Fatigue Design Rules

General Introduction

Content

- General Introduction to Fatigue Design Rules
- Review of EN 13445 Fatigue Design Rules
- Review of EN 13480 Fatigue Design Rules (later)
- Review of EN 12952 Fatigue Design Rules (later)
- Examples of Fatigue open points
- EPERC General Strategic Plan
- EPERC TG1 Potential R&D Program

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Rev. 5

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European P

Fatigue Analysis Procedure

Cyclic loading

Elastic Strain History
Temperature History

Plastic Shakedown
Elastic / Non linear analysis

Cycle combination
Design transients: shocks/ramp
-Spectrum / Sub cycles/ Monitoring
-Strain rate of combined cycles

Damage Cumulation
Miner Rule / "Rainflow" / other

CUF
Cumulative Usage Factor

Crack Growth
Exceptionally for Design/
Possible in operation for LTO
Crack size for CUF=1 ?

Vessels- Pipes-Valves
Other components

Base metal/ Cast
Cladded-not cladded
Welds / Crack like defects

+ HCF + Seismic loads

Plasticity
- Ke, Kν or
- Non-linear Analysis

Small specimen tests

Material Properties:
- Cyclic Stress Strain Curves
- (S,N) and da/dN-ΔK Curves
- environmental effects

Detrimental factors (DF)
temperature, cold work,,
bi-axiality, mean stress, surface finished, welds, residual stresses…

Transferability & criteria
(initiation-Ithrough wall eak ?)

Mock-up / Structure Tests

Benchmarking

Codified Rules

-Thermal Transients - Stratification
- Thermal Mixing areas (HCF)
-- Seismic loads
-- Crack like defects

To all European C&S

Fatigue Design Rules and Justification

- ✓ **Fatigue Damage**: cyclic loads leading to "engineering crack of 2 to 3 mm" ???
- ✓ **Fatigue Damage Evaluation**: **U = Ratio** $N_{applied}$ / $N_{allowable}$ through material (S, N) design fatigue curves
- ✓ **Fatigue Damage** proportional to Number cycles and **Strain amplitude around power 5**
  ➔ 15% on strain amplitude ➔ 2 on life of the components (!!!!!)

- ✓ If **Fatigue** codified **U_{max} value is reached** ➔can fatigue crack growth be considered?

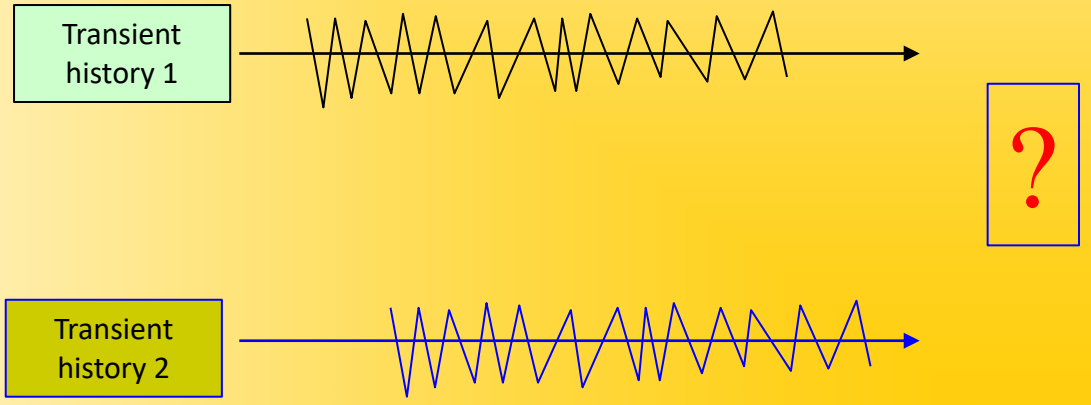
- ✓ **Fatigue** of sharp discontinuities, crack like defects and welded joins ???

