The Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials

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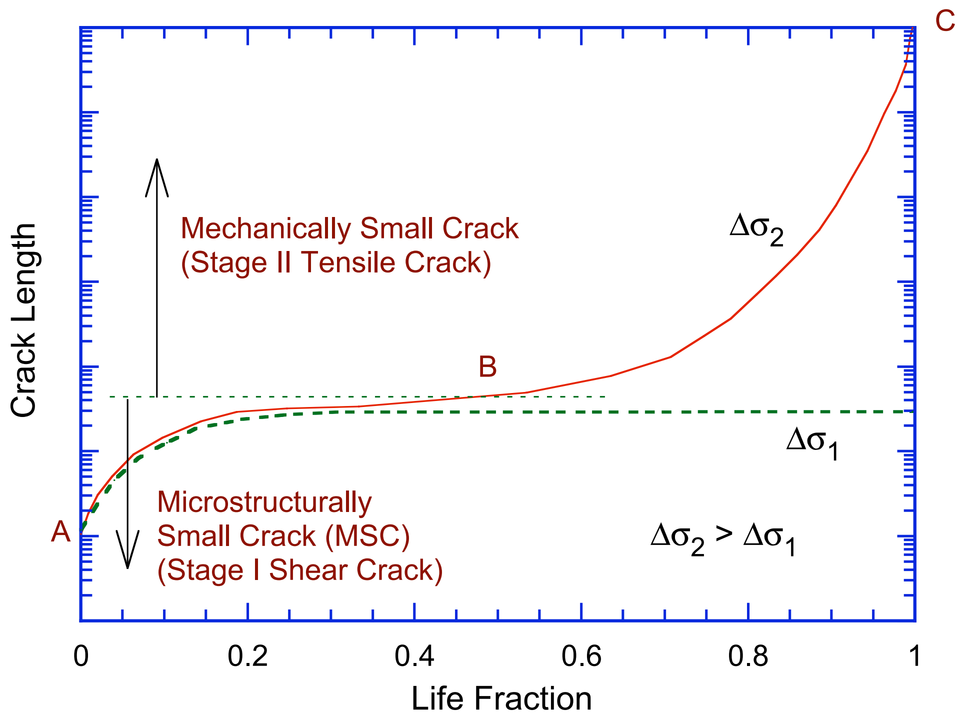
Fatigue Life

- Code design curves define fatigue life as cycles to failure; however, small–specimen fatigue ε–N data define life as cycles to form a ≈3 mm crack



- *Surface cracks ≈10 µm deep form early during fatigue loading*
- *Fatigue life is growth of small cracks; 10 to 3000 µm for smooth specimens*
- *Represented by two stages:*
  Initiation: microstructurally small cracks
  100 to 300 µm
  Propagation: mechanically small cracks
  300 to 3000 µm (LEFM / EPFM)
- *Fatigue damage is current crack size, accumulation is growth to critical size*

ASME Code Fatigue Design Curves

- Code fatigue design curves based on data obtained on small, smooth specimens in RT air under constant loading conditions
- To use small–specimen data to obtain fatigue lives of reactor components, best–fit curves of specimen data must be adjusted to cover effects of variables that influence fatigue life but were not investigated in the data
  - Such variables include mean stress, data scatter & material variability, differences in surface condition & size between test specimen & components, and loading history
- Factors of 2 & 20 used in current Code curves to account for these variables, to obtain Code design curves the best-fit curves of specimen data were
  - First adjusted for effects of mean stress on fatigue life
  - Then reduced by factor of 2 on stress or 20 on life, whichever is more conservative

