Design by Analysis Methods in the Modernized Code

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Abstract

Design by Analysis Methods in the Modernized Code

In general Section I of the ASME Boiler Code was originally developed for industrial boilers through to sub-critical boilers operating at relatively low temperatures and pressures under steady state conditions. Current and future boilers do and will operate at higher temperatures and pressures under cyclic loading requiring a more detailed assessment and examination to ensure safe and reliable operation.

Design by Analysis (DBA) methods will be fundamental to the assessment process for key boiler components. It is intended that the Code will incorporate several DBA methods, ranging in complexity, to allow the user some flexibility to select the method appropriate to the design conditions.

The methods currently being considered include an elastic approach based on Section VIII Division 2, an inelastic approach based on the Omega method from API 579, the Section VIII Division 2 Code Case 2843 based on the Section III Part NH rules utilizing the strain deformation method and a new Section III Code Case based on the EN 13445 approach.

This presentation will look at the key aspects of some of the methods and highlight the limitations of each.

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Method 1 : Elastic Approach (based on Section VIII Division 2, New (DRAFT) Part 5.6)

Part 5.6 is organized with each sub-paragraph addressing one of the potential failure modes that are addressed in the rest of part 5: rupture, buckling, creep/fatigue interaction, and ratcheting.

The procedure evaluates protection against stress rupture from primary loading using elastic stress analysis.

It also includes a fatigue screening method.

This procedure is based on the computation and categorization of equivalent stress at a location in a component, and to determine the acceptability of the resulting stress state at each point in time of the operating cycle. Alternatively, if the controlling temperature and loading conditions can be identified, a single calculation may be used to determine acceptability.

Stress Category	*Design*	*Level A and Level B*	*Level C*	*Level D*
primary membrane	$P_m \leq S_m$	$P_m \leq 110\% S_m$ for Level B	$P_m \leq$ greater of $1.2S_m$ and S_y	$P_m \leq 2.4S_m$ and $0.7S_u$
primary bending	$P_L+P_b \leq 1.5S_m$	$P_L+P_b \leq 110\% (1.5S_m)$ for Level B	$P_L+P_b \leq$ greater of $1.8S_m$ and $1.5\ S_y$ ----------OR---------- $P_L+P_b \leq 0.8C_{L\text{-limit}}$	*elastic system analysis* $P_L+P_b \leq (1.5)2.4S_m$ and $(1.5)0.7S_u$ ----------OR---------- Load $\leq 0.9C_{L\text{-limit}}$* or $C_{L\text{-plastic or test}}$ *yld=lesser $2.3S_m$ & $0.7S_y$
secondary	no limit	$P_e \leq 3S_m$ $P_L+P_b+Q \leq 3S_m$	no limit	no limit
peak	no limit	$\frac{1}{2}(P_L+P_b+Q+F) = S_{alt}$ $\sum n / N \leq 1$	no limit	no limit

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Method 1 : Elastic Approach (based on Section VIII Division 2, New (DRAFT) Part 5.6)

Stress Rupture is addressed in a 7 step process:

STEP 1 – Define the loads and load combinations, evaluating those associated with “load-controlled” loads (e.g. pressure or weight) and “strain-controlled” loads (e.g. thermal gradients or imposed displacements). Tables 5.1 and 5.3 give guidance.

STEP 2 – At the location of interest calculate the stress tensor (6 components of stress) and assign to either (1) General primary membrane, (2) Local primary membrane, (3) Primary bending, or (4) Secondary as defined by Figure 5.1 (Noting that Service Stress is currently not considered).

STEP 3 – Sum the stress tensors for each stress category

STEP 4 – Determine the principal stress for each stress tensor and compute the equivalent stress

STEP 5 – Apply appropriate weld strength reduction factor

STEP 6 – Determine the time dependent allowable stress

STEP 7 – Evaluate protection against plastic collapse (time independent regime) or stress rupture (time dependent regime)

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Method 1 : Elastic Approach (based on Section VIII Division 2, New (DRAFT) Part 5.6)

Creep Buckling – is considered for external pressure, generally utilizing the isochronous stress-strain curve approach of Annex 3G.

Creep-Fatigue Interaction – To use this Part of the Code a fatigue screening process must be undertaken to demonstrate no creep-fatigue interaction.

Two fatigue screening criteria which must be met (1) the number of full-range pressure cycles must not exceed 250 and (2) the total number of cycles (including full-range and significant pressure cycles and significant temperature cycles) must not exceed 500.

If both these criteria are met then a detailed creep-fatigue analysis is not required.

Creep Ratcheting – the summation of local primary membrane, primary bending and secondary stress must be kept within the cold to hot stress range.

