Reliability and Design Strength Limit Calculations on Diesel Particulate Filters

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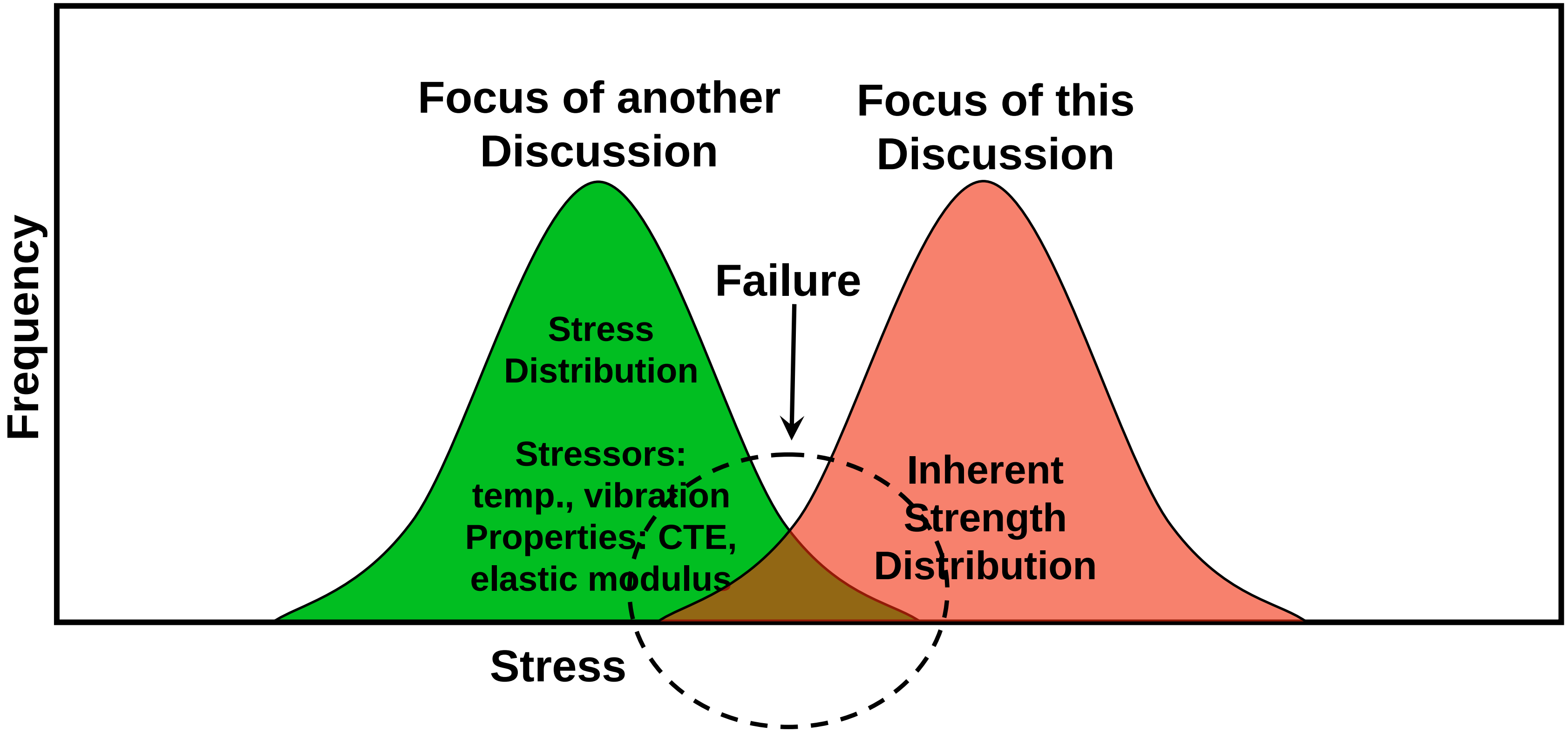
Objectives:

- Communicate a methodology for assessing design strength limits (residual strength) in Diesel Particulate Filters
- Sensitivity of each parameters used in the methodology
- Show implications of these sensitivities for materials characterization

Summary

- Methodology presented for residual strength based on
  - Probability Effects
  - Size Effects
  - Fatigue Effects
- Residual strength ~ 27% for given variables; subject to:
  - Quality of strength data
  - Assumptions made
  - Modification due to understanding of the applied stress distribution and it's potential to change with time
- Residual strength calculation most sensitive to the Weibull modulus, m and Fatigue constant, n

Comments on Stress and Strength



Assumptions

- DPF is a monolithic extruded honeycomb ceramic structure (methodology could also be extended to segmented filters)
- Strength is statistical and described by the Weibull distribution
- The strength distribution and its time dependency are based on “Griffith” flaws and sub-critical crack growth theory

Factors influencing design strength limits

- Probability Effect – describes the strength distribution (flaw population)
  - Unlike most metals, the strength of ceramics is statistical
  - Strength is a function of a defined failure probability
  - Lower failure probabilities correspond to lower strengths
- Size Effects – difference between product and MOR test bars
  - Strength is surface area or volume dependent
  - Results from the statistical nature of strength
  - Weak link theory, weak link controls strength, longer chain – weaker weak link
- Fatigue Effects – decrease in strength over time
  - Strength decreases with environmental exposure
  - Strength impact requires definition of product lifetime

