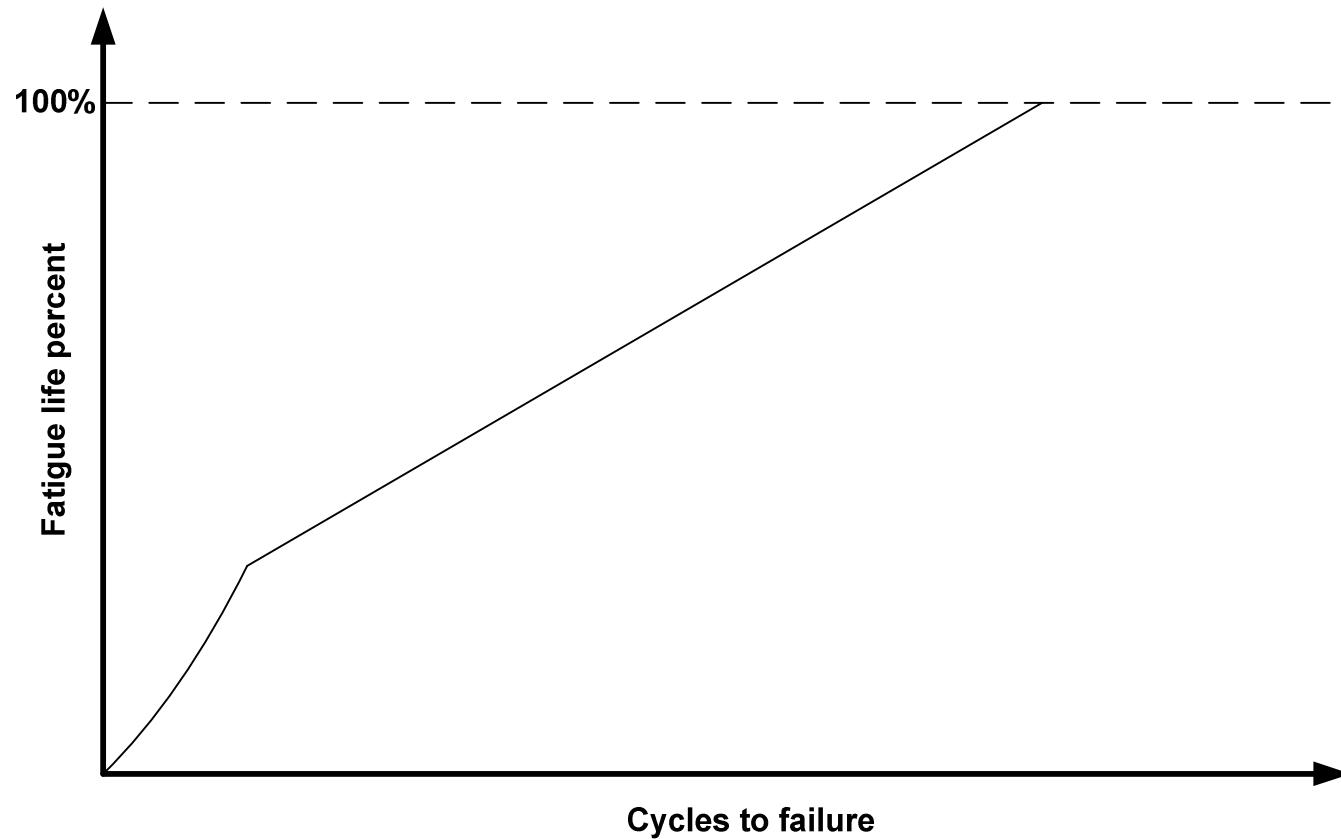
Fatigue damage accumulation



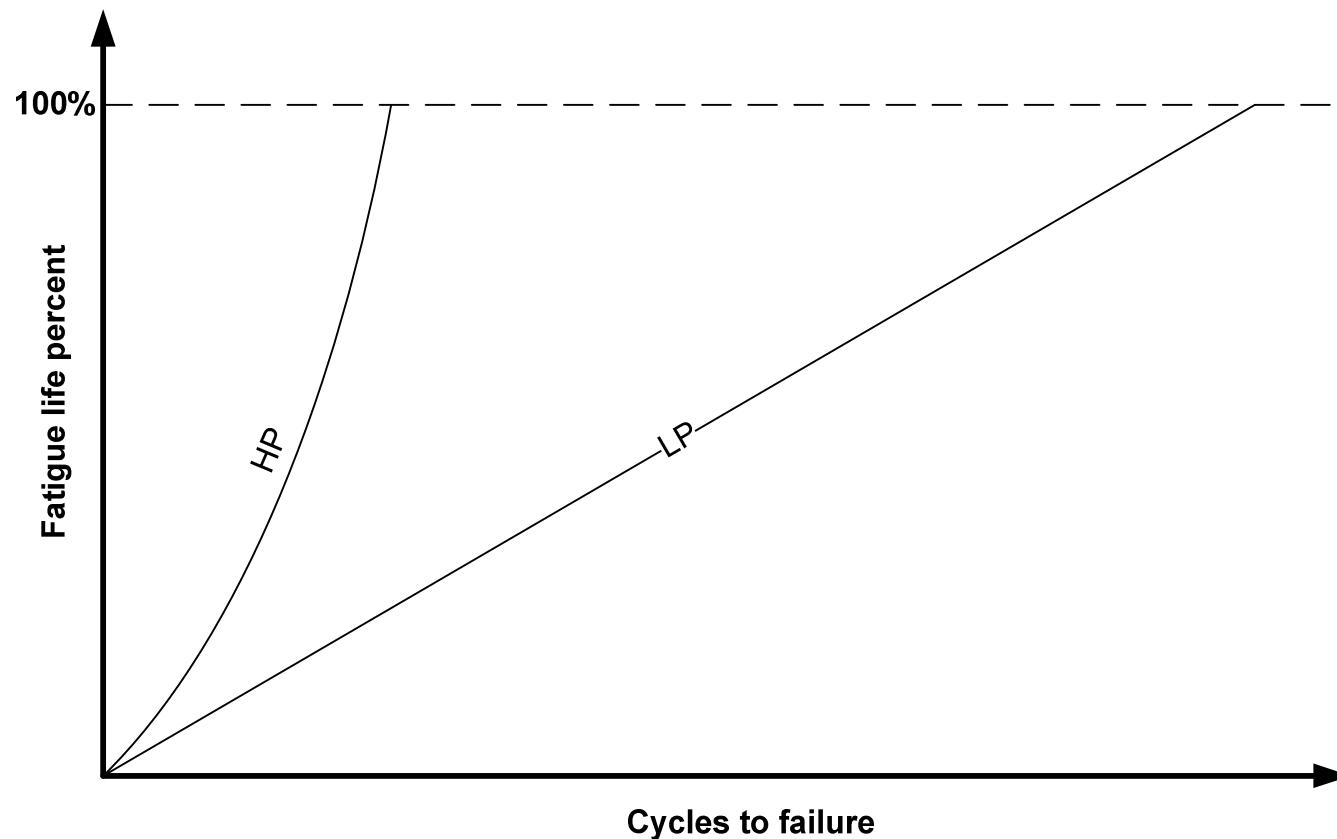
Fatigue damage accumulation



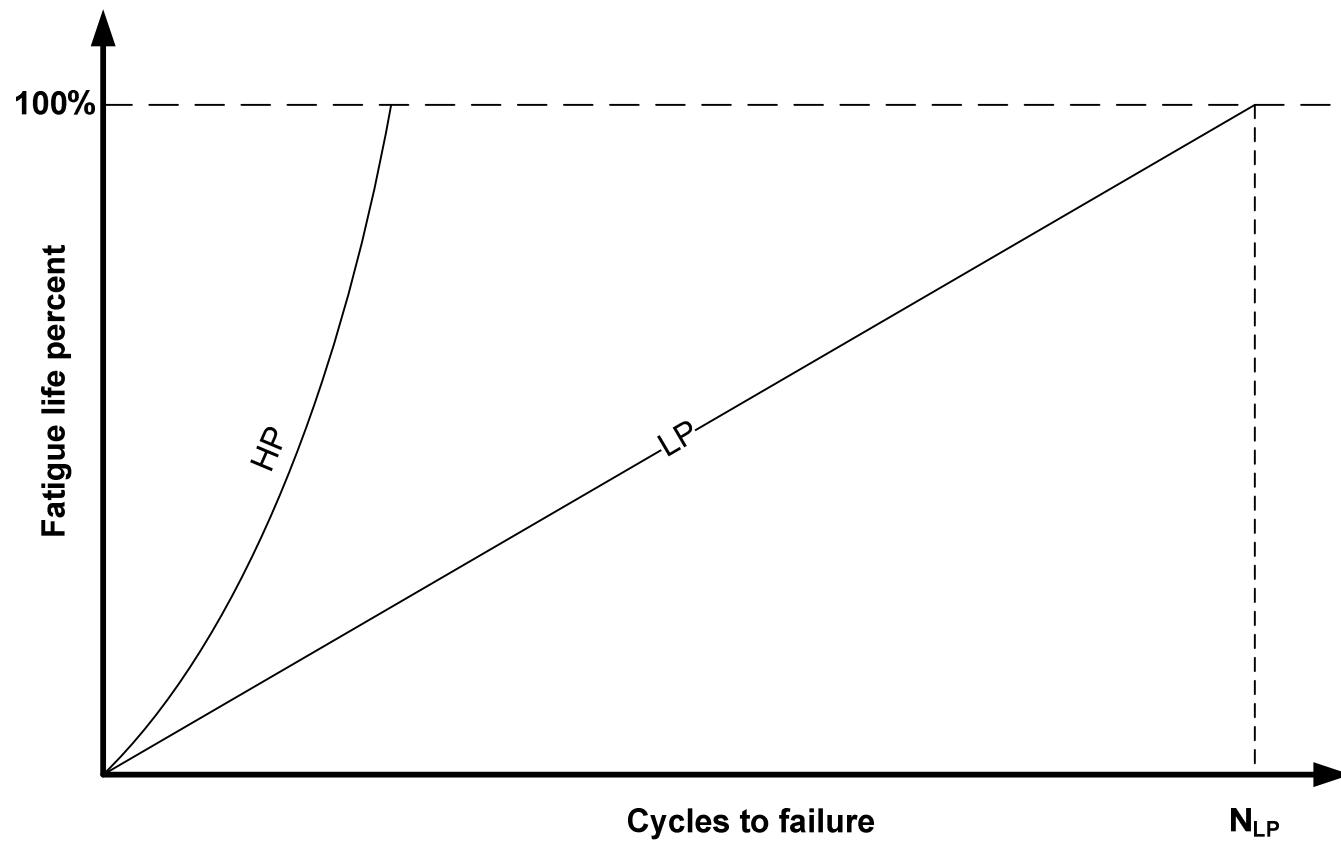