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Method 1 : Elastic Approach (based on Section VIII Division 2, New (DRAFT) Part 5.6)

Stress Category	Primary			Secondary Membrane plus Bending	Peak
	General Membrane	Local Membrane	Bending		
Description (see Annex 2D and VIII-2, Part 5)	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.	1. Increment added to primary or secondary stress by a concentration (notch). 2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F

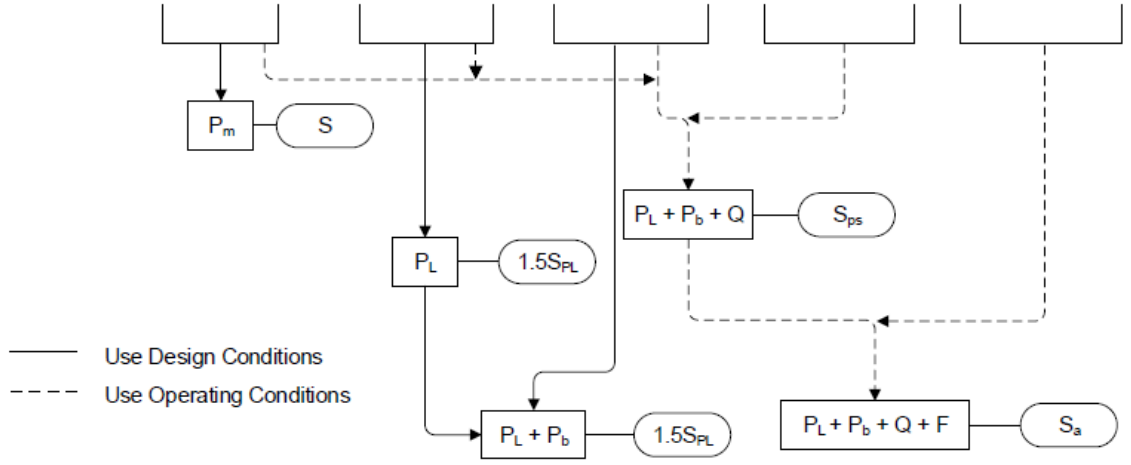

Figure 5.1 – Stress Categories and Limits of Equivalent Stress

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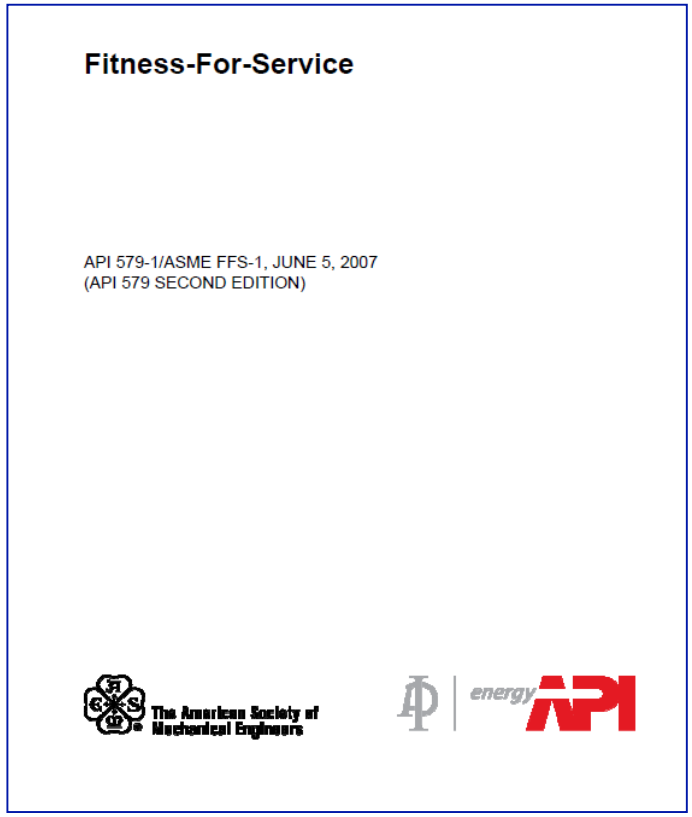
Method 2 Inelastic Approach (based on the Omega method from API 579)

5 failure modes are evaluated:

1) Protection against plastic collapse
2) Protection against local failure
3) Protection against collapse from buckling
4) Protection against failure from Cyclic Loading
5) Protection against Creep and/or Creep-Fatigue

Modes 1 through 4 are covered by Annex B1

Mode 5 is covered by Part 10



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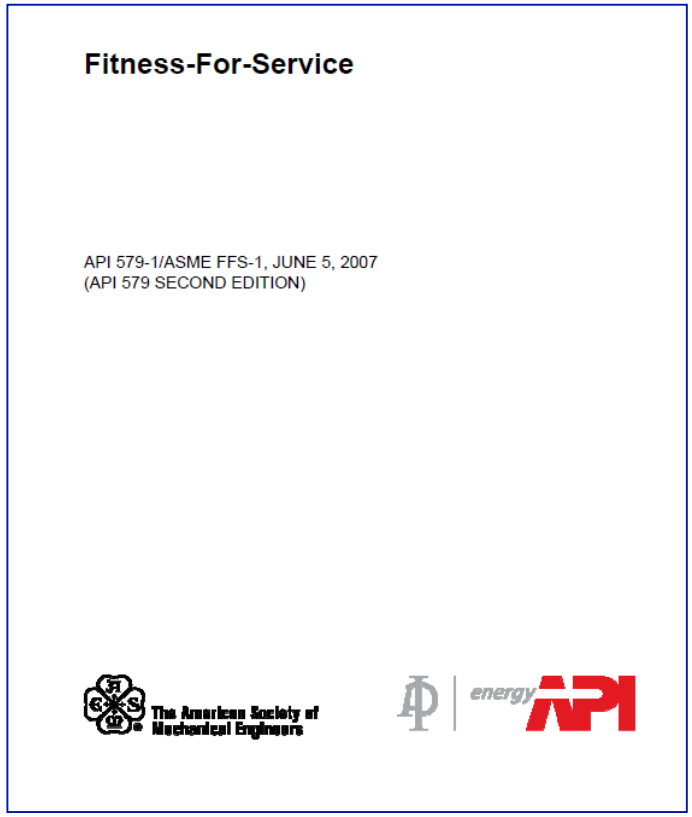
Method 2 Inelastic Approach (based on the Omega method from API 579)