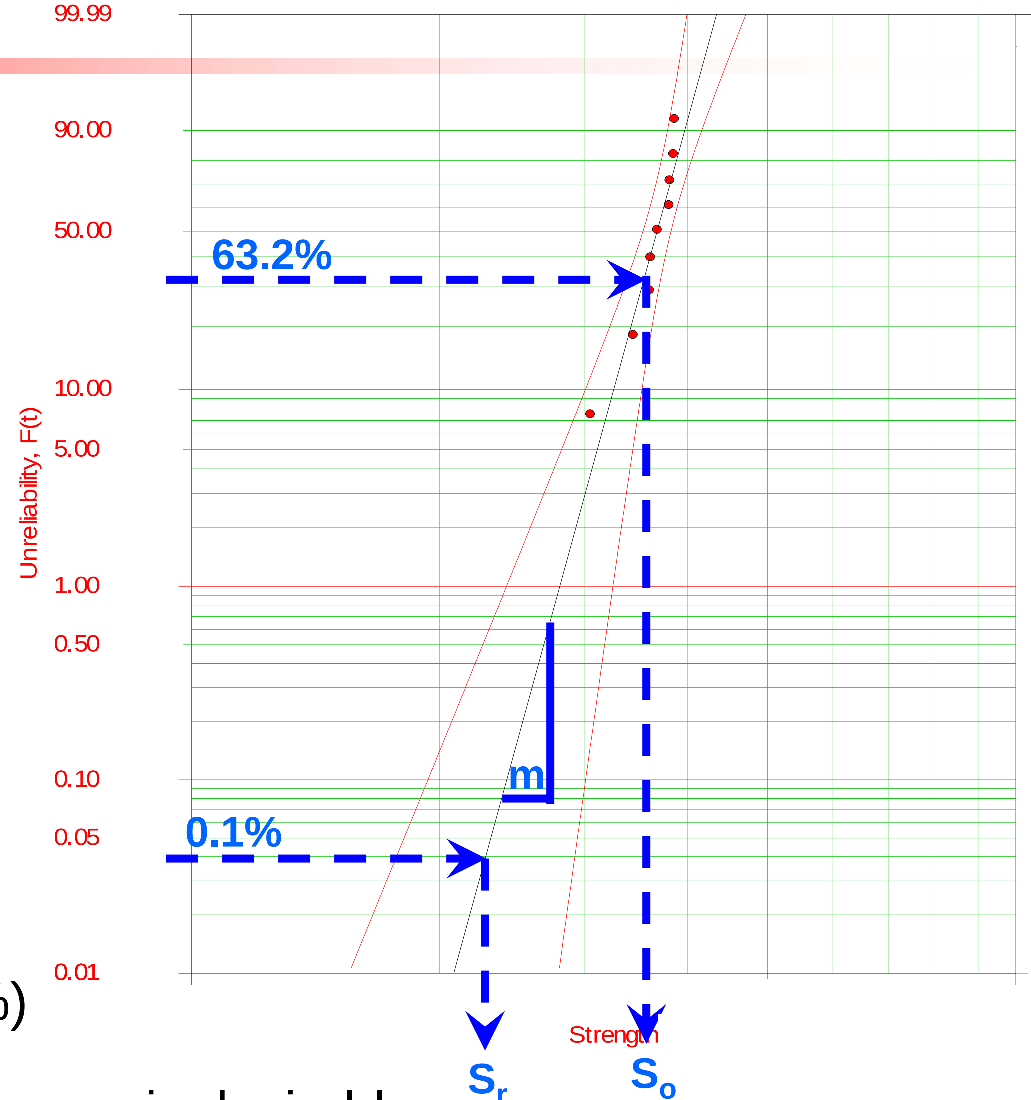
Weibull Statistics Refresher

Unreliability

$$F = 1 - \exp\left(-\left(\frac{S}{S_o}\right)^m\right)$$

Reliability

$$R = 1 - F = \exp\left(-\left(\frac{S}{S_o}\right)^m\right)$$



Key Parameters

S = strength value of interest

S_o = characteristic strength (63.2%)