Fatigue damage accumulation



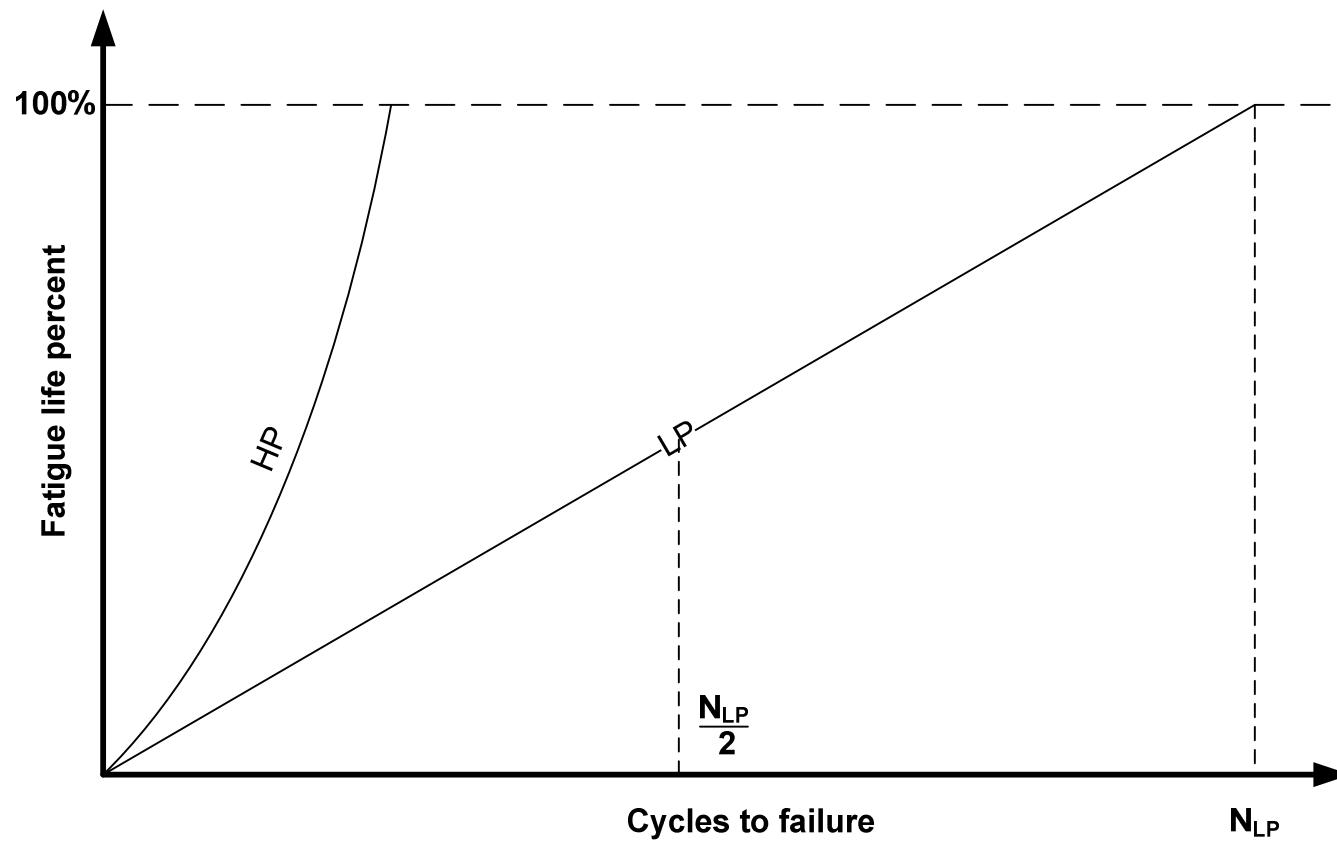
Fatigue damage accumulation



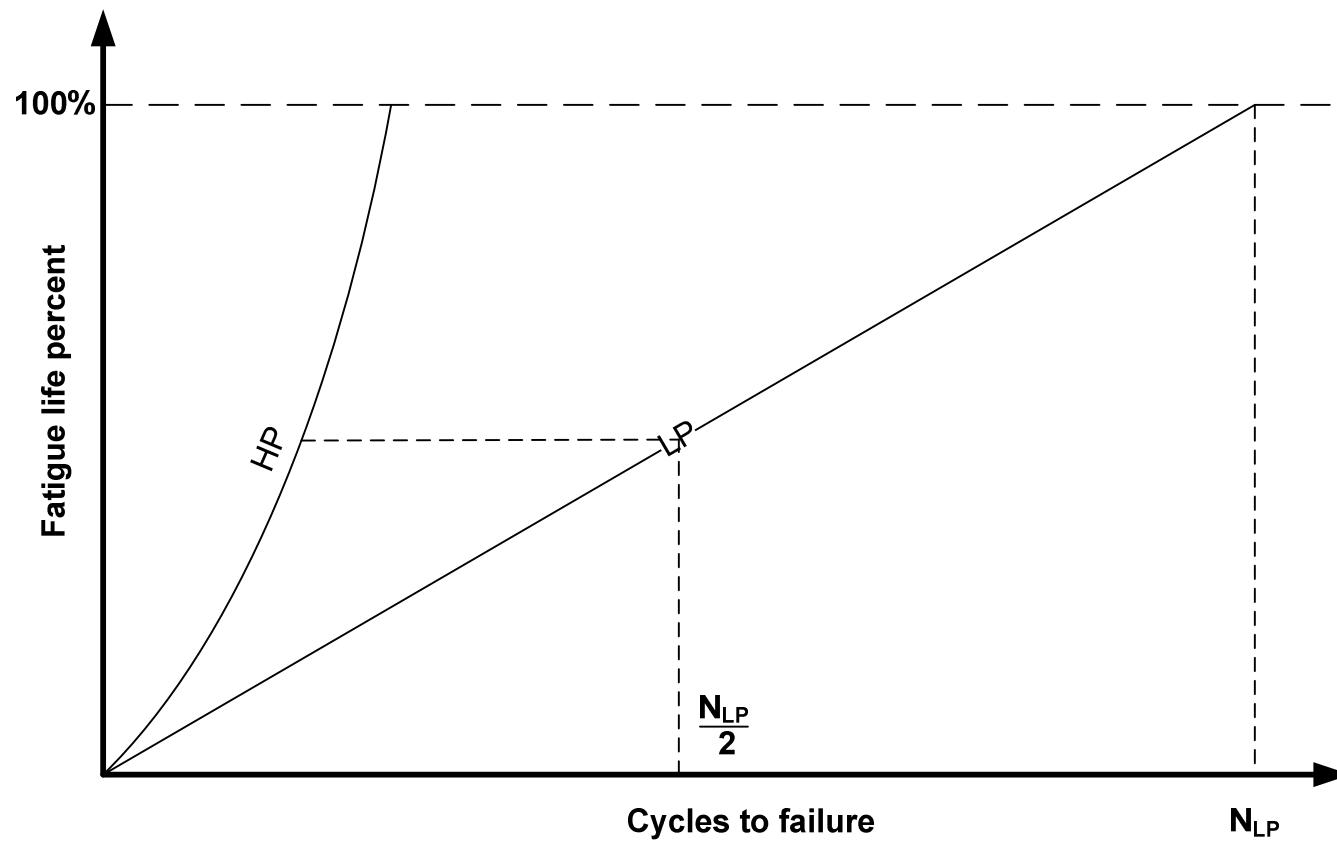
Fatigue damage accumulation



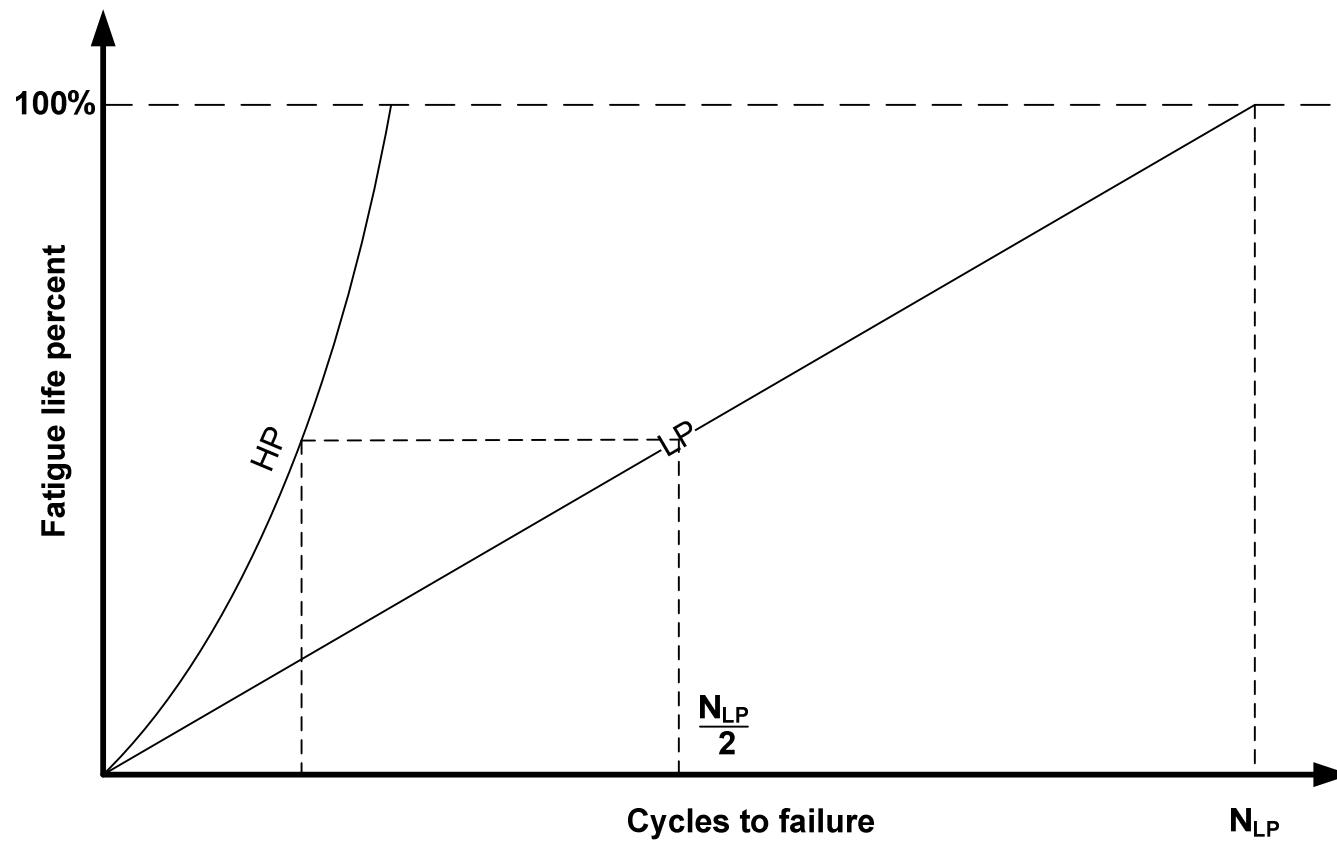