- ✓ **Material properties**:
  - (S,N) curves, standards, uncertainties on **mean to design curves**, and **environmental effects** (including in particular H_2),
  - cyclic stress-strain curve…

…

Fatigue Design Rules and Justification

- ✓ Questions on **strain range evaluation**:
  - ➢ **plastic shakedown rules** and justification of strain control fatigue tests used
  - ➢ **plasticity and K_e and cycle combination rules:** principal stress rotation, HC fluctuations, mean stress-mean strain, seismic cyclic loads…
  - ➢ **Multi-axial loads**
  - ➢ **Load combination**
    - When principal stresses turn during the transient
    - Fluctuations/ Vibration/Seismic loads with main transient
    - 2 level of fluctuations:

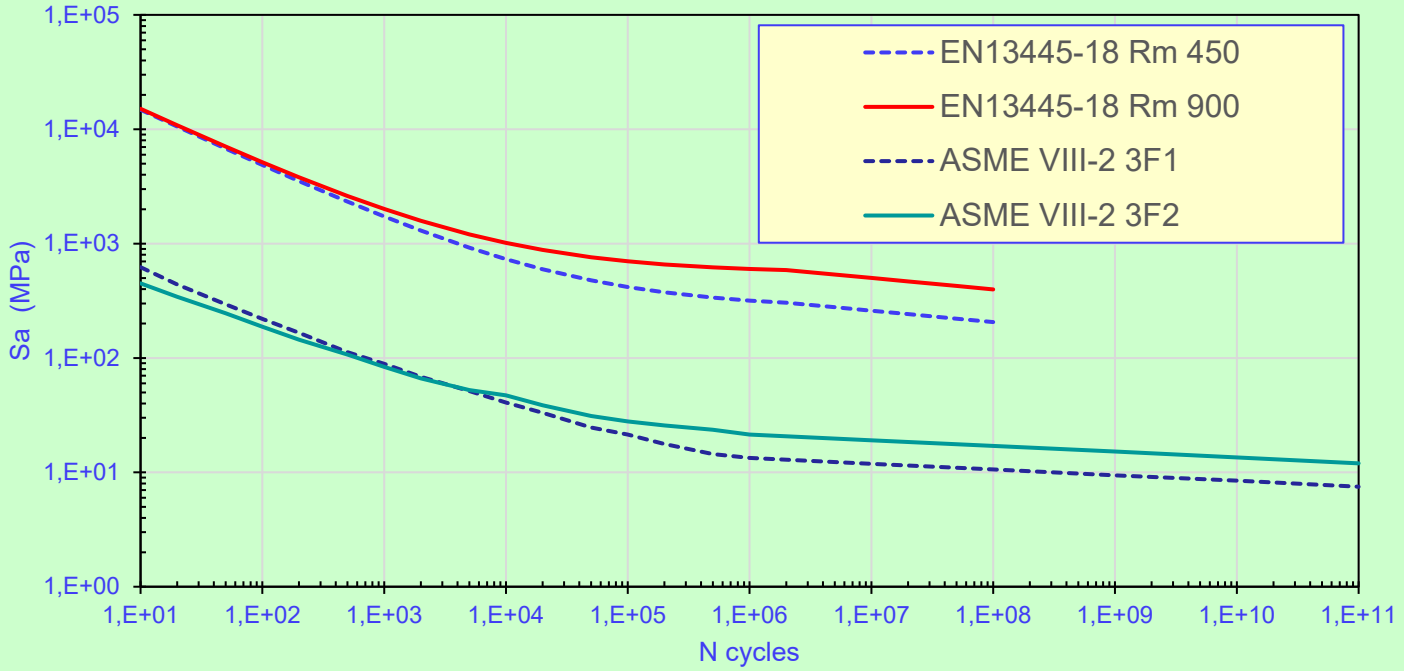


Fatigue Design Rules and Justification

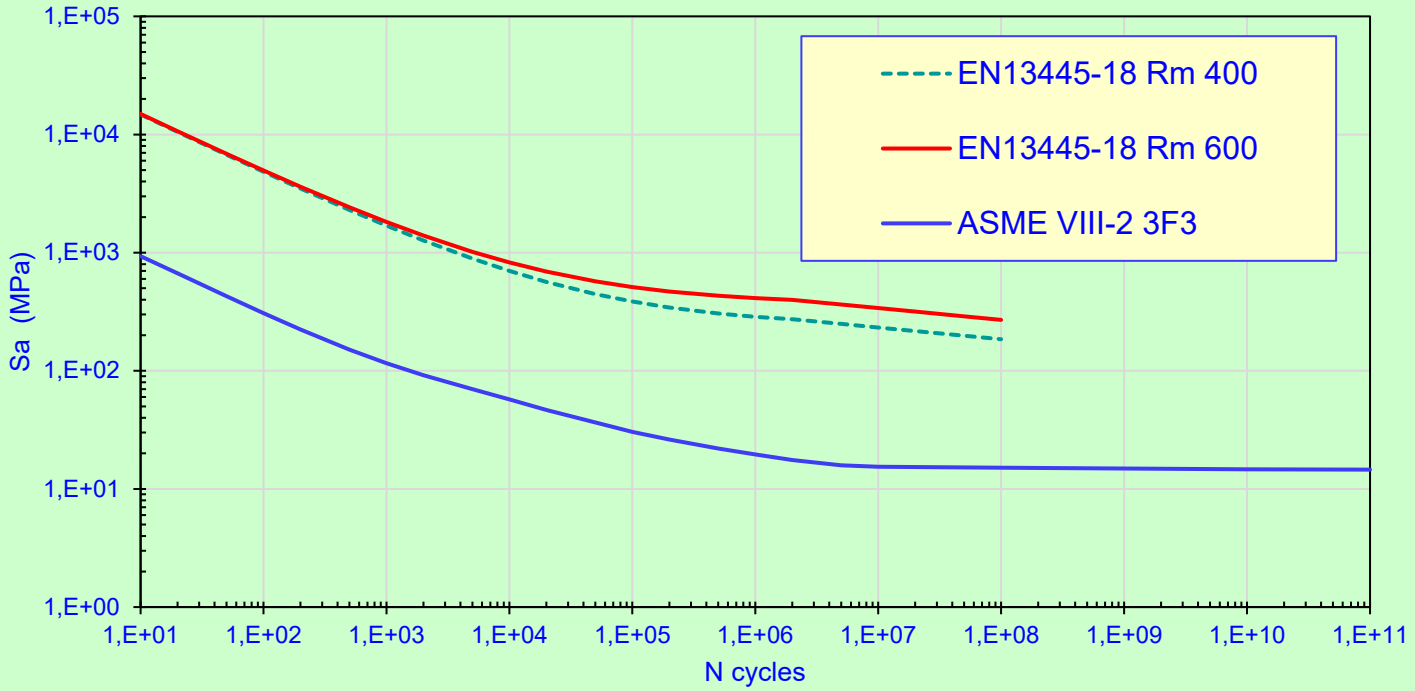
Questions on Material properties

- ✓ Fatigue Design Curves
  - (S,N) curves data banks and standard used
  - Major uncertainties on **mean**
  - **Mean to Design curves reduction factors**,
  - **Consequences of environmental effects** (including in particular H_2),
- ✓ Cyclic stress-strain curves

Fatigue Curves Comparison ASME VIII-2 and EN13445-18
Carbon and Low Alloys Steels