m = Weibull slope or modulus – large m is desirable

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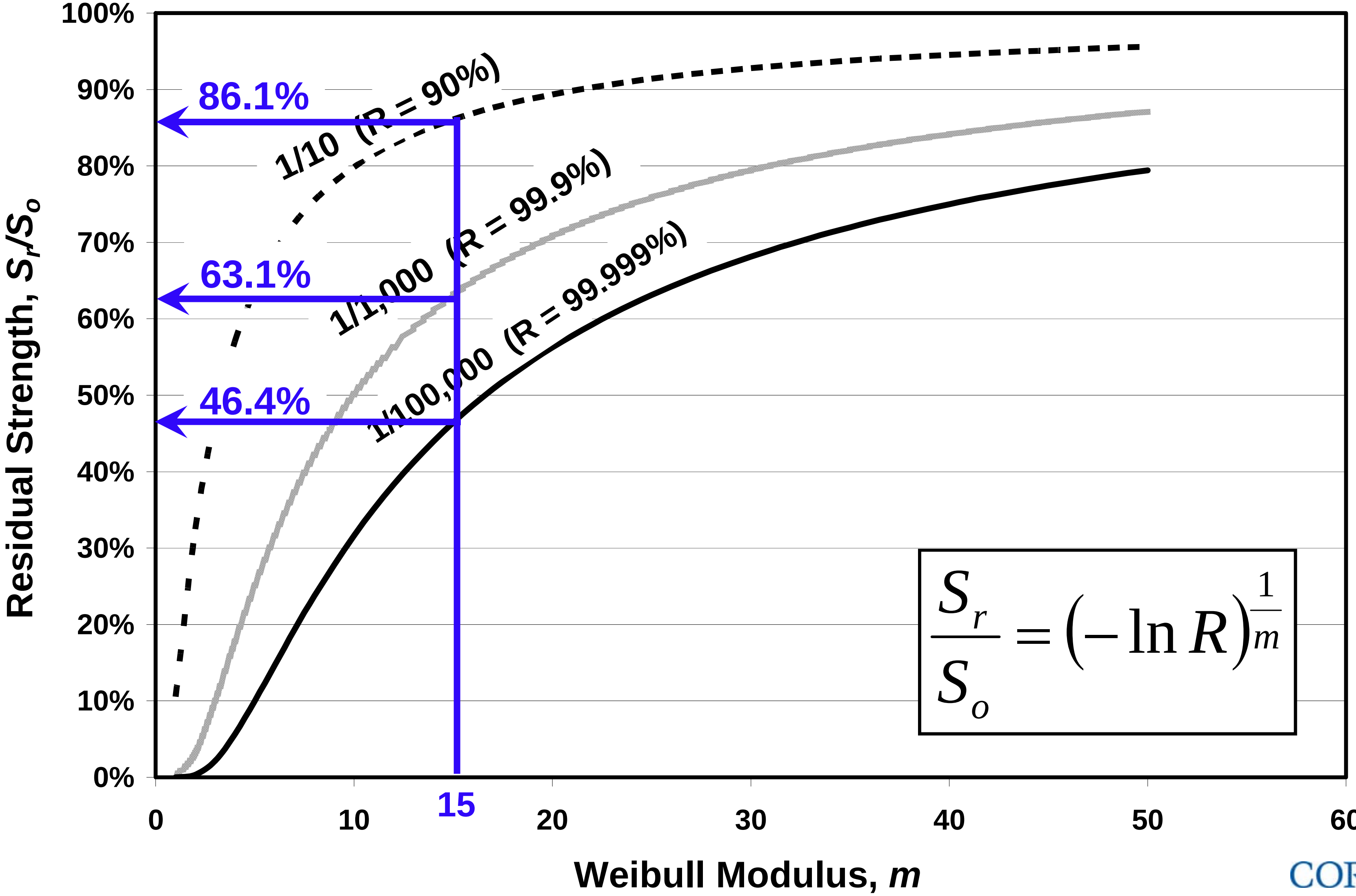
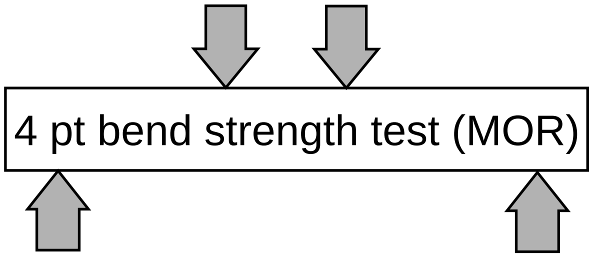
Reliability Levels

Unreliability	Reliability	Unreliability
F	R (1-F)	PPM
1/10	90%	100,000
1/1,000	99.9%	1,000
1/100,000	99.999%	10

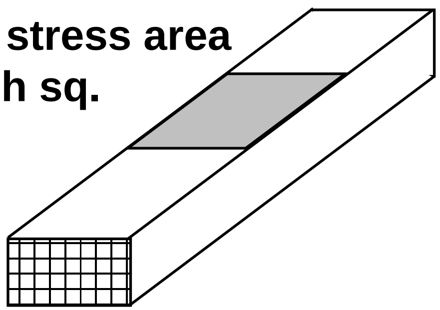
Residual Strength: Probability Effect



Size Effect: Size dependent strength / Area Ratio

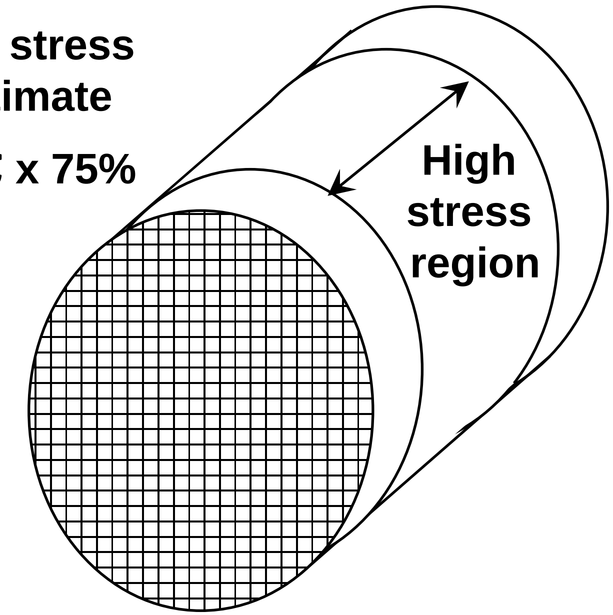


MOR bar high stress area
0.75 inch sq.