Fatigue damage accumulation



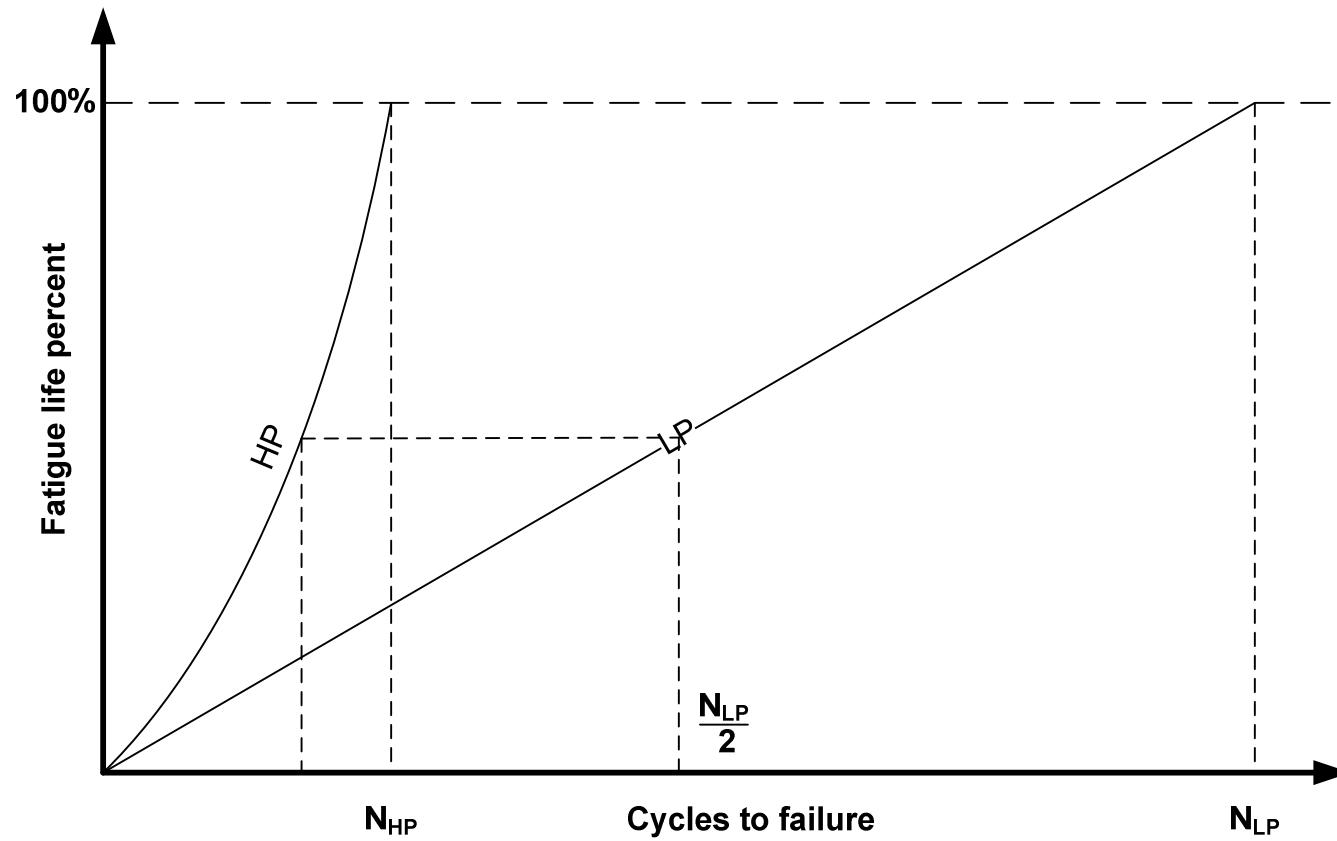
Fatigue damage accumulation



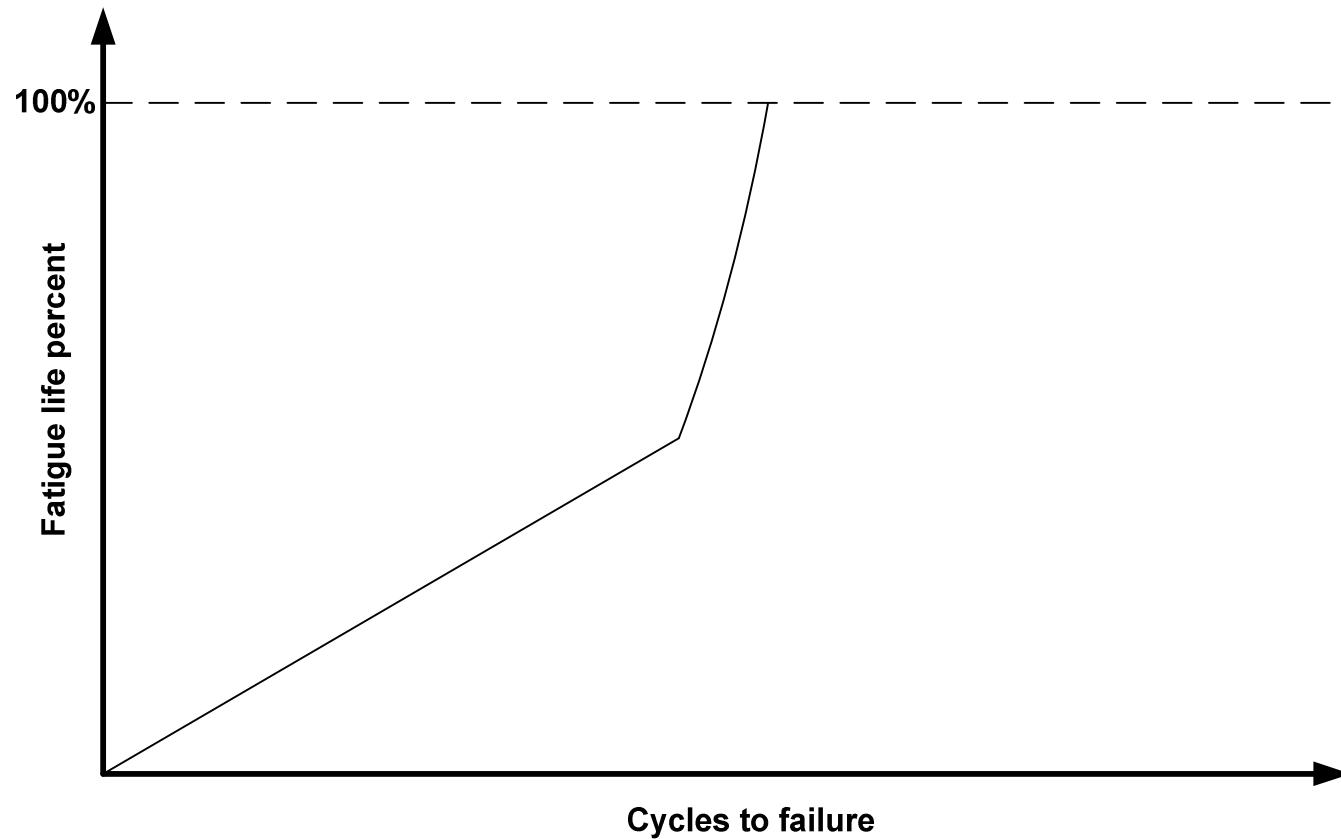
Fatigue damage accumulation



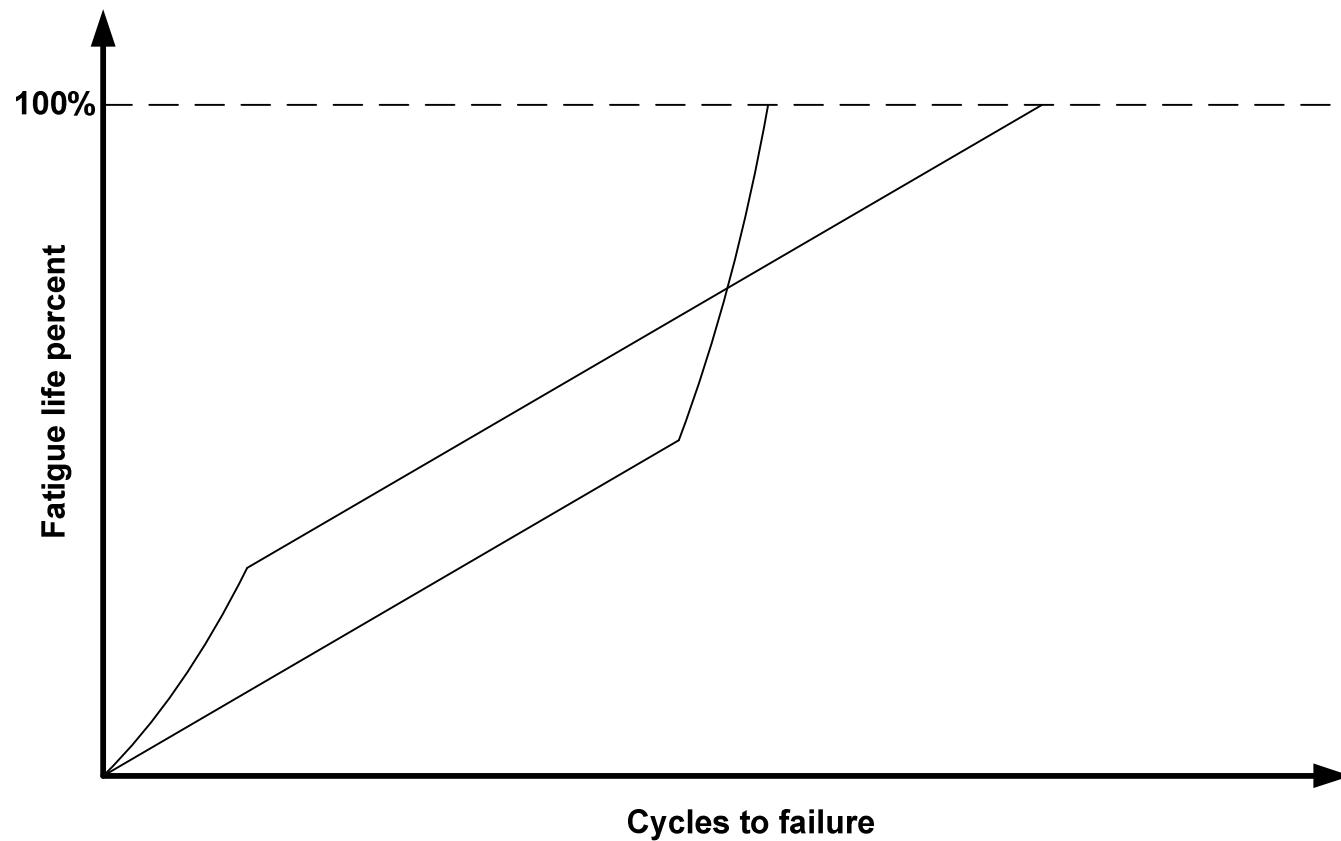