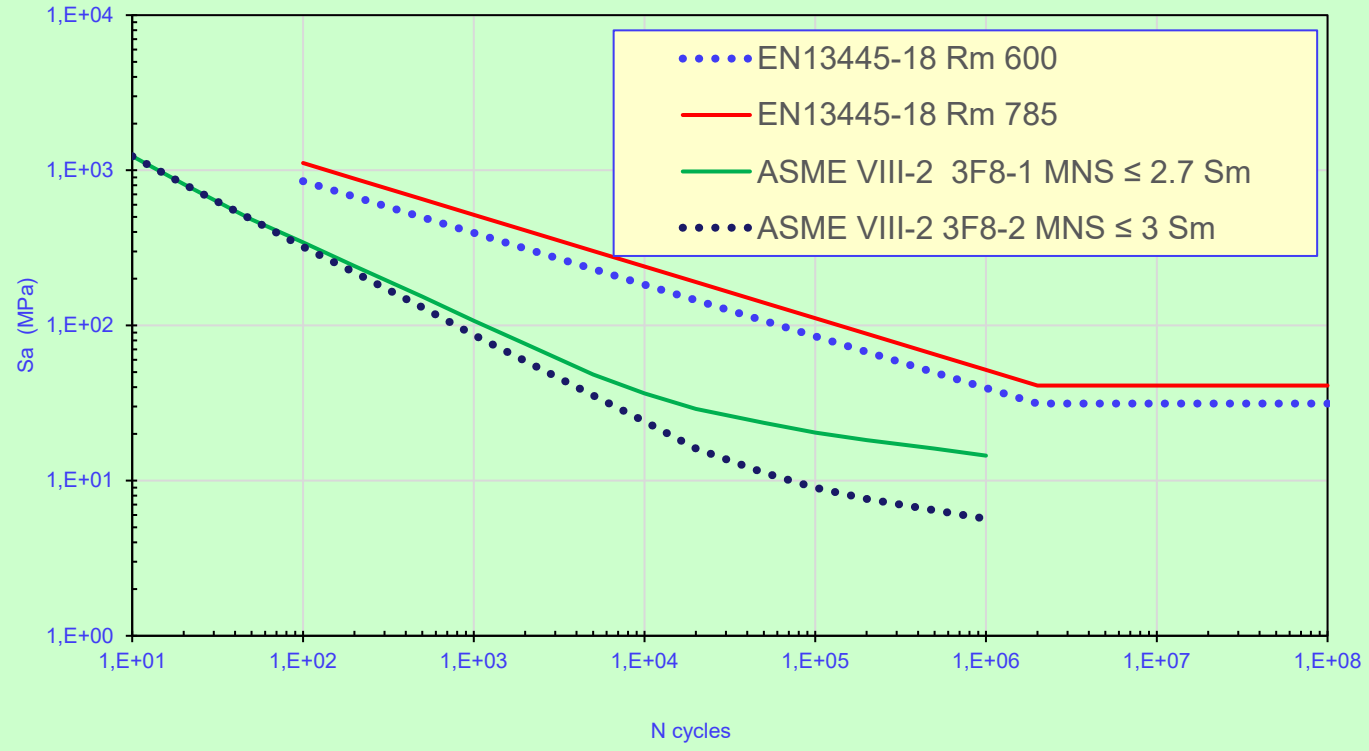


Fatigue Curves Comparison ASME VIII-2 and EN13445-18
Austenitic Stainless Steels



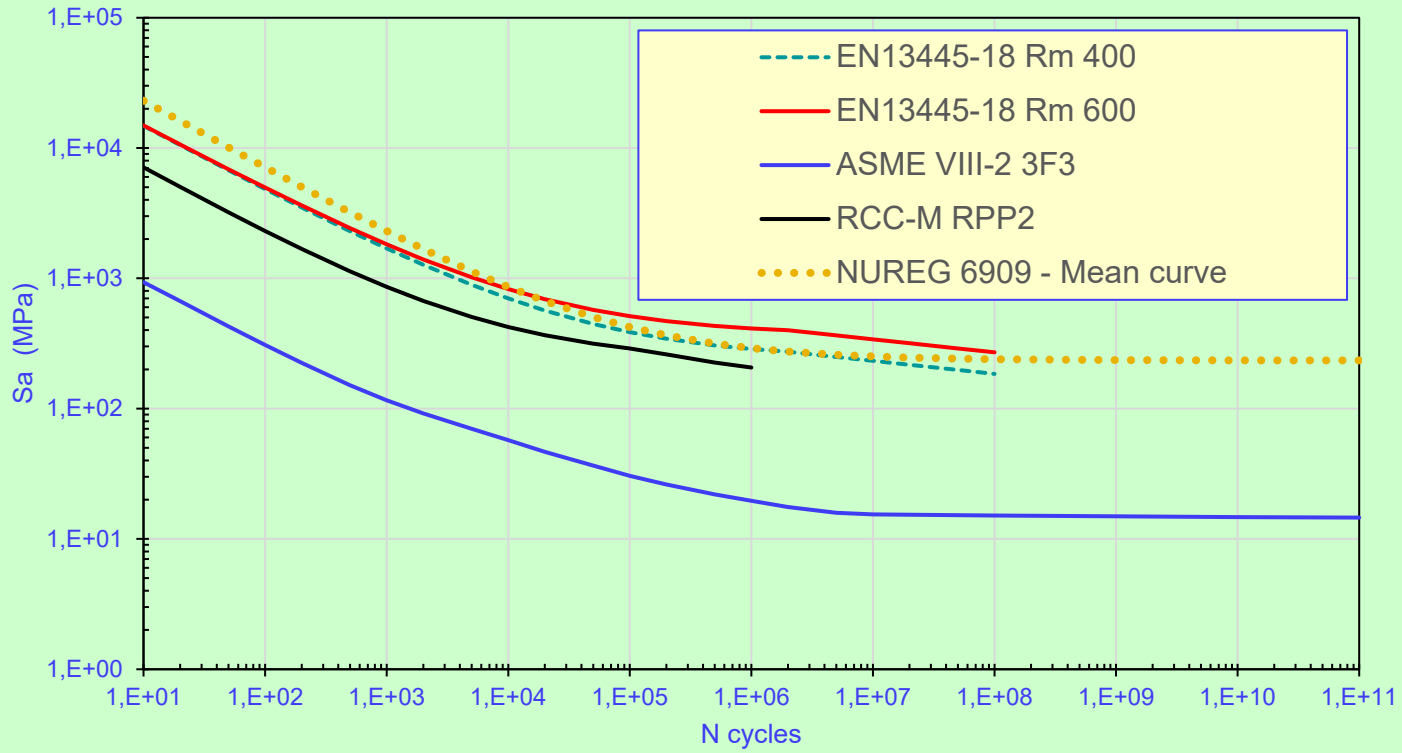
E = 209000 MPa

Fatigue Curves Comparison ASME VIII-2 and EN13445-18 High Strength Bolts



E = 209000 MPa

Fatigue Curves Comparison ASME VIII-2 and EN13445-18 - Austenitic Stainless Steels

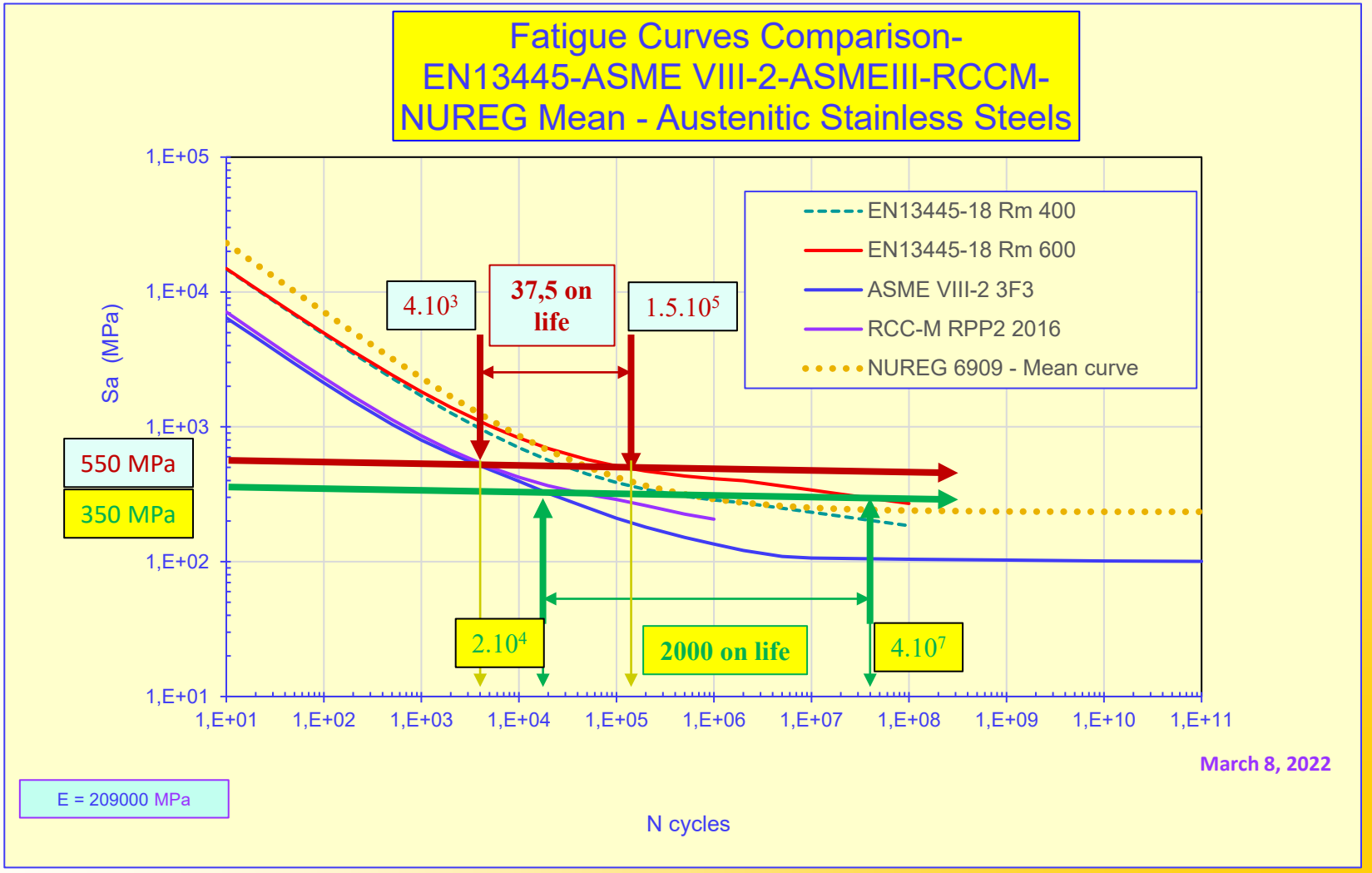


E = 209000 MPa

TG1 : Fatigue

Design Fatigue Curve and uncertainties

Austenitic Stainless Steels



Open Points for Comparison

Austenitic Stainless Steels

✓ Open Point on the comparison

- **Background of EN Fatigue curve**: Standard used, data used, steels considered, reduction factors from mean to design curve+ reduction factors in the Codified procedure…
- If **NUREG mean curve** is an International reference curve for SS, **reduction factors are different by Codes**:

Through Wall Crack ➔
ASME in the past: 2 on Stress and 20 on number of cycles
ASME new one: 12 and 2 (including mean stress effects)

3mm Crack ➔
RCCM:new Code Case: 10 and 1.4 (not including mean stress effects)

- EN 13445: ???

- NUREG proposal for SS under "some water" environment:

$F_{en} = N_{air}/N_{water}$

$F_{en,nom} = \exp(-T' O' \dot{\varepsilon}')$

T' = 0 (T ≤ 100°C)
T' = (T – 100)/250 (100°C ≤ T < 325°C)

$F_{en,nom} = 1$ for $\varepsilon_a < 0{,}10\ \%$

$\dot{\varepsilon}' = 0$ ($\dot{\varepsilon}' > 10\%/s$)
$\dot{\varepsilon}' = \ln(\dot{\varepsilon}/10)$ ($0.0004\%/s \le \dot{\varepsilon}' \le 10\%/s$)
$\dot{\varepsilon}' = \ln(0.0004/10)$ ($\dot{\varepsilon}' < 0.0004\%/s$)

$1 < F_{en} < 10$!!!

For DO less than 0.1 ppm, i.e., for PWR or BWR HWC water:
O' = 0.29 (all wrought and cast SSs and heat treatments and metals)
For DO greater than or equal to 0.1 ppm (i.e., for BWR NWC water):
O' = 0.29 (sensitized high-carbon wrought and cast SSs)
O' = 0.14 (all wrought SSs except sensitized high-carbon SSs)

-	RF_{sct}	scatter	on Nc
-	RF_{scl}	scale	on Nc
-	RF_{temp}	temperature	on Nc
-	RF_{cwo}	cold work	on Nc
-	RF_{biax}	biaxiality	on Nc
-	RF_{ht}	hold time	on Nc
-	RF_{sha}	transient shape	on Nc
-	RF_{rou}	roughness	on Nc
-	RF_{en}	environment	on Nc
-	RF_{mst}	mean stress	on Nc
-	RF_{inter}	interaction	on Nc
-	RF^*_{wld}	weld	on $\Delta\varepsilon$
-	RF**hcy	high cycle	on $\Delta\varepsilon$

International SS "mean" curve:
$\Delta\varepsilon/2\ \% = 32{,}093/(N^{0,5})+ 0{,}112$
Mainly 304L-316L tests

Ex. RCCM : **50** Stainless Steels
$450 < R_{m,20} < 900$ MPa (!!!)
Consequences on Fatigue Curves ????
➔ **1** Codified Fat. Curve for SS…

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K_e-K_υ EN 13445 – K_e RCCM

Mech. Load

$$\Delta\sigma_f = k_e \cdot \Delta\sigma_{eq,t}$$

$$k_e = 1 + A_0\left(\frac{\Delta\sigma_{eq,l,mechanical}}{2R_{p0,2/T^*}} - 1\right)$$

A_0	= 0,5 for ferritic steels with $800 \le R_m \le 1000$ (MPa);
	= 0,4 for ferritic steels with $R_m \le 500$ (MPa) and for all austenitic steels;
	$= 0,4 + \frac{(R_m - 500)}{3000}$ for ferritic steels with $500 \le R_m \le 800$ (MPa).