Environmental Effects on Austenitic SSs

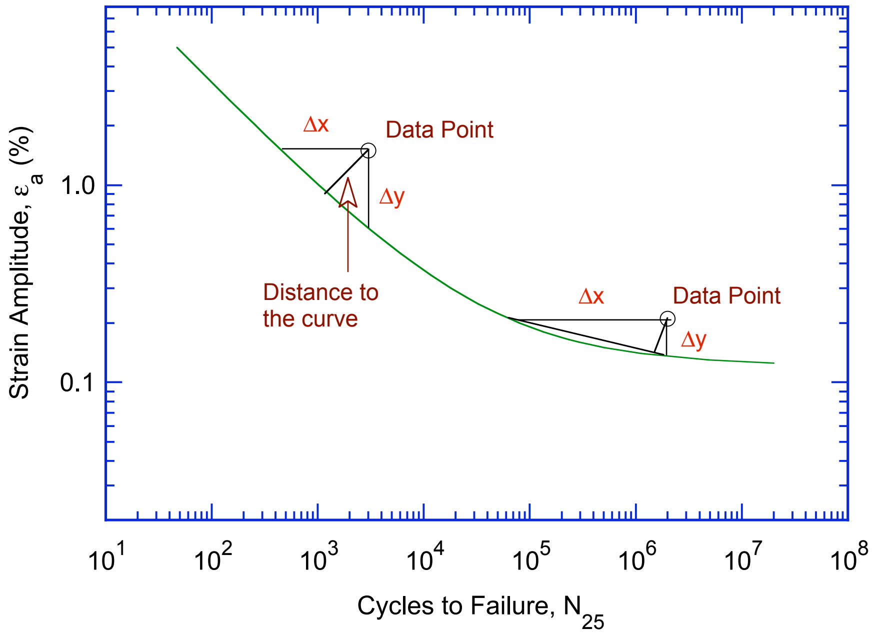
- The effects of critical parameters on fatigue life & threshold values:
  - Steel type: environmental effects similar for wrought Types 316 & 304 and cast SS; for cast SS, insignificant effect of ferrite between 12–28%
  - **Strain amp**: threshold slightly above fatigue limit; effects independent of strain
  - **Strain rate**: threshold 0.4%/s & decreasing, saturation at 0.0004%/s; logarithmic decrease in life between 0.4 and 0.0004%/s
  - **Temperature**: threshold 150°C & increasing; life decrease linearly up to ≈325°C
  - Dissolved Oxygen: threshold 0.05 ppm & lower; effect different than for ferritic steel in low–DO water, effect significant for all steels & heat treatment conditions; in high–DO water, environmental effect may be lower for solution annealed steel and increase with increasing degree of sensitization
  - Surface roughness: life of rough specimens decreased both in air & low–DO water
  - Flow rate: no effect of flow rate on fatigue life in high–purity water at 289°C
- For environmental effects to be significant, threshold values of all critical parameters (in bold red) must be satisfy

Environmental Effects on Carbon/Low-Alloy Steels

- The effects of critical parameters on fatigue life & threshold values:
  - Steel type: environmental effects identical for CSs & LASs
  - **Strain amp**: threshold slightly above fatigue limit; effects independent of strain
  - **Strain rate**: threshold 1%/s & decreasing, saturation at 0.001%/s; logarithmic decrease in life between 1 and 0.001%/s
  - **Temperature**: threshold 150°C & increasing; life decrease linearly up to ≈320°C
  - **Dissolved Oxygen**: threshold 0.04 ppm and above, saturation at 0.5 ppm, logarithmic decrease in life between 0.04 and 0.5 ppm
  - **Sulfur**: no threshold, saturation at 0.015 wt.%; effects increase linearly with S
  - Surface roughness: fatigue life of rough specimens is decreased in air; in high–DO water, surface roughness has little or no effect on fatigue life
  - Flow rate: in high–DO water, environmental effects decrease with flow rate; e.g., factor of up to 2 lower in high flow (>0.3 m/s)
- For environmental effects to be significant, threshold values of all critical parameters (in bold red) must be satisfy

Fatigue Strain vs. Life (ε-N) Curve

- Fatigue design curve obtained from best-fit curve of fatigue ε-N data expressed in terms of modified Langer equation; ln[N] = A – B ln(ε_a–C)