Level 3 Assessment

For Creep Rupture Assessment it is a 12 Step Process:

1. Determine the load history (can be design or service based)
2. For each cycle determine the time increments
3. For each time increment determine the temperature
4. Carry out stress analysis to determine stress components
5. Determine protection against plastic collapse
6. Determine principal stresses and effective stress
7. Determine remaining life
8. Repeat Steps 3 through 7 for each time increment.
9. Calculate accumulated creep damage
10. Repeat Steps 2 through 9 for each cycle
11. Calculate the total creep damage for all cycles
12. Compare with allowable creep damage, limited to 0.8.

Accumulated creep strain is also evaluated.



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Method 2 Inelastic Approach (based on the Omega method from API 579)

This method requires:

- use of an elastic-plastic material model
- Consider the effects of non-linear geometry
- Calculate the plastic collapse load (the load that causes overall structural instability)

Material data is taken from the MPC Project Omega Data (Annex F of FFS-1)

API 579-1/ASME FFS-1 2007 Fitness-For-Service

Table F.30 – MPC Project Omega Creep Data

Material	Notes	Strain Rate Parameter – $\dot{\varepsilon}_0$		Omega Parameter Ω	
Carbon Steel	• See Notes 1 and 2	A_0	-16.3	B_0	-1.0
		A_1	38060	B_1	3060.0
		A_2	-9165	B_2	135.0
		A_3	1200	B_3	-760.0
		A_4	-600	B_4	247.0

$$ {}^{n}L = \frac{1}{\dot{\varepsilon}_{co}\Omega_m} \tag{10.13}$$

where

$$ \log_{10}\dot{\varepsilon}_{co} = -\left\{\left(A_o + \Delta_{\Omega}^{sr}\right) + \left[\frac{1}{460 + {}^{n}T}\right]\left[A_1 + A_2 S_l + A_3 S_l^2 + A_4 S_l^3\right]\right\} \tag{10.14}$$

$$ \Omega_m = \Omega_n^{\delta_\Omega + 1} + \alpha_\Omega \cdot n_{BN} \tag{10.15}$$

$$ \Omega_n = \max\left[\left(\Omega - n_{BN}\right),\ 3.0\right] \tag{10.16}$$

$$ \log_{10}\Omega = \left(B_o + \Delta_{\Omega}^{cd}\right) + \left[\frac{1}{460 + {}^{n}T}\right]\left[B_1 + B_2 S_l + B_3 S_l^2 + B_4 S_l^3\right] \tag{10.17}$$

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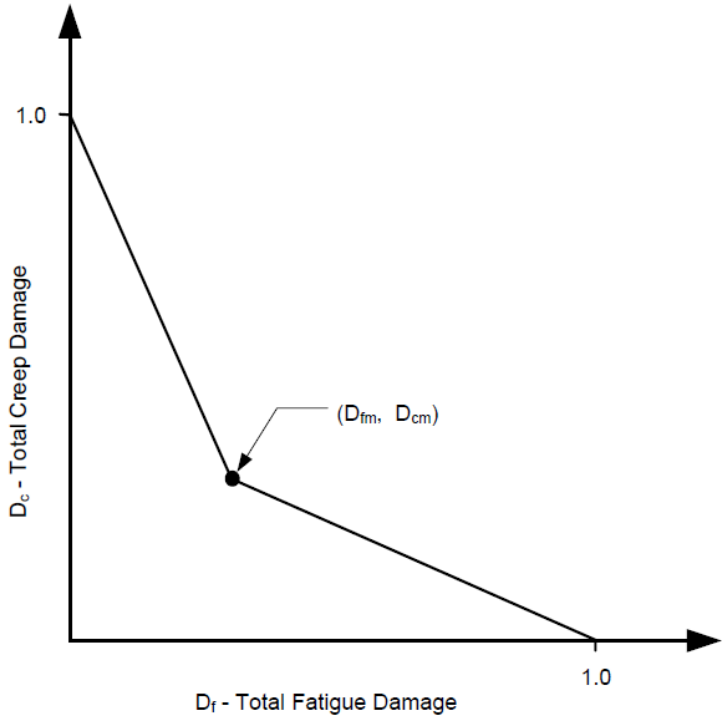
Method 2 Inelastic Approach (based on the Omega method from API 579)

Fatigue life is also evaluated independently and then creep-fatigue interaction is assessed, by reference to the interaction diagram.