Fatigue damage accumulation



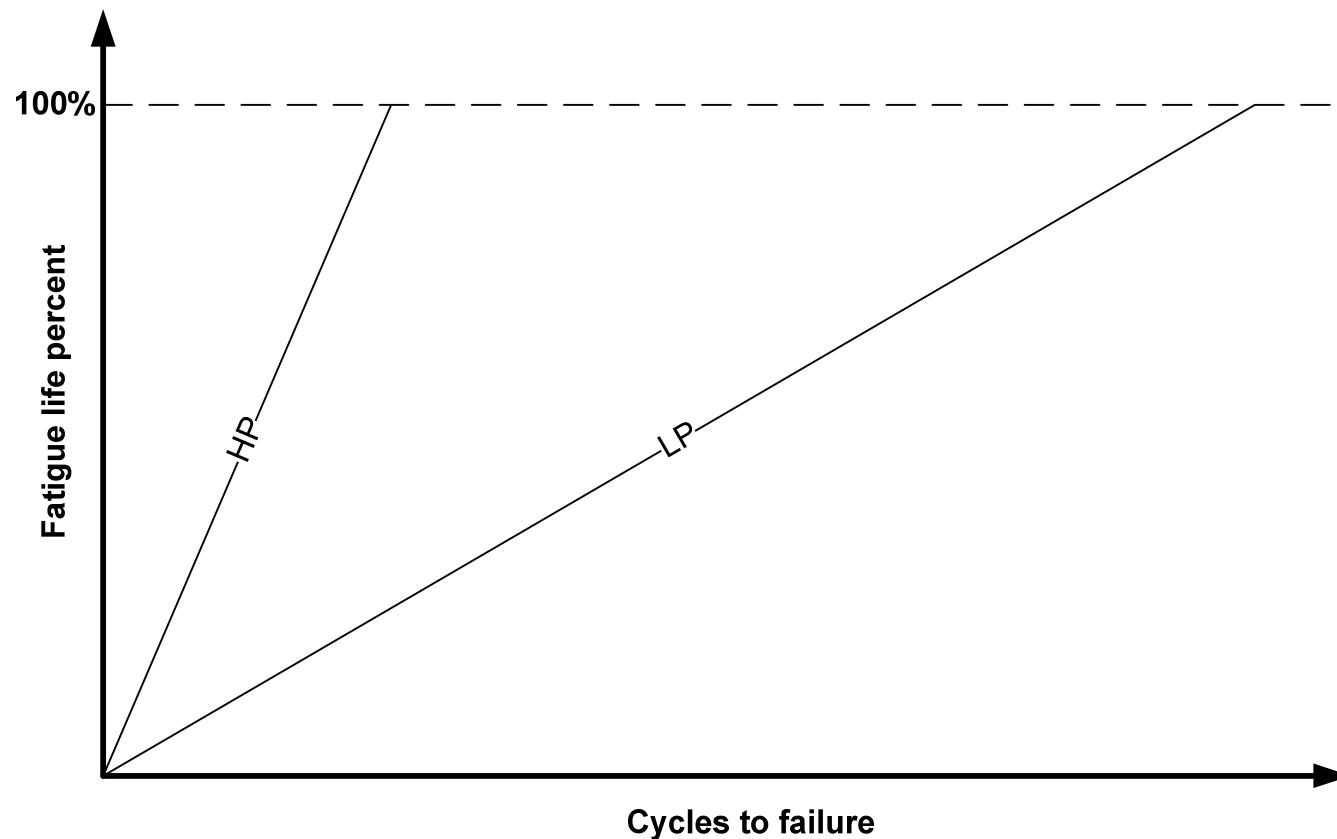
Fatigue damage accumulation



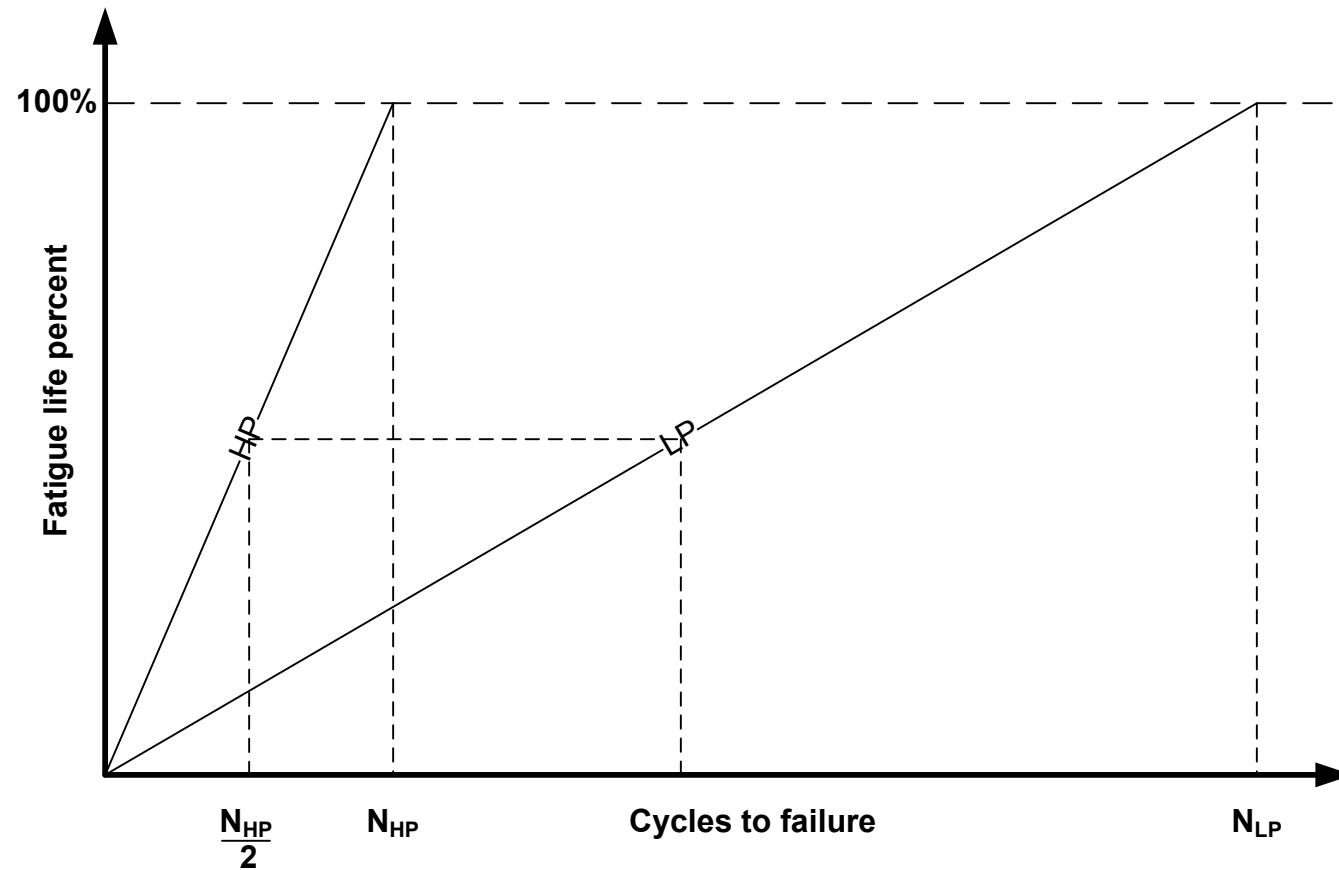
Fatigue damage accumulation