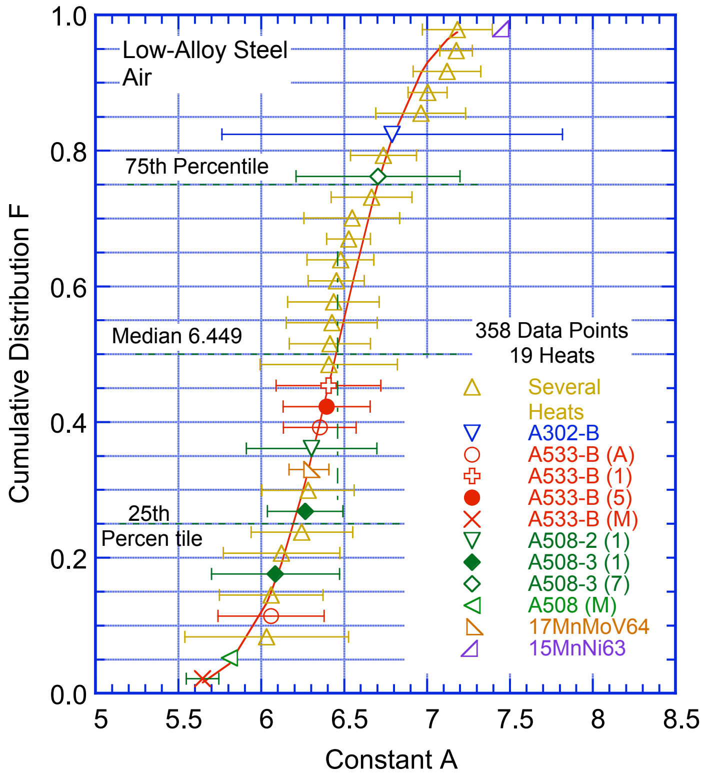


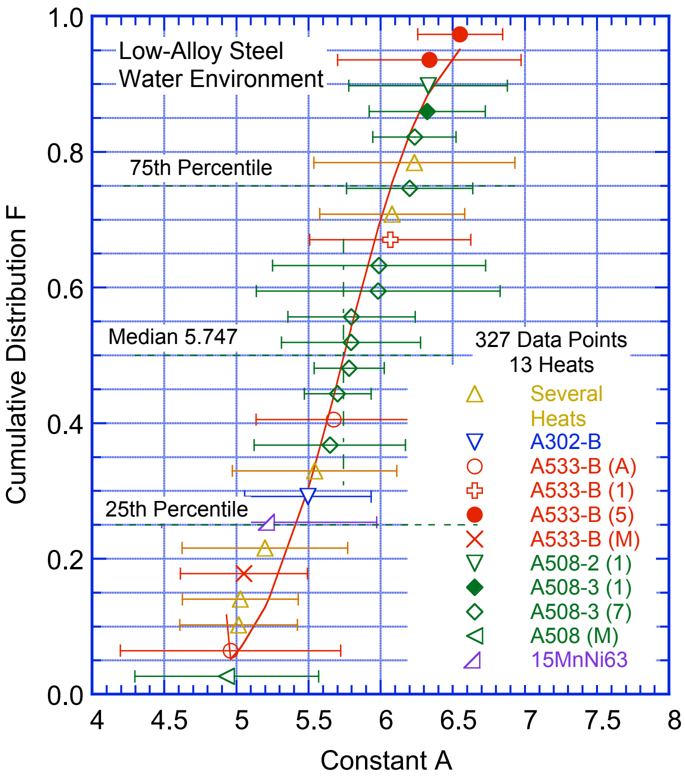
  - Constants A & B are obtained by minimizing the error on life; however, data with ε_a less than C can not be included in the analysis
  - Constant C (or fatigue limit) is obtained from high-cycle fatigue data for several heats of materials
  - ANL model obtained by minimizing the distance between curve & data point

- Statistical model should not only describe available data but also represent all materials in the field; e.g., if data were obtained on heats that are resistant to fatigue, design curves will not be adequate for most materials in the field

Cumulative Distribution of Constant A - Low-Alloy Steel

- Model constant A for data sets of heats & test conditions may be used to determine cumulative distribution of A for the population of heats of interest





  - The 5th percentile of these distributions give ε–N curve that is expected to bound fatigue lives of 95% of heats of material & test conditions of interest

Revised Model - Carbon & Low-Alloy Steels

Air $\ln[N] = 6.583 - 1.975 \ln(\varepsilon_a - 0.113)$ (Carbon Steels)
$\ln[N] = 6.449 - 1.808 \ln(\varepsilon_a - 0.151)$ (Low-Alloy Steels)

Env. $\ln[N] = 5.951 - 1.975 \ln(\varepsilon_a - 0.113) + 0.101\, S^* T^* O^* \dot{\varepsilon}^*$ (CSs)
$\ln[N] = 5.747 - 1.808 \ln(\varepsilon_a - 0.151) + 0.101\, S^* T^* O^* \dot{\varepsilon}^*$ (LASs)

where $S^* = S$ $(S \le 0.015 \text{ wt.\%})$
$S^* = 0.015$ $(S > 0.015 \text{ wt.\%})$