The “knuckle” point is set at 0.15 for all carbon and low alloy steels (note some other Codes only restrict sum to be less than unity)



Material Parameters to Define the Acceptable Creep-Fatigue Envelope

Material	D_{fm}	D_{cm}
Carbon Steels	0.15	0.15
Low Alloy Steels	0.15	0.15
Type 304 SS	0.30	0.30
Type 316 SS	0.30	0.30
Alloy 800H	0.15	0.15

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Method 3 – Elastic Approach Utilizing Section VIII Division 2 Code Case 2843 (based on the Section III Part NH rules utilizing the strain deformation method)

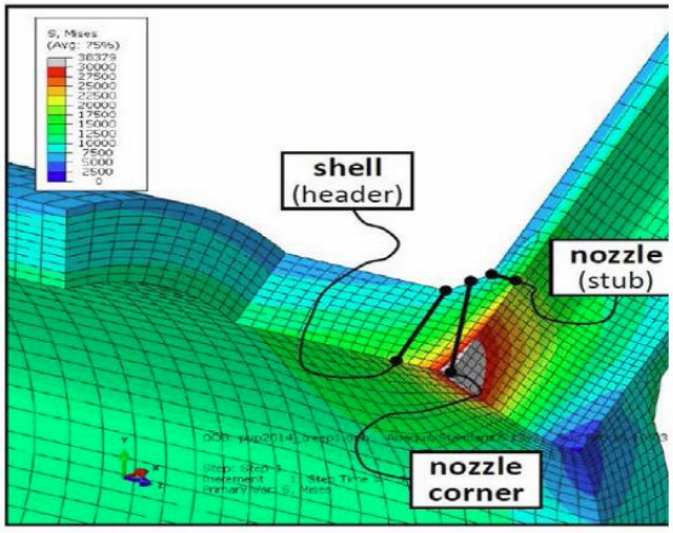
This recently published Code Case includes for time dependent cases.

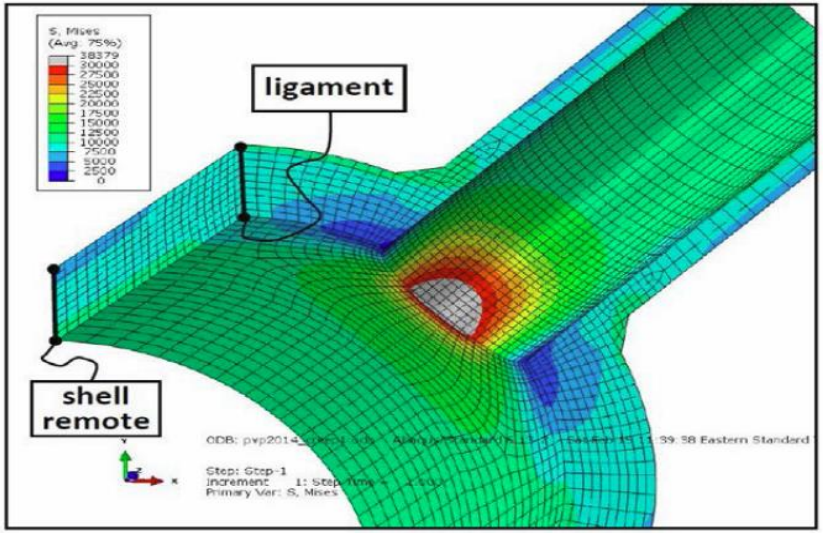
It uses load controlled limits and strain controlled limits.

Load controlled limits to ensure stress levels are maintained below code allowable values.

Strain controlled limits to ensure protection against racheting

The Code Case also addresses creep-fatigue criterion which brings in the lifetime specification for components.





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Method 3 – Elastic Approach Utilizing Section VIII Division 2 Code Case 2843 (based on the Section III Part NH rules utilizing the strain deformation method)

As with the Section VIII Division 2 Part 5 the different loads and combinations are assessed for adequacy.