DPF High stress area estimate

L x D x π x 75%

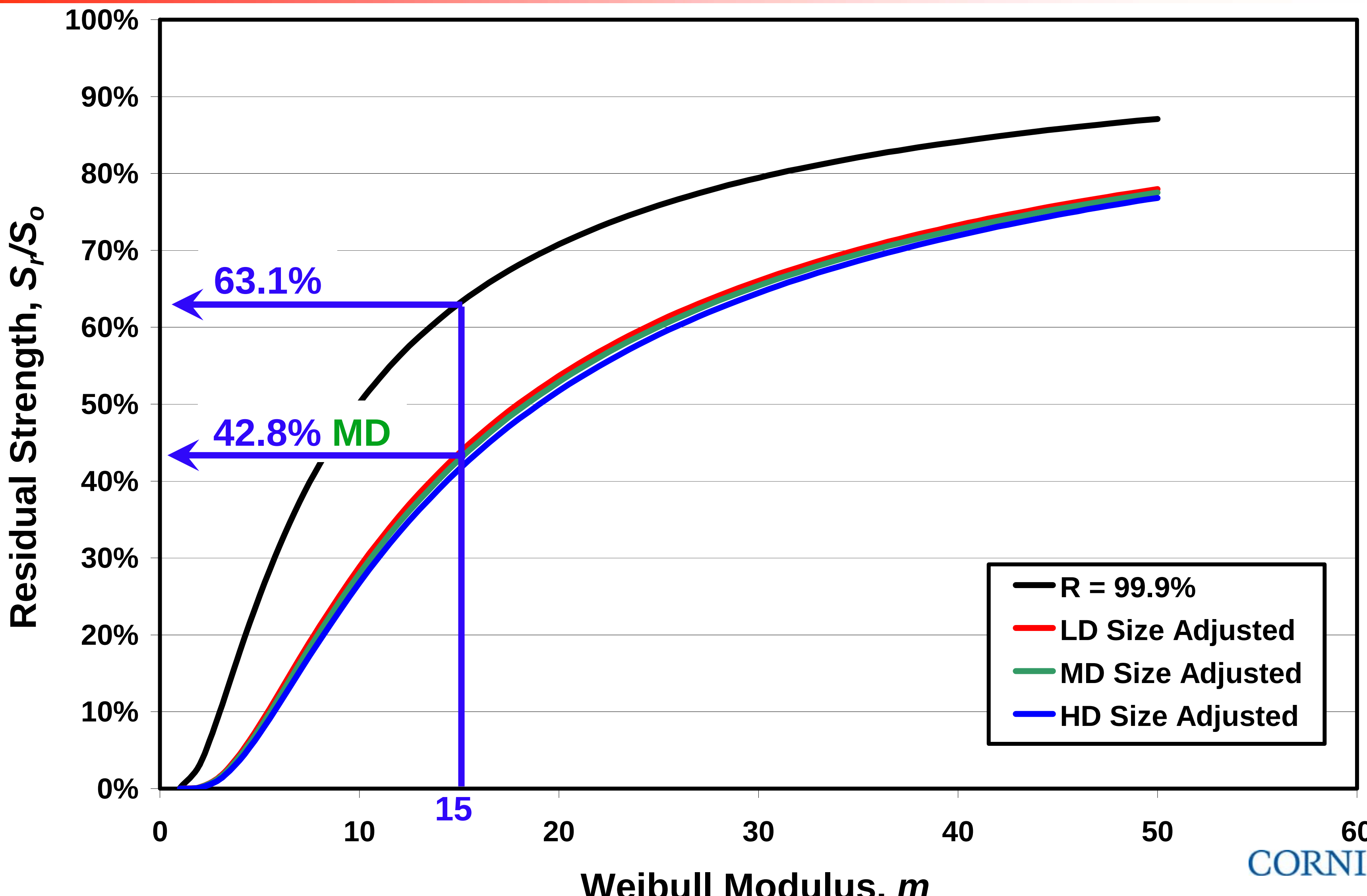


DPF Type	Length (inches)	Diameter (inches)	Area Ratio (A/A_o)
HD	14	12	**528**
MD	12	9	**339**
LD	9	9	**254**

Size Effect

$$\frac{S_r}{S_o} = \left(\frac{A_o}{A}\right)^{\frac{1}{m}}$$

Residual Strength: Probability and Size Effects



Fatigue Effect: environmental exposure strength decrease

- Mechanism - in glass and ceramic materials, natural flaws extend by corrosion of stressed crack tip bonds by polar molecules such as H_2O
  - Water
  - Stress
  - Time
- Characterized by the fatigue exponent, n   n = 20 to 50
  large n desirable

DPF Type	Lifetime* (miles)	Regen. Frequency (miles)	Regen. Time (seconds)	Total Regen. Time (seconds)
MD	185,000	400	30	13,900