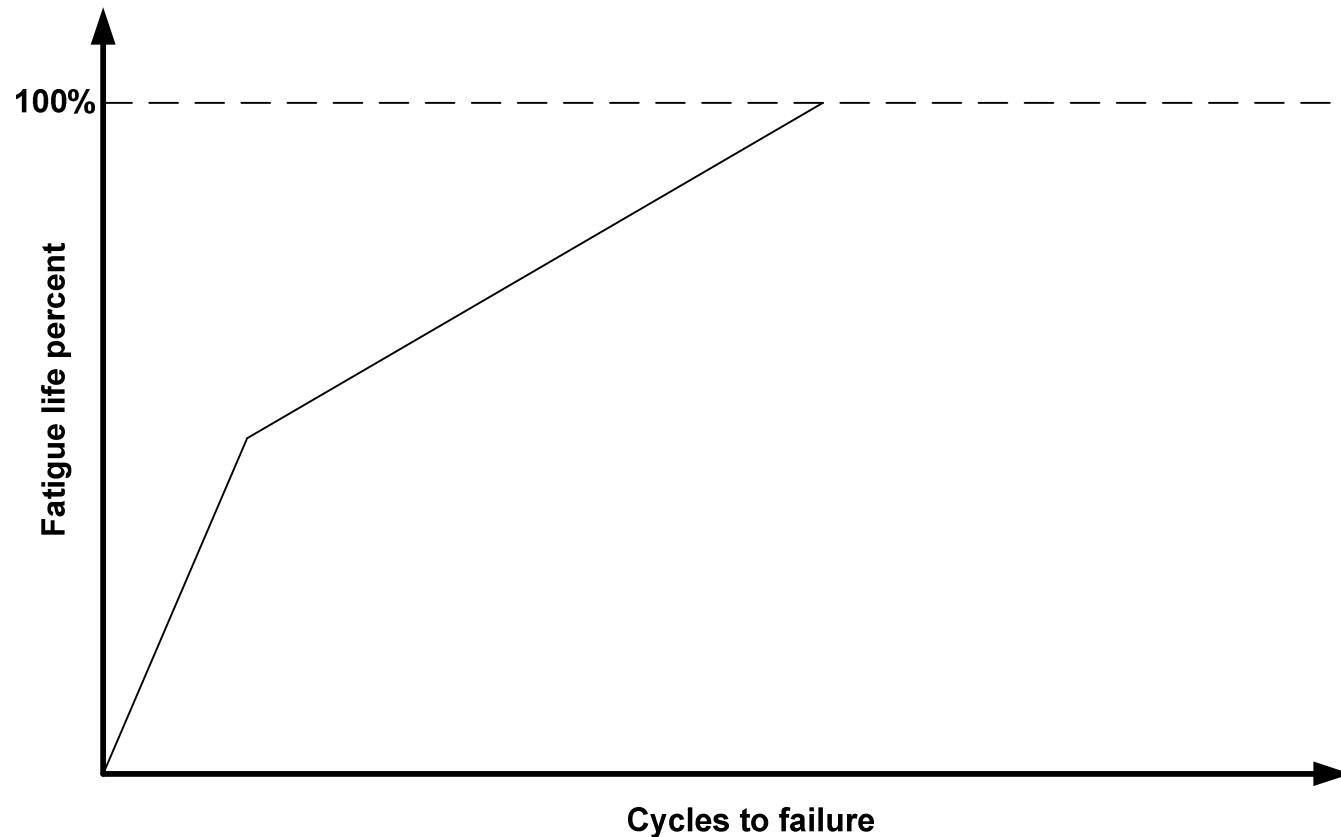
Fatigue damage accumulation



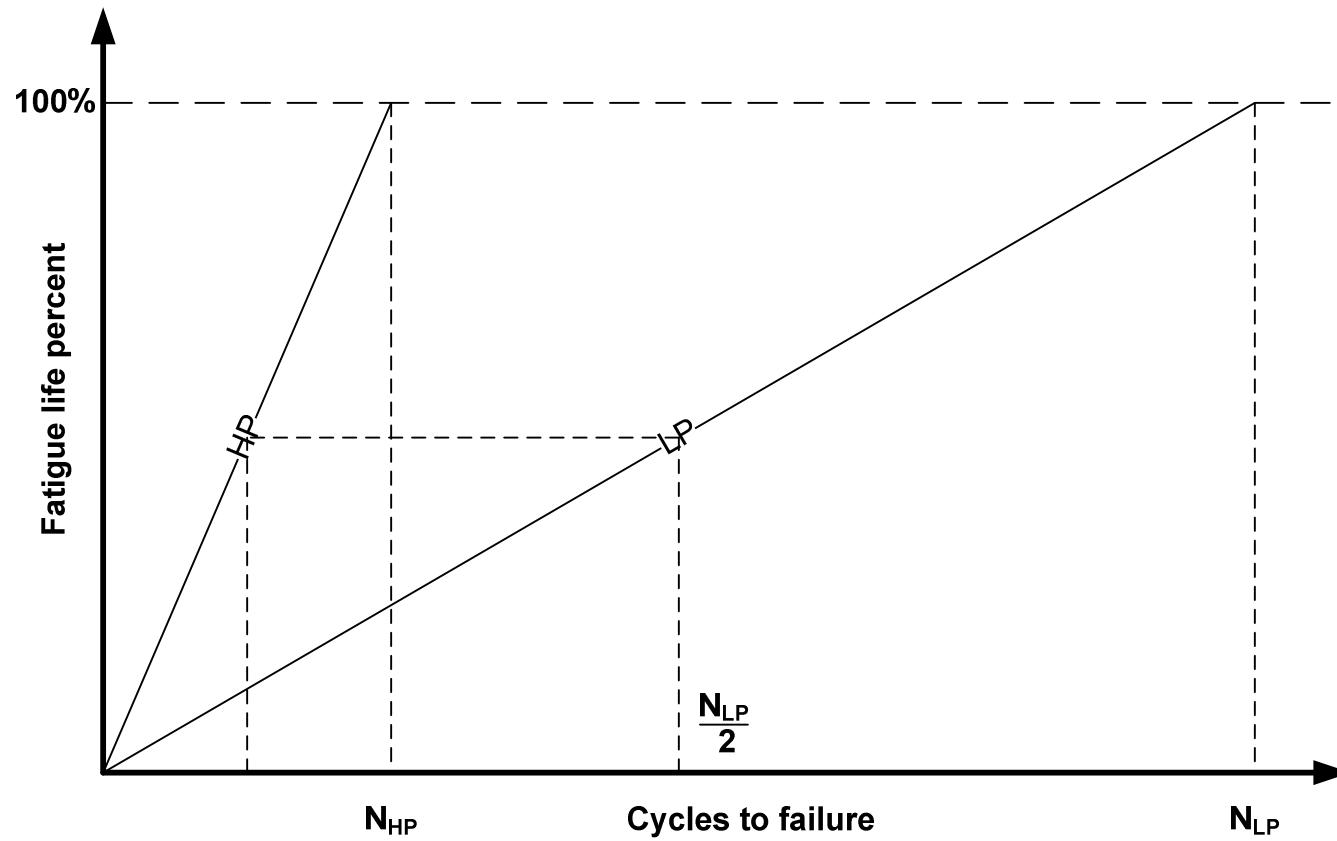
Fatigue damage accumulation



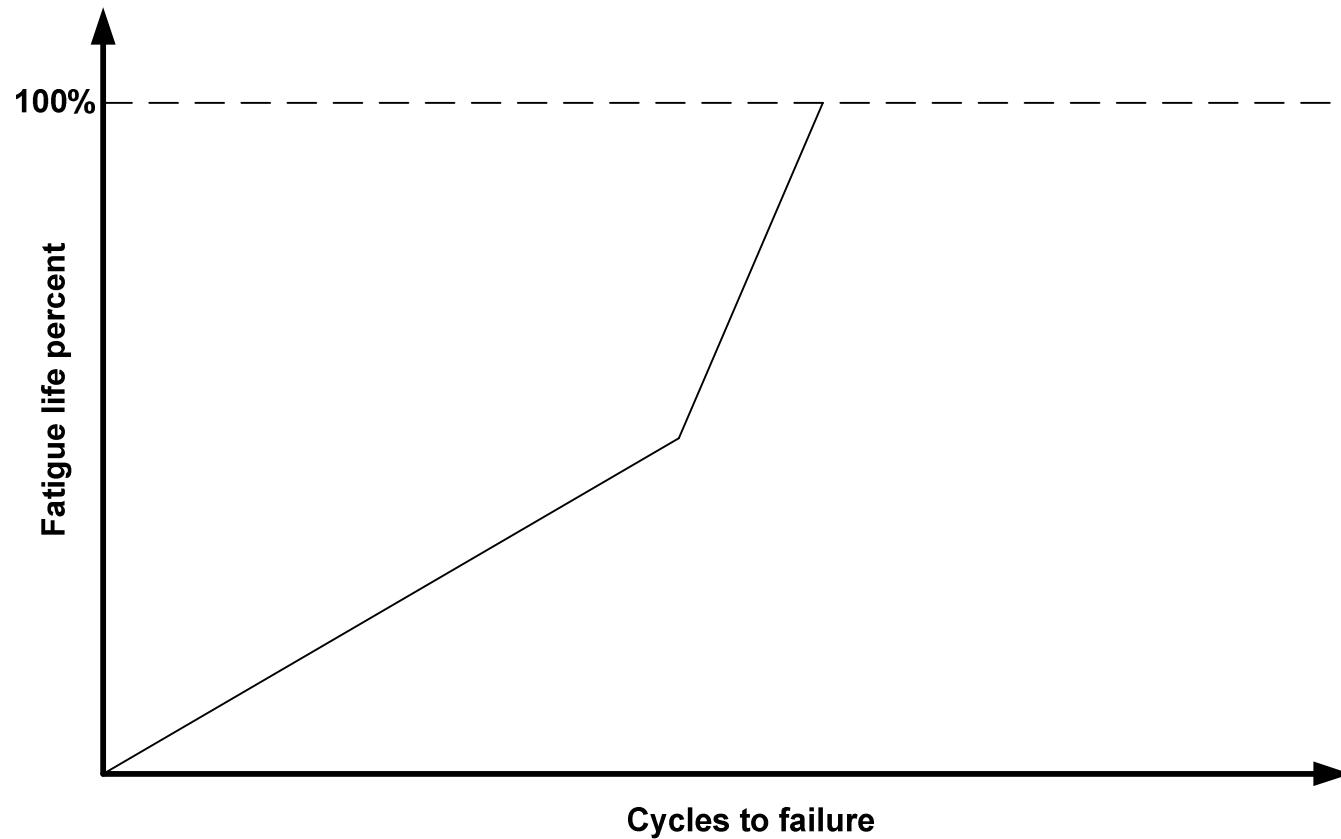
Fatigue damage accumulation