Therm. Load

$$\Delta\sigma_{eq} = k_v \cdot \Delta\sigma_{eq,l}$$

$$k_v = \max\left(\frac{0,7}{0,5 + \frac{0,4}{\Delta\sigma_{eq,l,thermal}/R_{p0,2/T^*}}}; 1,0\right)$$

Comb Mech & Therm. Load

the Ke correction factor shall be used for both

$$[S_{alt}\ (1)]_{pq} = \frac{1}{2}\max_{ij}\left\{(K_{e\ mech})_{pq}\,(S_{p\ mech}\ (1))_{ij} + (K_{e\ ther})_{pq}\,(S_{p\ ther}\ (1))_{ij}\right\}$$

$K_{e\ mech} = 1.0$ for $S_n \le 3\ S_m$

$$K_{e\ mech} = 1.0 + \frac{1-n}{n\ (m-1)}\left(\frac{S_n}{3\ S_m} - 1\right)$$

for $3\ S_m < S_n < 3m\ S_m$

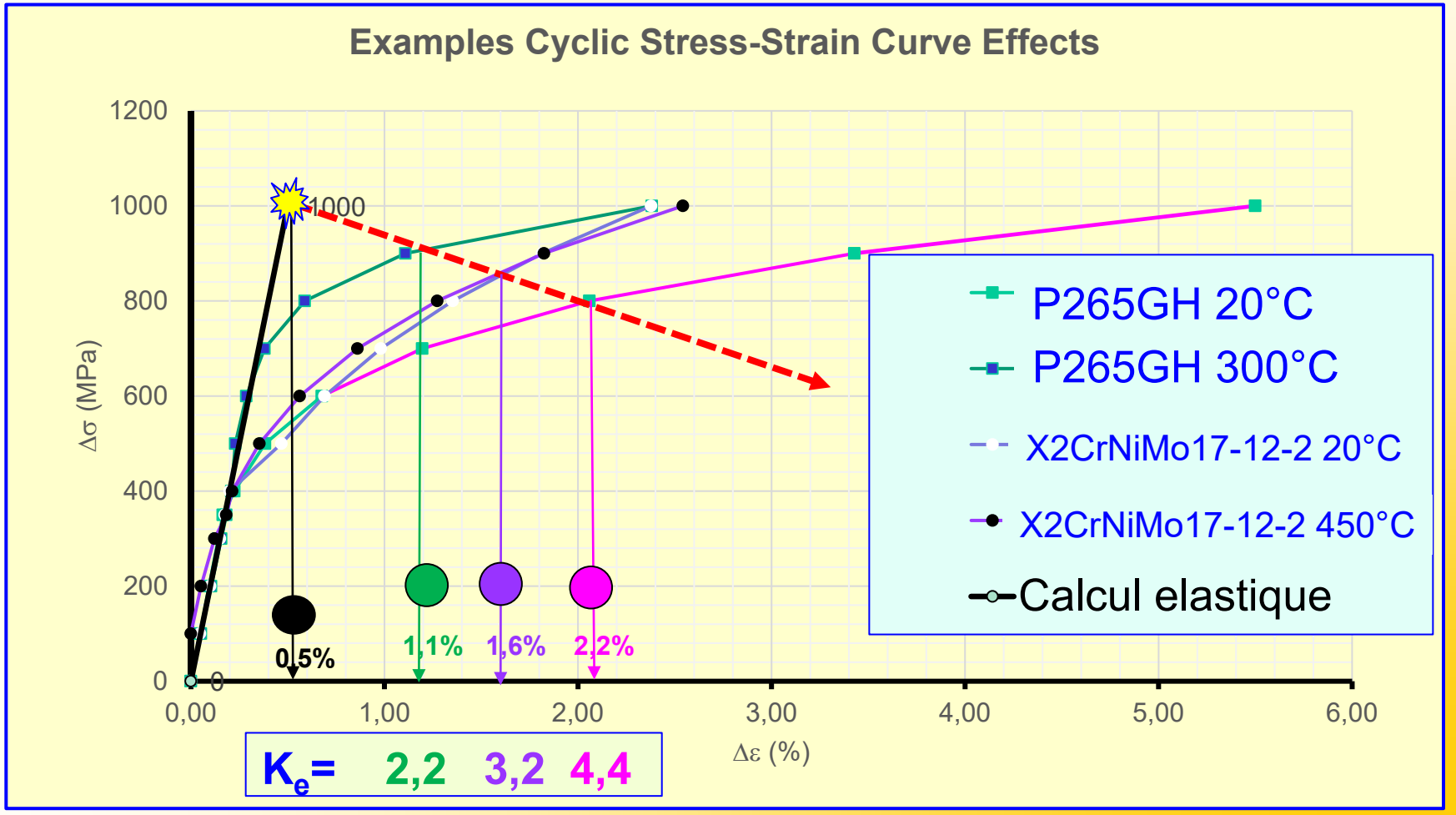
$$K_{e\ mech} = \frac{1}{n}$$ for $S_n \ge 3m\ S_m$

	m	n	Maximum temperature
Low alloy steel	2.0	0.2	370 ° C
Martensitic stainless steel	2.0	0.2	370° C
Carbon steel	3.0	0.2	370° C
Austenitic stainless steel	1.7	0.3	430 ° C
Nickel-chromium-Iron alloy	1.7	0.3	430 ° C

$$K_{e\ ther} = \max\left|\begin{array}{l} 1.86\left\{1 - \frac{1}{1.66 + (S_n/S_m)}\right\} \\ 1 \end{array}\right.$$