*EPA Useful Life 2004 and later

$$T_f \approx S^n$$

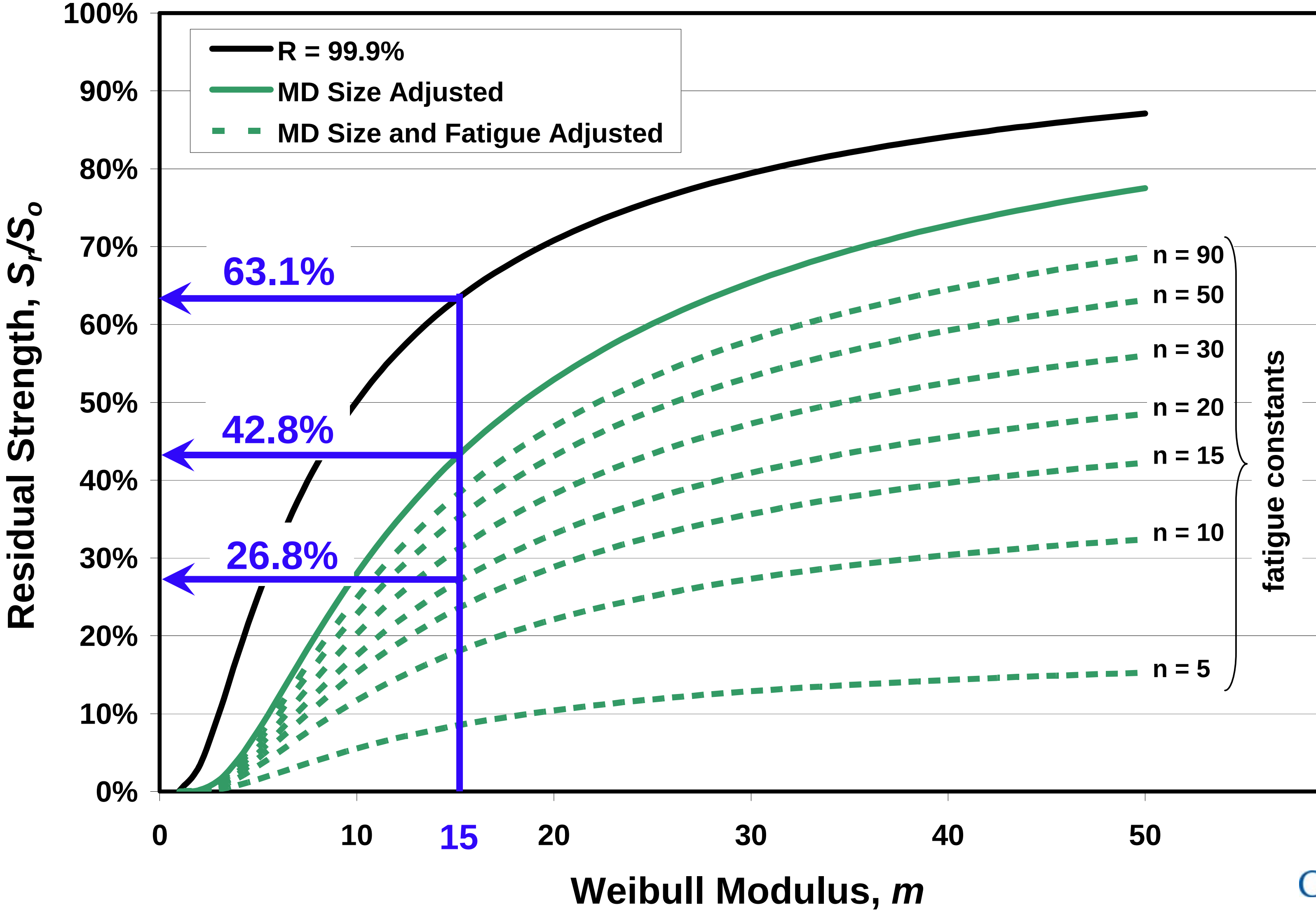
Time to failure proportional to strength raised to n