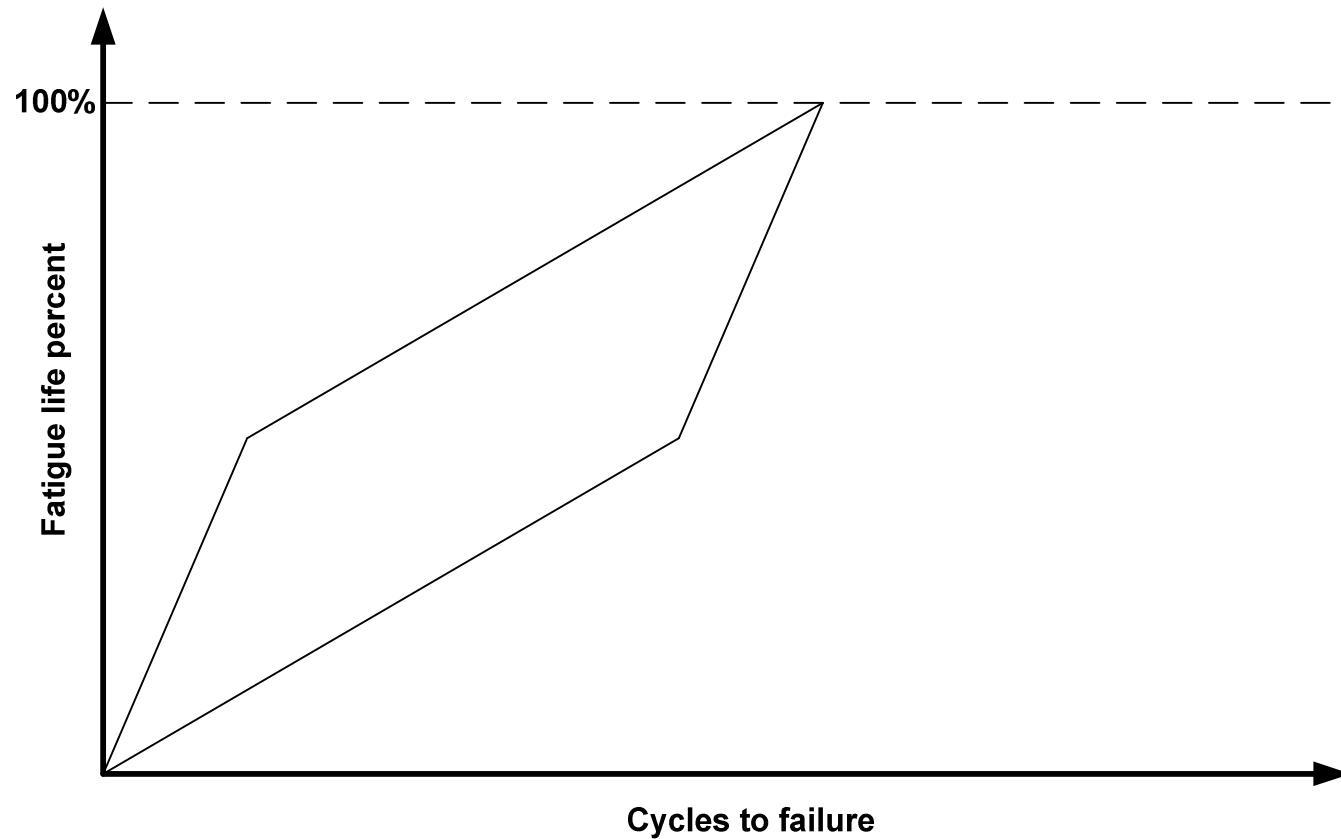
Fatigue damage accumulation



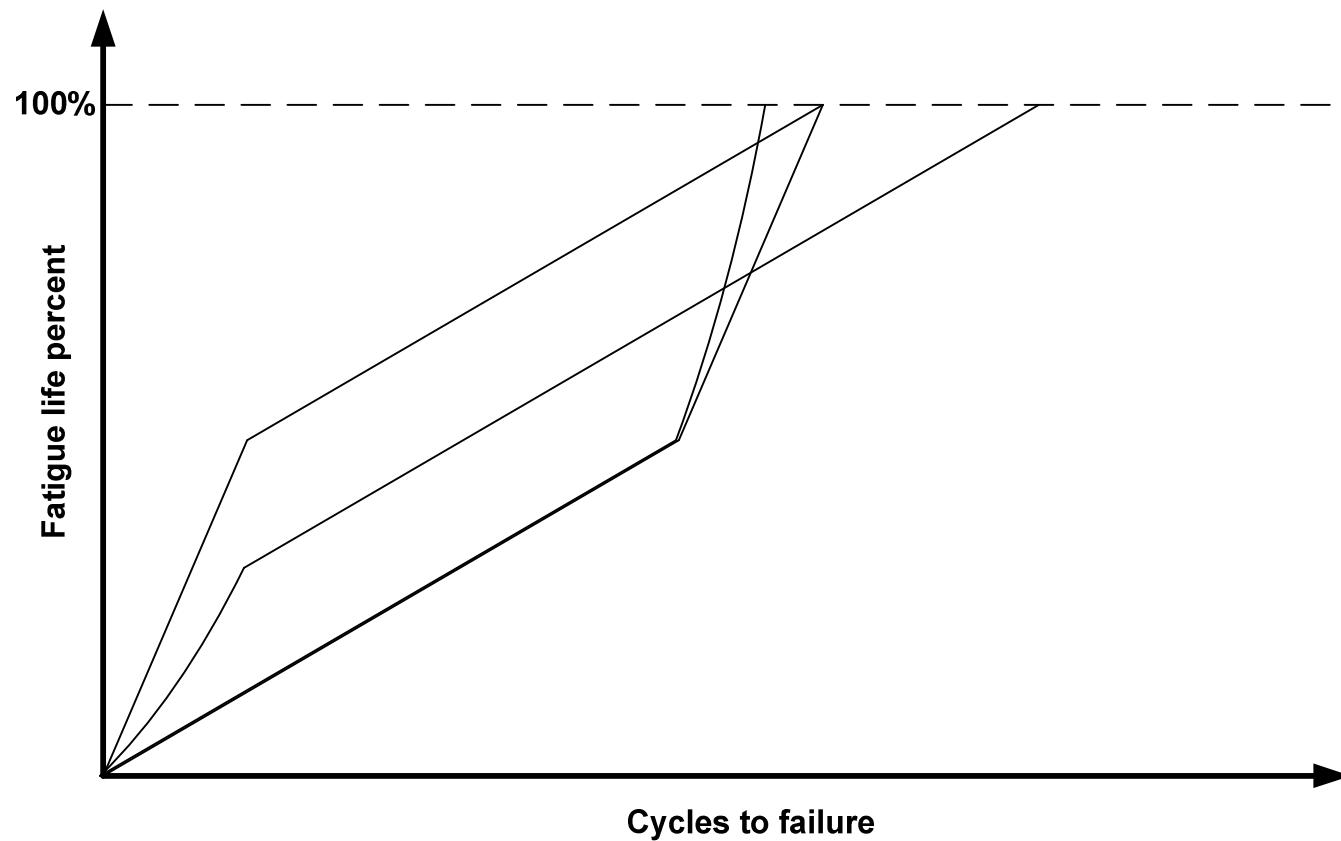
Fatigue damage accumulation



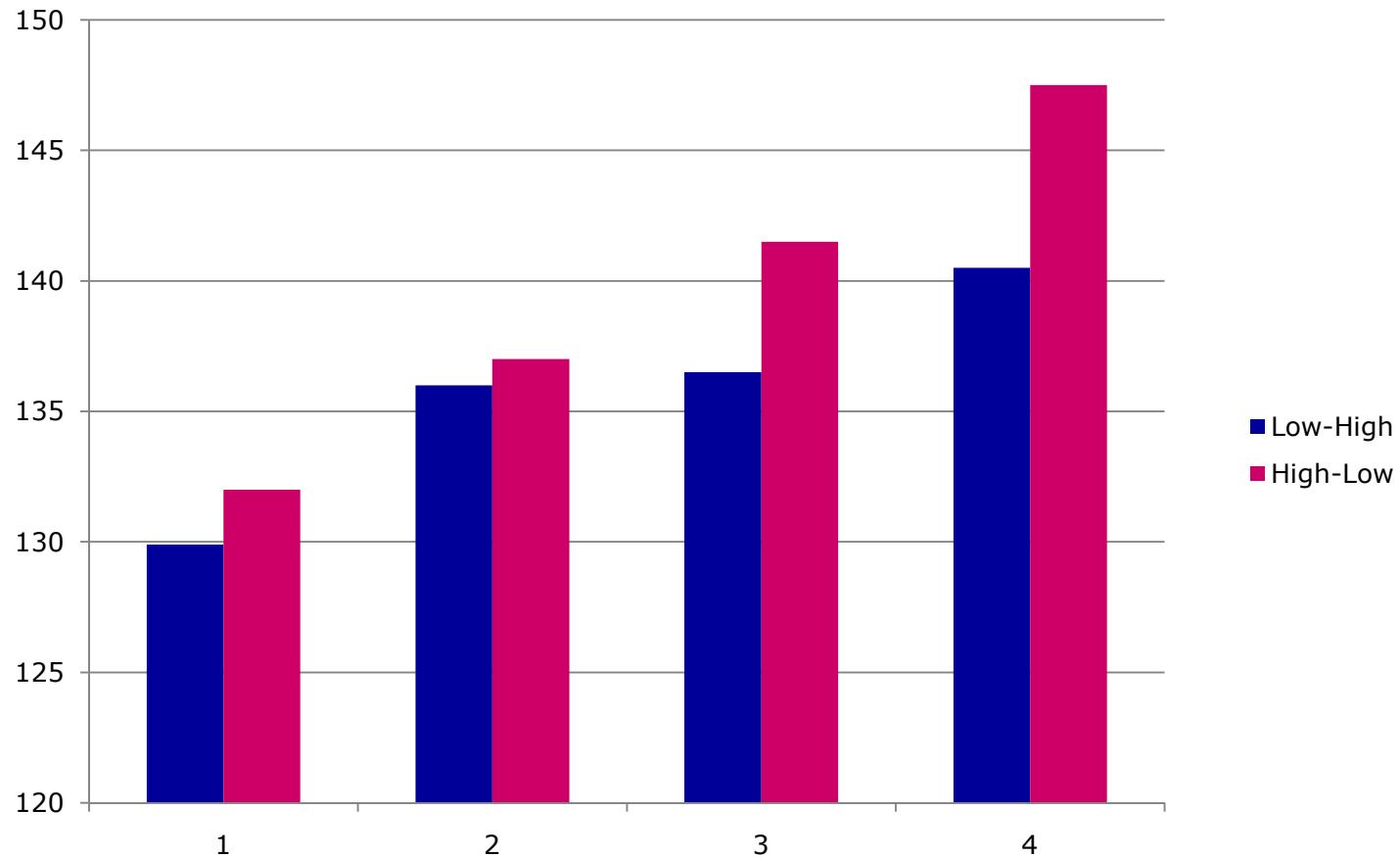
Fatigue damage accumulation



Fatigue damage accumulation



Fatigue damage accumulation



Conclusions



- Fatigue testing and fatigue modeling can be defined by two independent parameters.
- Manson-Coffin relationship can be extended to include hoop stress
- Ballooning rate (DSPC) appears constant (linear ballooning)
- Fatigue accumulation rate appears nearly constant (linear fatigue)



Questions?