Fatigue Design Rules and Justification

K_e and cyclic stress-strain curve



The plasticity Ke factor is EXTREMELY DEPENDANT of the Cyclic Stress-Strain curves

EN 13445 Fatigue Design Rules and Justification

- ✓ Clarification of **"Scope and Validation windows of EN13445"**:
  - for components (vessel, support, bolt, pump, valve, bellow….),
  - temperatures and pressures loads, vibrations and seismic loads
  - strain (or stress) amplitude evaluation
  - materials: cyclic SS curves and mean / design fatigue curves
  - environmental fatigue
- ✓ in order to confirm status of the last edition, and define needs to enlarge it, perhaps with some anticipation with potential innovation needs…
- ✓ Perhaps some benchmarking with other Codes on existing Experimental Tests or practical cases

EN 13480 Fatigue Design Rules and Justification

- ✓ Clarification of **"scope and validation windows of EN13480"**: materials, temperatures and pressures, environments, in order to confirm status of last edition, and needs to enlarge it, perhaps with some anticipation with potential innovation…
- ✓ Detailed review and comparison with other international Code

- ✓ Similar Questions than EN 13445
  - ➢ + Elastic Follow-up rules
  - ➢ + flexibility factors and stress indices
  - ➢ + high seismic load consideration for fatigue
  - ➢ + fatigue and proof tests
  - ➢ + fatigue design exemption rules

- ✓ Clarification of **"scope and validation windows of EN12952"**

- ✓ **Check consistency between the 3 sets of EN Fatigue Design Rules:**

EN 13445, EN 13480, EN 12952

Fatigue – Open Points – R&D needs

- Detailed Comparison of **last Editions**
  - EN 13445 and ASME VIII - API
  - EN 13480 and ASME B 31 – API
  - EN 12952 and ASME I - API
  - ASME III - RCC-M / RCC-MRx – JSME - KEPIC
  - Czech, Chinese, UK or other international Codes

- **Fatigue objectives** to be clarified: "small cracks" or "through wall cracks" ?
- **Elastic versus Inelastic rules**, including K_e , cyclic analyses and plastic shakedown, elastic follow-up …
- **Experimental** fatigue analyses
- **Fatigue curves** (mean and design) and cyclic stress-strain curves
- **Fatigue design curves** reduction factors and uncertainties
- **Cycle combination**, including large seismic event
- **Crack like defects** and notches: comparison of existing methods
- **Environmental Effects**: different types as steams, waters… hydrogen…petro-chemical…
- **Negligible creep** rules and creep/fatigue interaction
- Review of **Exemption of fatigue analysis** rules
- **Fatigue crack growth** analysis methods and data
- **Fatigue analyses exemption rules**

EPERC – TG 1 – Potential R&D Topics

R&D program: set of tests (standards and specimen)
for validation/new developments + Technical Synthesis Reports + Code Cases to EN

1. New Fatigue Curves for (Many ?) Steels and non-steel materials
2. Cyclic Stress-strain Curves For (Many ?) Steels
3. Cycle combination rules
4. Crack Like Defect, Notches and Weld joins
5. Effect of different Environments: water, hydrogen…
6. Mean to Design Fatigue curves: reduction factors
7. Negl. Creep design rules for Ferritic and Austenitic Steels and other EN materials
8. Update the Comparison of Last Edition of International Codes for Fatigue Design Rules (for Vessels, Piping, Valves, Pumps, Bolts, Tubes…)
9. Connection with other EPERC TG's: **TG4** Non-linear Design Rules, **TG9** EN 13445 Vessel Design Rules Background, **TG10** Piping Design Rules, **TG7** FFS, **TG6** Creep…
10. + Mean stress + Roughness effects
11. + Fatigue Design Rules for Non proportional and Multi-axial loading
12. + Enlarge vessels scope to piping, to boilers and other EN pressure equipment

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All volunteers remain welcome !