$$T_f \approx \frac{1}{\sigma^n}$$

Time to failure inversely proportional to applied stress raised to n

$$\frac{S_r}{S_o} = \left(\frac{t_{fo}}{t_{fr}}\right)^{\frac{1}{n}}$$

Residual Strength: Probability, Size, and Fatigue Effects



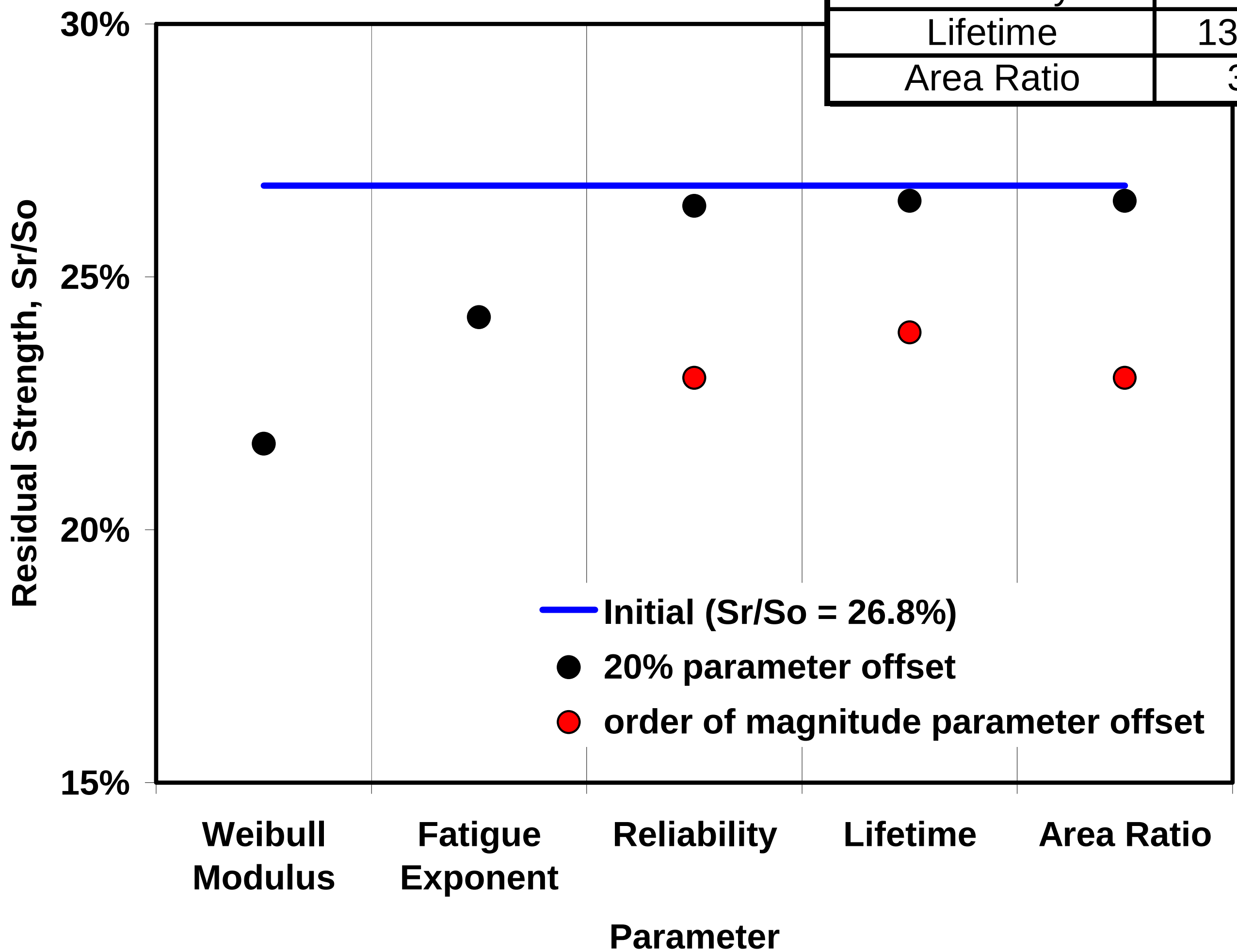
Residual Strength Summary

Probability Effect	(99.9%)	63.1%	$\frac{S_r}{S_o} = (-\ln R)^{\frac{1}{m}}$
Size Effect	(MD)	67.8%	$\frac{S_r}{S_o} = \left(\frac{A_o}{A}\right)^{\frac{1}{m}}$
Fatigue Effect	(MD)	62.6%	$\frac{S_r}{S_o} = \left(\frac{t_{fo}}{t_{fr}}\right)^{\frac{1}{n}}$
Combined Effect	**(63.1% X 67.8% X 62.6%)**		**26.8%**