$T^* = 0$ $(T < 150°C)$
$T^* = T - 150$ $(T = 150 \text{ to } 320°C)$

$O^* = 0$ $(DO < 0.04 \text{ ppm})$
$O^* = \ln(DO/0.04)$ $(0.04 \text{ ppm} < DO \le 0.5 \text{ ppm})$
$O^* = \ln(12.5)$ $(DO > 0.5 \text{ ppm})$

$\dot{\varepsilon}^* = 0$ $(\dot{\varepsilon} > 1\%/s)$
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.001 \le \dot{\varepsilon} \le 1\%/s)$
$\dot{\varepsilon}^* = \ln(0.001)$ $(\dot{\varepsilon} < 0.001\%/s)$

- Only the constant term has been changed in the revised/updated model

Revised Model - Austenitic Stainless Steels

Air $\ln[N] = 6.891 - 1.920 \ln(\varepsilon_a - 0.112)$ (wrought & cast SSs)

Env. $\ln[N] = 6.157 - 1.920 \ln(\varepsilon_a - 0.112) + T^* O^* \dot{\varepsilon}^*$ (wrought & cast SSs)

where

$T^* = 0$ $(T < 150°C)$

$T^* = (T - 150)/175$ $(150 \leq T < 325°C)$

$T^* = 1$ $(T \geq 325°C)$

$O^* = 0.281$ (all DO levels)

$\dot{\varepsilon}^* = 0$ $(\dot{\varepsilon} > 0.4\%/s)$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/0.4)$ $(0.0004 \leq \dot{\varepsilon} \leq 0.4\%/s)$

$\dot{\varepsilon}^* = \ln(0.0004/0.4)$ $(\dot{\varepsilon} < 0.0004\%/s)$

- Data reanalyzed to develop a single model for wrought & cast austenitic SSs; constant C is based on models by Tsutsumi et al. and Jaske & O'Donnell, slope B determined from best-fit of fatigue ε-N data, and constant A obtained from cumulative distribution of A for various data sets