Figure 2
Flow Diagram for Load-Controlled Stress Limits

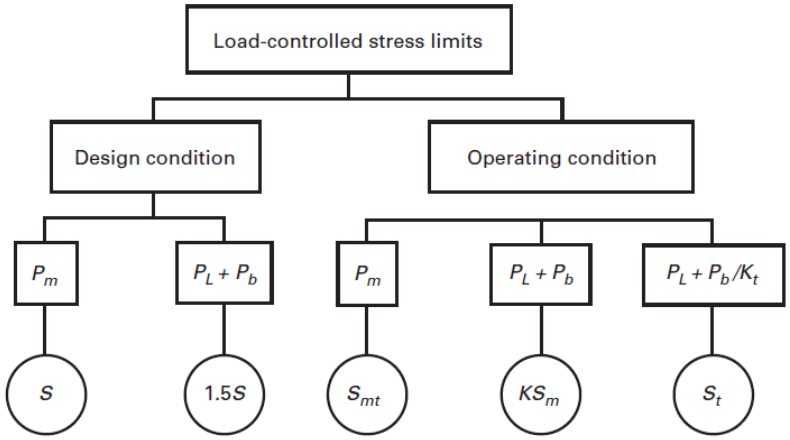


Figure 3
Use-Fractions for Membrane Stress

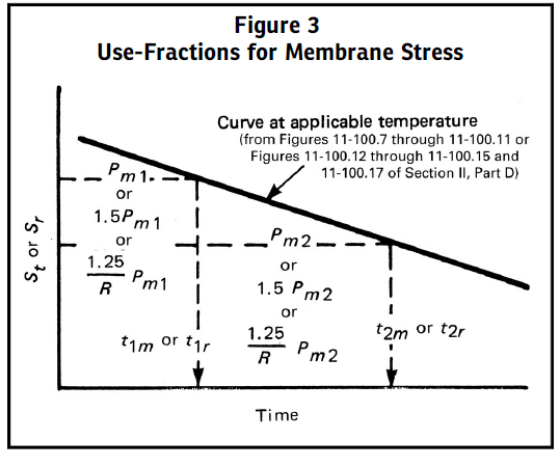
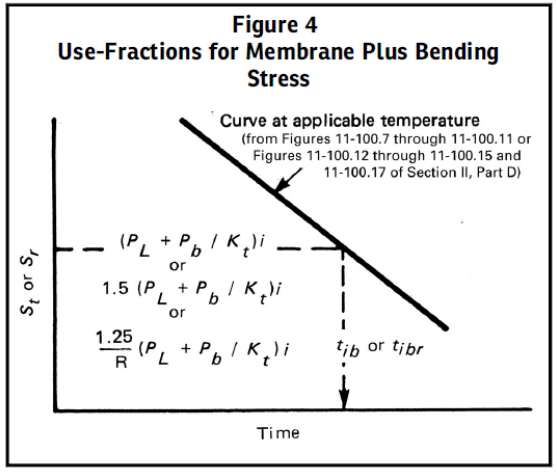


Figure 4
Use-Fractions for Membrane Plus Bending Stress



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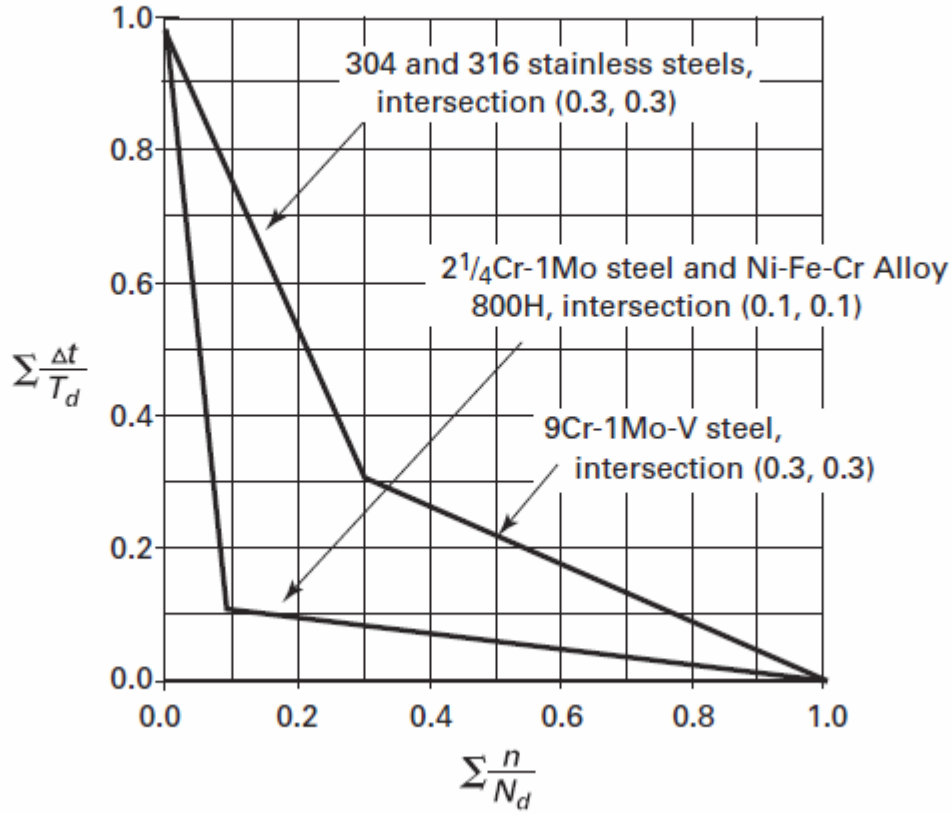
Method 3 – Elastic Approach Utilizing Section VIII Division 2 Code Case 2843 (based on the Section III Part NH rules utilizing the strain deformation method)

Creep-Fatigue is evaluated using a modified interaction diagram from Section III Part NH.