$$\frac{S_r}{S_o} = \left[(-\ln R)^{\frac{1}{m}}\right]\left[\left(\frac{A_0}{A}\right)^{\frac{1}{m}}\right]\left[\left(\frac{t_{fo}}{t_{fr}}\right)^{\frac{1}{n}}\right]$$

Sensitivity Analysis

Parameter	Standard Value	20% offset value	order of magnitude offset
Weibull Modulus	15	12	-
Fatigue Exponent	20	16	-
Reliability	0.999	0.9992	0.9999
Lifetime	13900s	16700s	139,000s
Area Ratio	339	407	3390



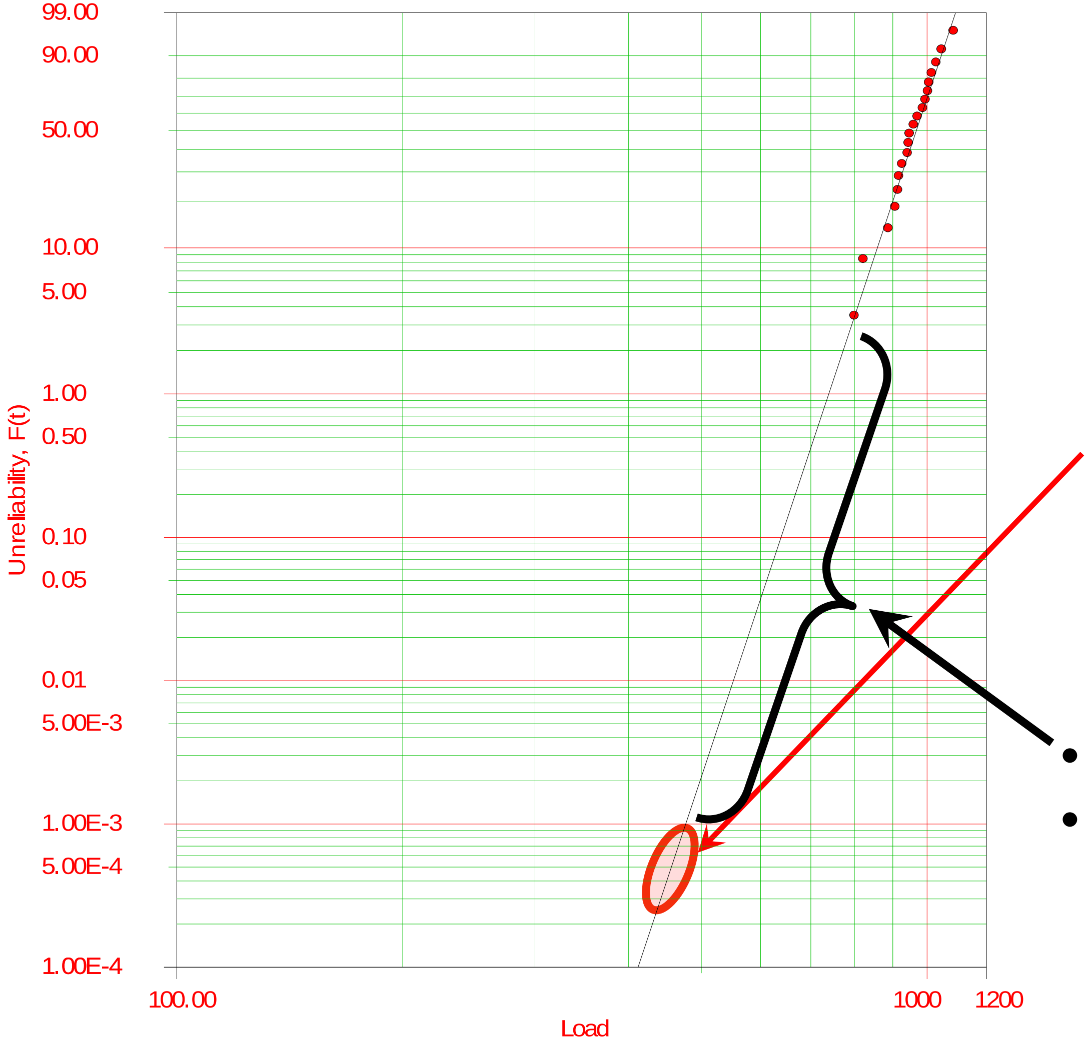
- Variance in m and n have the largest impact on S_r/S_o
- Large changes in t_f and A/A_o are required to affect S_r/S_o