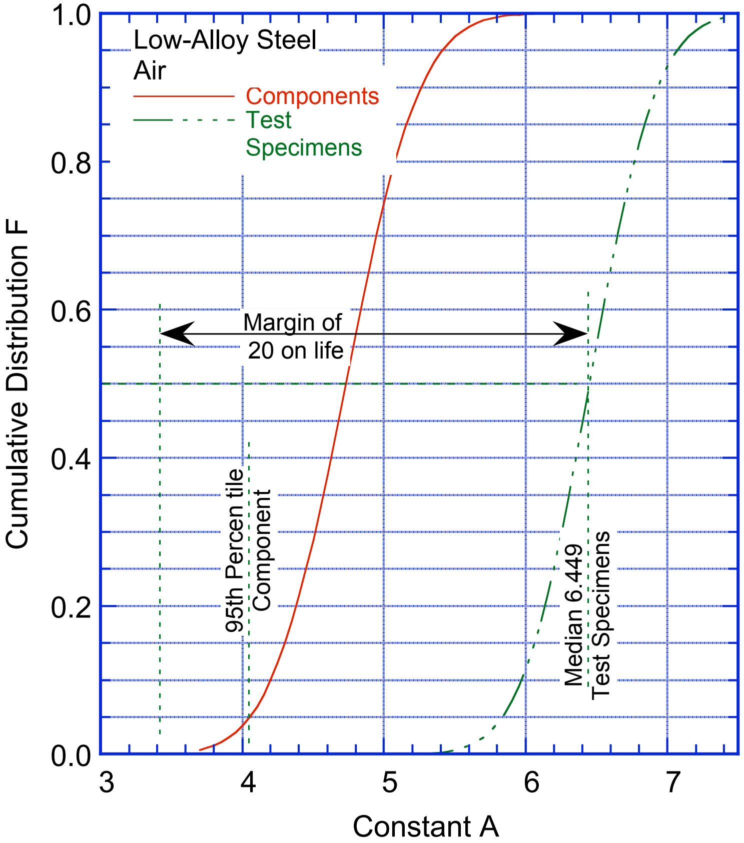
Fatigue Design Margins

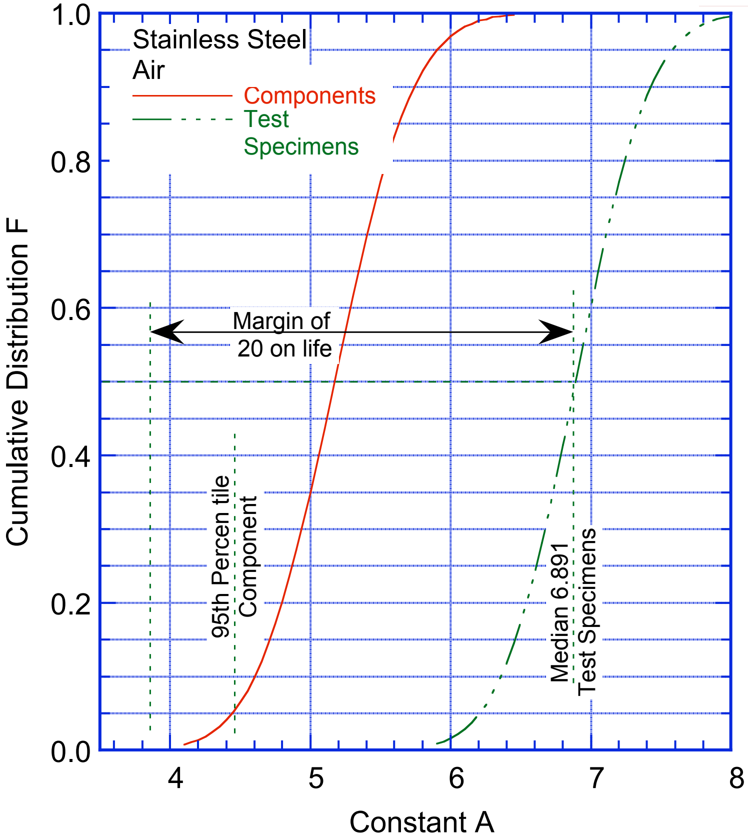
- Available information has been reviewed to define the margins on life that must be applied to the mean-data curve to account for the effects of variables that influence fatigue life but were not investigated in the data

Parameter	Section III Criterion Document	Present Analysis
Material Variability & Data Scatter	2.0	2.1 – 2.8
Size	2.5	1.2 – 1.4
Surface Finish	4.0	2.0 – 3.5
Loading History	–	1.2 – 2.0
Total Margin	20	6 – 27

  - Monte Carlo simulations were performed to determine the distribution of A for adjusted fatigue curve that represents the behavior of actual component.
    - *Use material variability & data scatter results from the present analysis (distribution of parameter A of test specimen)*
    - *Assume a lognormal distribution for the effects of size, surface finish, & loading history and, the min and max values of adjustment factor assumed to represent 5th and 95th percentile, respectively*

Fatigue Life of Components





- Margin applied to mean values of specimen fatigue life to bound component fatigue life of 95% of population is ≈12. Thus, current Code requirements of factor of 20 on life contain at least a factor of 1.7 conservatism

F_{en} Method for Incorporating Environmental Effects

- Environmental fatigue correction factor, F_{en}, is defined as ratio of fatigue life in air at RT to that in water under service conditions

$$\ln[F_{en}] = \ln(N_{RTair}) - \ln(N_{water})$$

$$F_{en} = \exp(0.632 - 0.101\, S^{*} T^{*} O^{*} \dot{\varepsilon}^{*}) \qquad \text{(Carbon Steels)}$$

$$F_{en} = \exp(0.702 - 0.101\, S^{*} T^{*} O^{*} \dot{\varepsilon}^{*}) \qquad \text{(Low–Alloy Steels)}$$

$$F_{en} = \exp(0.734 - T^{*} O^{*} \dot{\varepsilon}^{*}) \qquad \text{(Stainless Steels)}$$

$$F_{en} = 1 \quad (\varepsilon \le 0.07\% \text{ carbon/low-alloy steels \& } \le 0.10\% \text{ wrought \& cast SS})$$