Figure 15
Creep-Fatigue Damage Envelope



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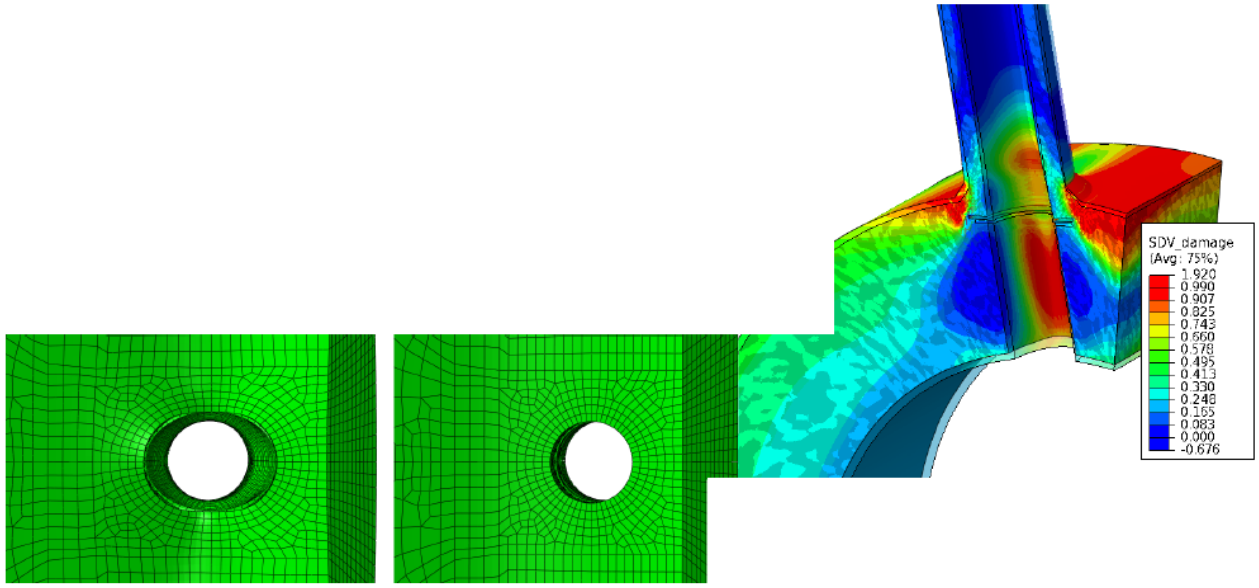
Method 3 – Elastic Approach Utilizing Section VIII Division 2 Code Case 2843 (based on the Section III Part NH rules utilizing the strain deformation method)

Currently there is a comparison of CC 2843 with Section I Design being undertaken.

Section I makes use of wall thickness or pressure capacity equations for component sizing, supplemented by rules for compensation of openings.

CC 2843 uses a combination of hand calculations for basic stresses (termed General Primary Stresses) and finite element analysis (FEA) with linearized through-thickness stress results at key locations (Local Primary as well as Secondary and Peak stresses and limits) which take the place of compensation rules. It also requires a definition of a specific design life, in addition to consideration of both Design and Operating cases.



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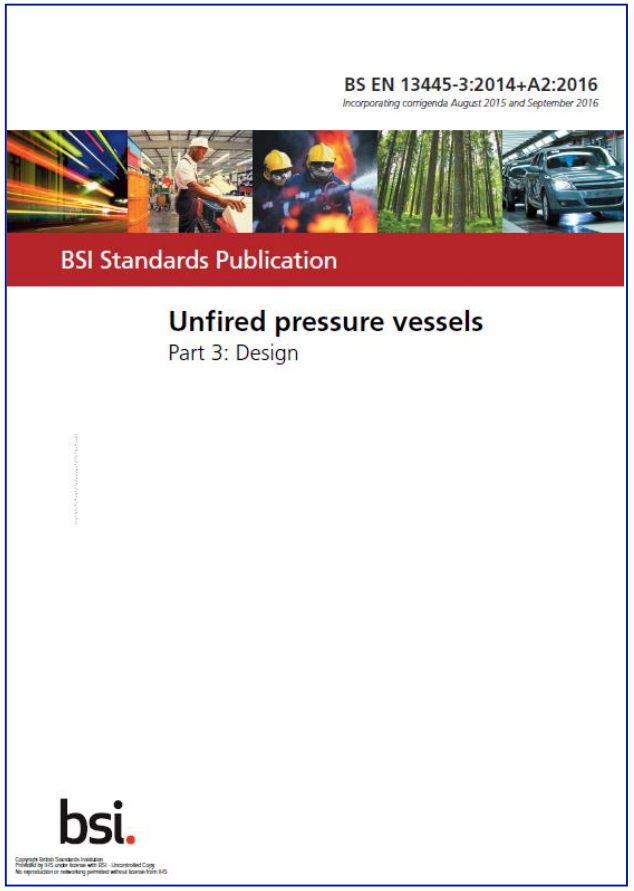
Method 4 – Simplified Inelastic Approach Utilizing a Draft Section III Code Case (based on EN 13445)

This final case is still being investigated for Section I use and was recommended by the authors of the ASME funded research project for Section I Modernization – STP-PT-070 “Design Guidelines for the Effects of Creep, Fatigue and Creep-Fatigue Interaction”.