Test Design Impact on **m** and **n** Confidence

Typical small test plan

- Dynamic Fatigue on 4 pt bend bars
  (load on bars is increased at constant loading rate until failure)
- One group at each of 4 loading rates
- Rates differ by order of magnitude each
  (1-1000 seconds equivalent static fatigue time)
- 20 bars in each group x 4 groups = 80

Probability Extrapolation (m sensitivity)



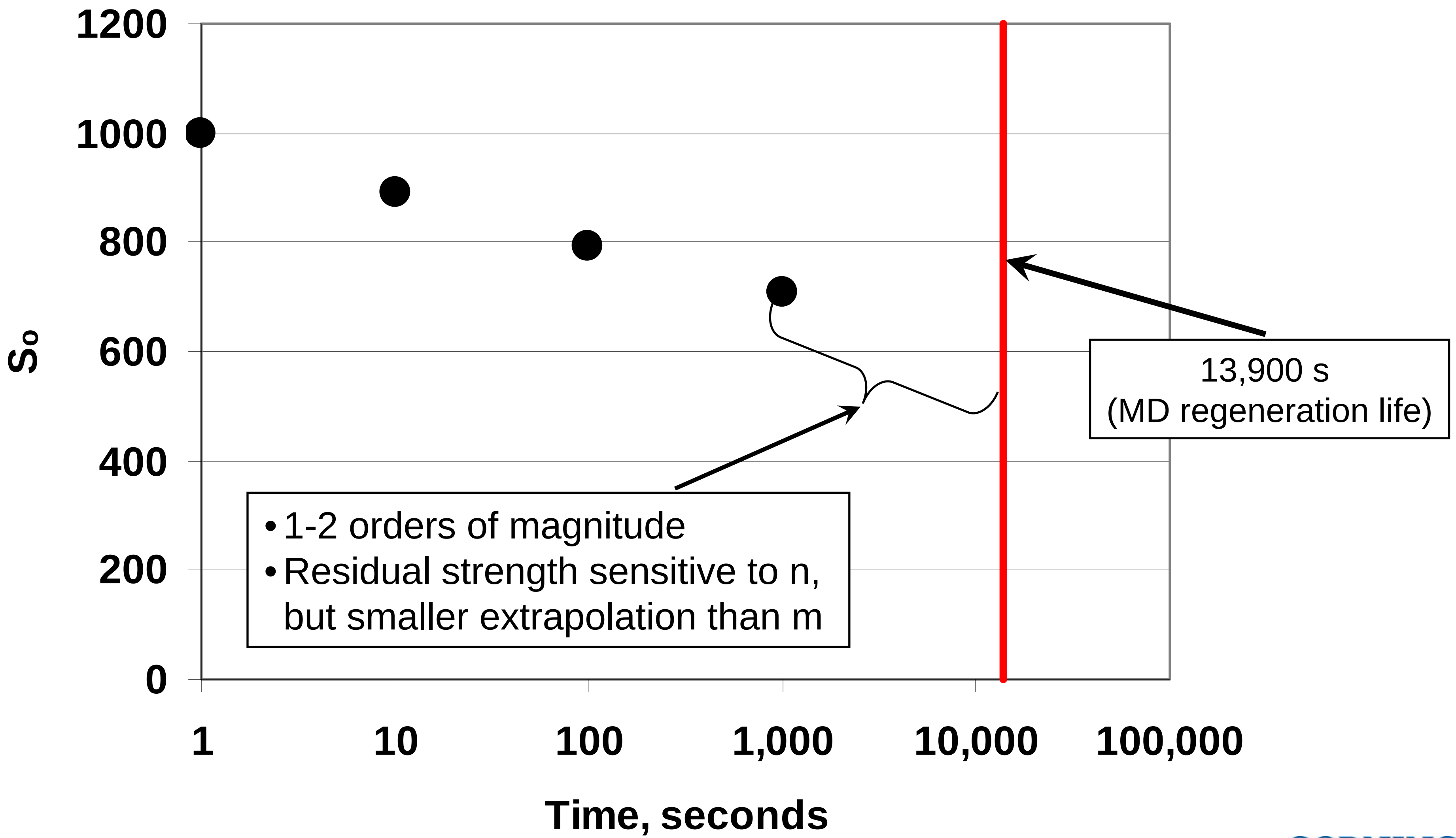
Sample Data

20 points
S_o = 1000
m = 15

Probability Range of Interest

- 3 or More orders of magnitude
- Residual strength sensitive to m

Time Extrapolation (n sensitivity)



Test Design Impact

- Small strength test designs produce significant extrapolations for probability and time
  - Weibull modulus sensitivity
  - Fatigue constant sensitivity
- Larger sensitivity for Weibull modulus due to larger extrapolation
- Improving confidence in the Weibull modulus, m, also improves confidence in determining the fatigue constant, n

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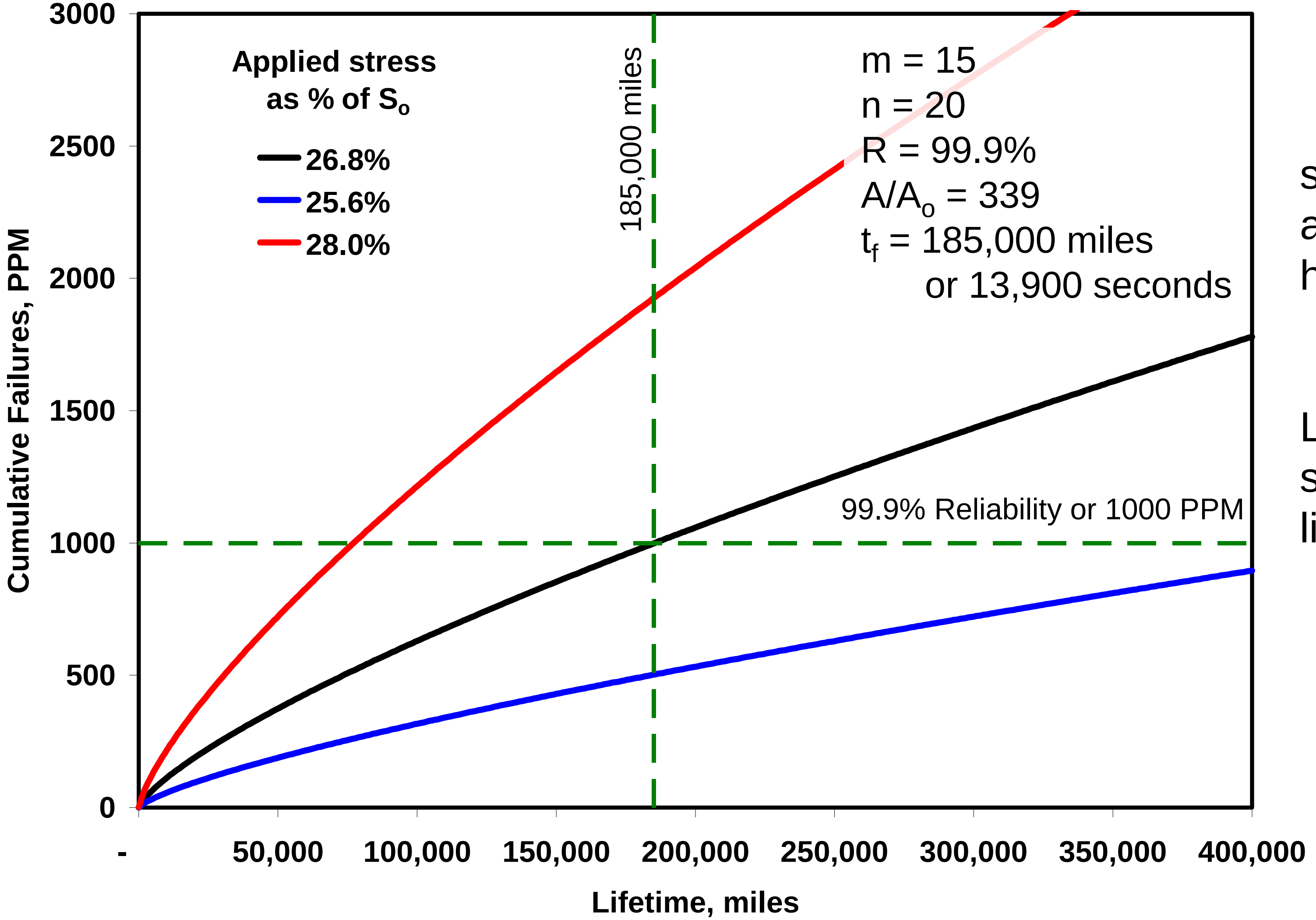
Final Analysis:
calculations in terms of cumulative failures and mileage



strong impact applied stress has on lifetime

Lower applied stress - longer life