- To incorporate environmental effects, fatigue usage in air is multiplied by F_{en}

$$U_{en} = U_1 F_{en,1} + U_2 F_{en,2} \ldots\ldots U_n F_{en,n}$$

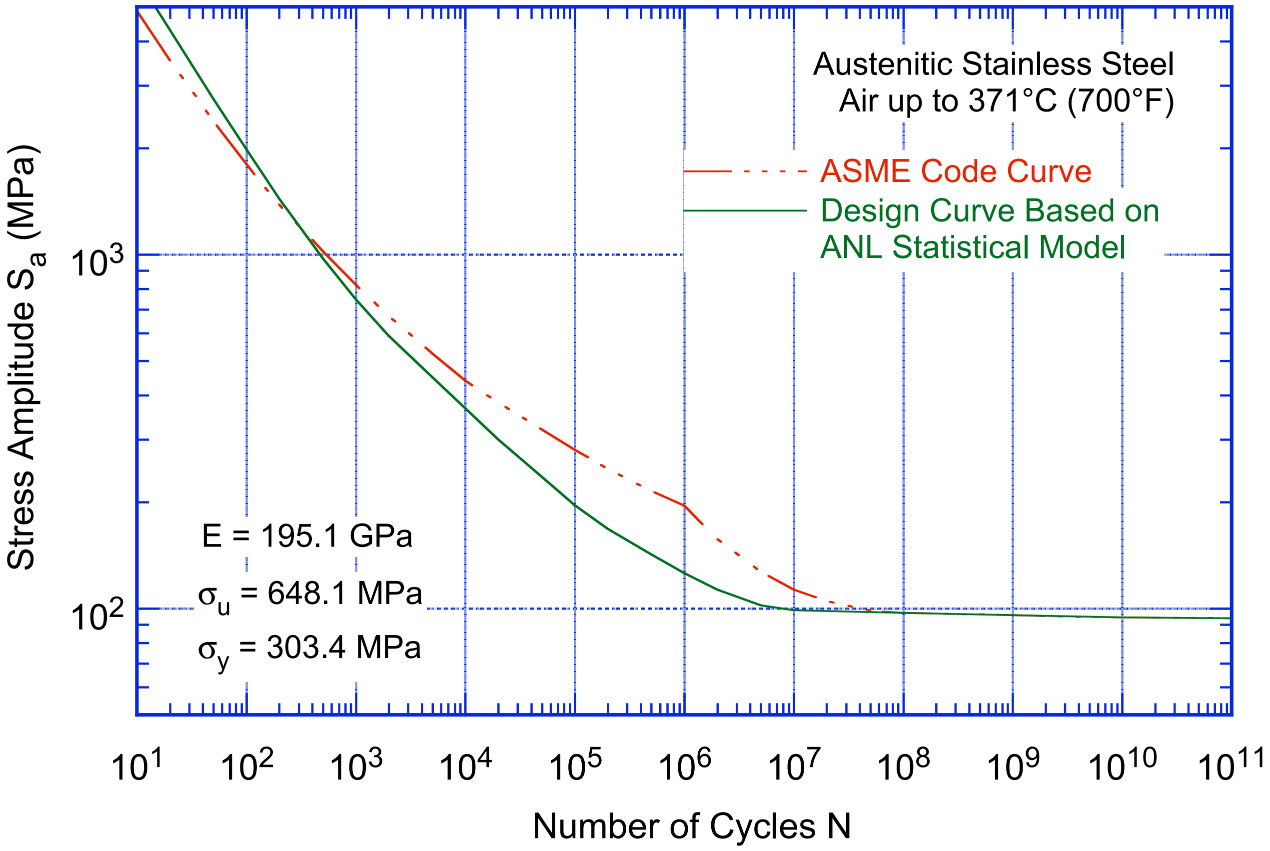
  - Fatigue usage in air is determined from fatigue design curve that is consistent (or conservative) with respect to existing fatigue ε–N data. Current Code curve for SSs should not be used because it will yield nonconservative estimates of CUF.

F_{en} Method (Contd.)

- Examples of calculating partial usage factors are as follows:
  - For carbon & low-alloy steels, usage factors obtained from current Code curves, or to reduce conservatism in the Code requirements of 20 on life, usage factors may be determined from design curves developed from ANL statistical models.
  - For wrought & cast austenitic SSs, usage factors determined from design curves developed from ANL statistical models.
- Guidance to define key loading & environmental parameters
  - Average strain rate for the transient always yields conservative estimate of F_{en}.
  - When results of detailed transient analysis are available an average temperature may be used to calculate F_{en}.