It is the method mandated by EN12952 for design by analysis as defined in EN 13445 Annex B

It assumes material is sufficiently ductile / creep ductile

It characterizes design (ultimate) loads and also service load conditions.



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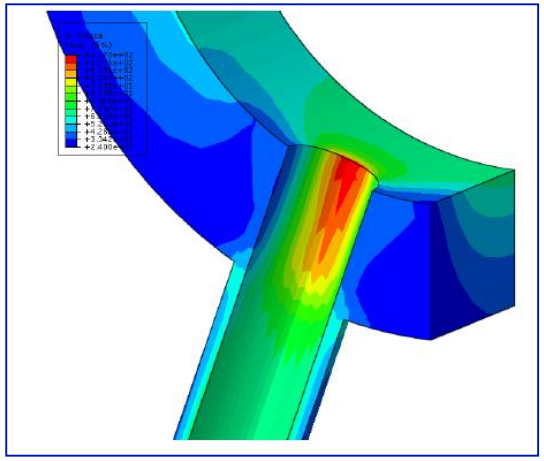
Method 4 – Simplified Inelastic Approach Utilizing a Draft Section III Code Case (based on EN 13445)

Design Checks for Time Independent Conditions:

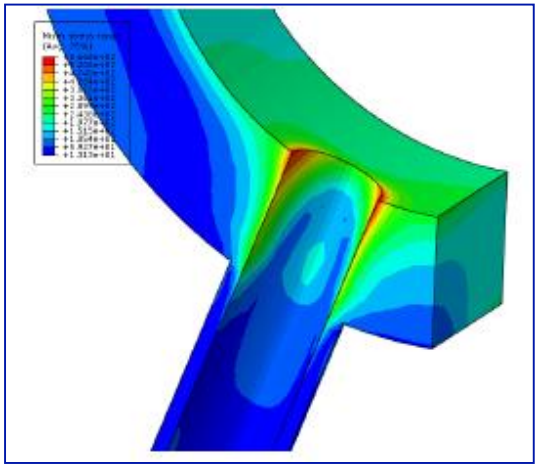
- Gross Plastic Deformation
- Progressive Plastic Deformation (Ratcheting)
- Instability
- Fatigue
- Static Equilibrium



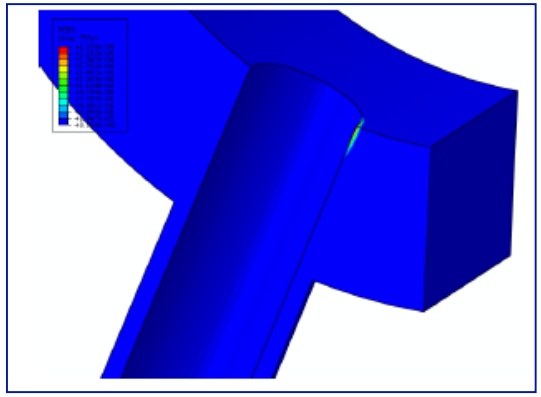
Tresca elastic Stress

Design Checks for Time Dependent Conditions

- Creep Rupture
- Excessive Creep strain
- Creep-Fatigue Interaction



Von Mises stress range



Plastic Strain

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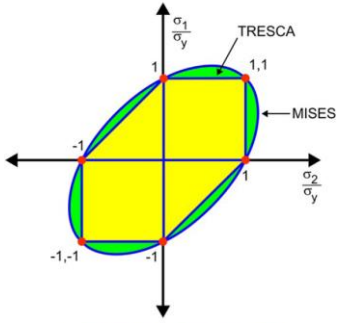
Method 4 – Simplified Inelastic Approach Utilizing a Draft Section III Code Case (based on EN 13445)

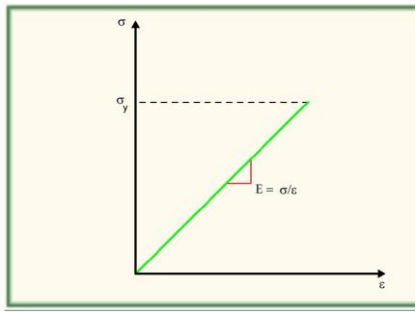
Model Basis:

- Gross Plastic Deformation check – linear-Elastic ideal plastic law using Tresca's yield condition (maximum shear stress).
- Progressive Plastic Deformation (Ratcheting), Creep Rupture and Excessive Creep Strain checks a linear-elastic ideal plastic law is used with von Mises' yield condition (maximum distortion energy)
- Instability check – either a linear-elastic or linear-elastic ideal-plastic law
- Fatigue check - a linear-elastic law

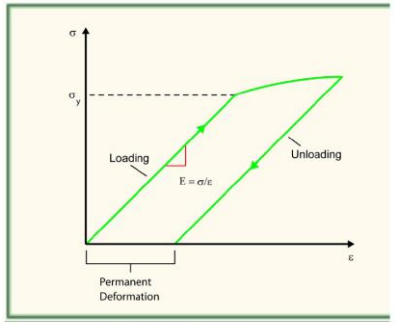
Note von Mises yield condition may be used for the Gross Plastic Deformation check if the strength parameter is modified by $\sqrt{3} / 2$