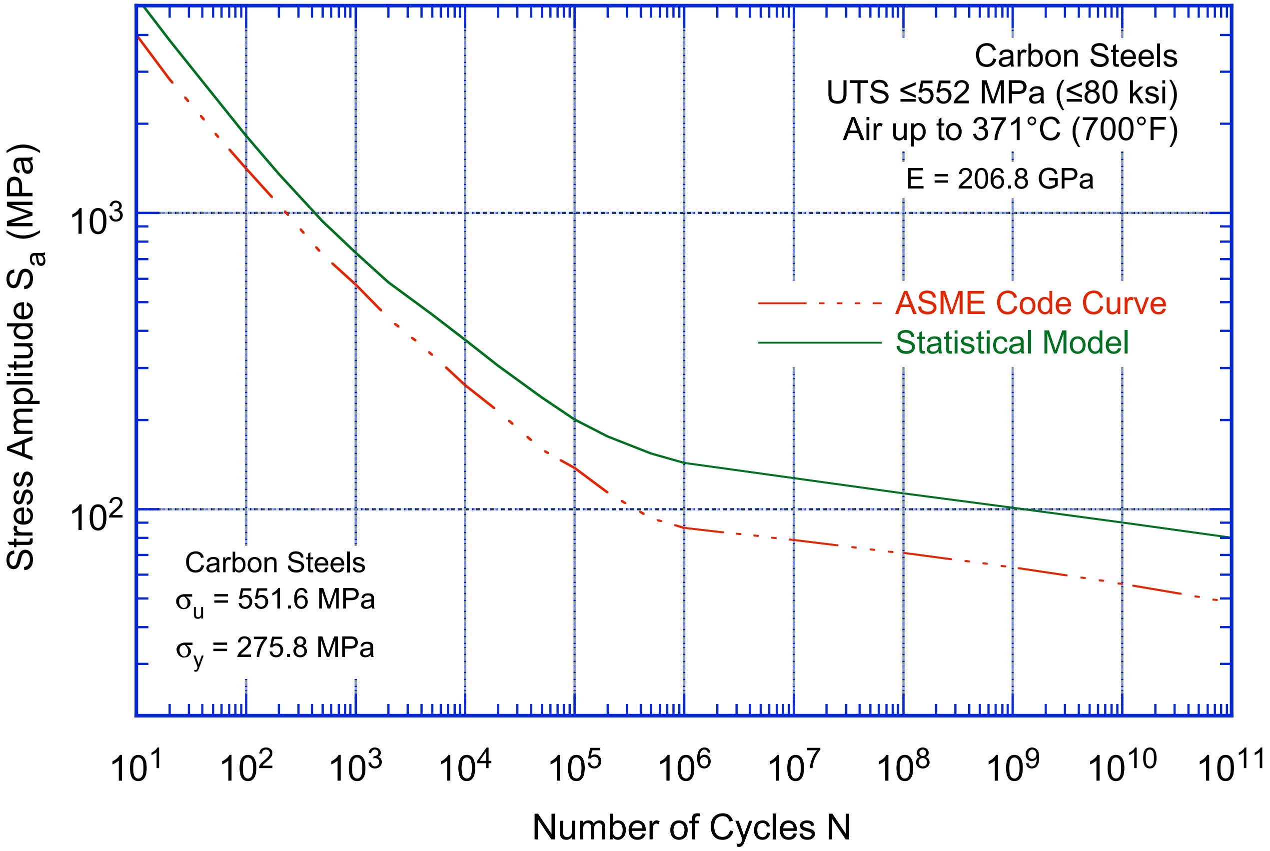
Fatigue Design Curve for Austenitic SSs in Air

- Fatigue design curve based on the ANL model for austenitic SSs and, to reduce conservatism, using a factor of 12 on life and 2 on stress.



Fatigue Design Curve for Carbon Steels in Air

- Fatigue design curve based on the ANL model for carbon steels and, to reduce conservatism, using a factor of 12 on life and 2 on stress.



Fatigue Design Curve for Low–Alloy Steels in Air

- Fatigue design curve based on the ANL model for low-alloy steels and, to reduce conservatism, using a factor of 12 on life and 2 on stress.