Comparison of Tresca and von Mises loci



Linear Elastic materiaL model



Linear-Elastic Plastic material model

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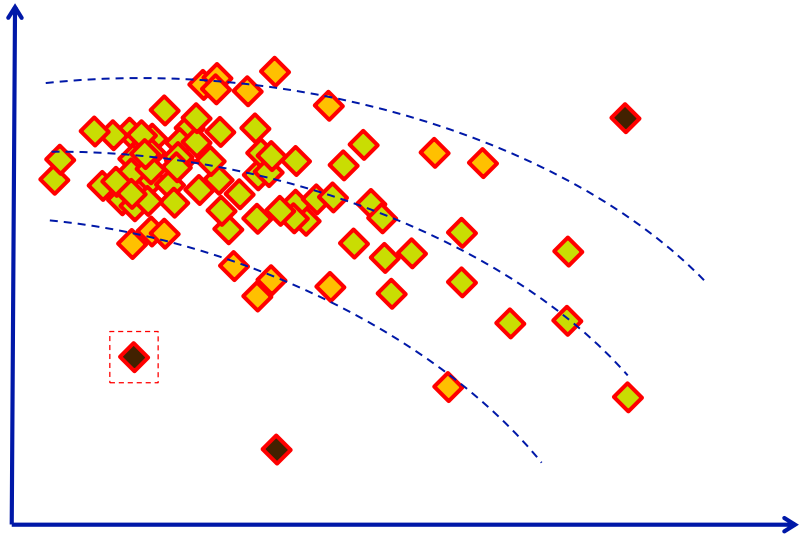
Additional Requirements

The use of Design by Analysis requires a range of additional requirements to be addressed to ensure a safe, reliable design is produced, such as:

- ✓ Material Properties
- ✓ Creep-Fatigue Flaw Growth parameters
- ✓ NDE Levels and Criteria



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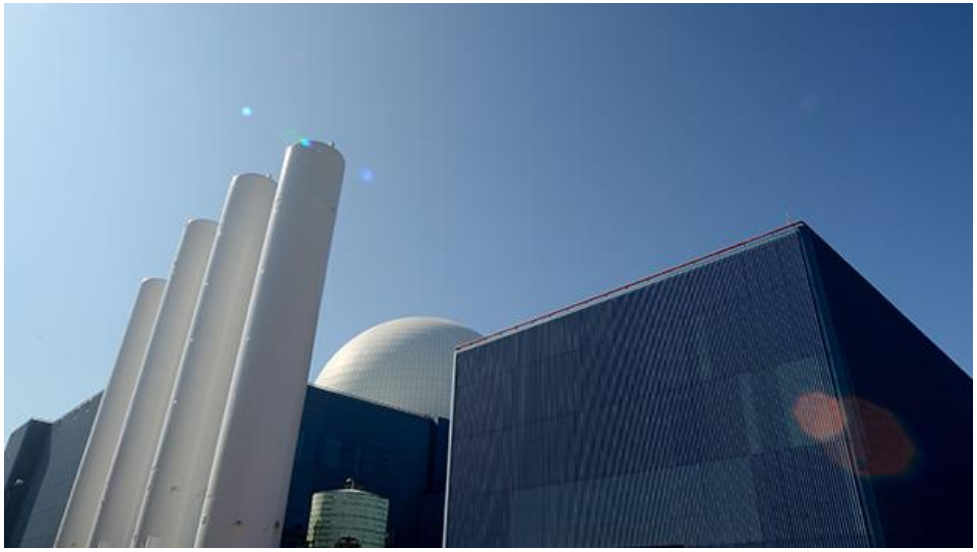
A proposed Research Project: Elevated Temperature Material Property Compilation for Design-by-Analysis has now been approved for funding by ASME ST LLC and started mid 2017.

It is currently formed to look at the following materials data and materials for boiler components as well as nuclear and petrochem type applications:



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Material Data:

- Creep rupture, average and minimum
- Creep ductility
- Creep strain vs. time curves
- Elevated temperature yield, tensile strength and physical properties
- Elevated temperature continuous cycling fatigue curves
- Elevated temperature hold time fatigue curves

Primary Materials:

- Grade 91
- Type 304H
- Type 347H
- Grade 22
- Grade 92
- Grade 22V
- Grade 9 (9Cr)
- Alloy 617
- Carbon Steel (SA-516, SA-299)
- C-1/2Mo
- SA-533/SA-508
- Type 316H
- 5Cr
- Alloy 800H
- Grade 11
- A709

Secondary Materials:

- Grade 23
- Type 321H
- 3Cr
- Type 410
- Grade 12
- 12Cr
- B16, B7 bolting
- B8 bolting
- Grade 660
- Alloy 601
- Inconel bolting

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Creep-Fatigue Flaw Growth Analysis to Support Elevated Temperature Flaw Size Acceptance Criteria.

The scope of this project is to analyze a matrix of typical elevated temperature components using recognized creep-fatigue flaw growth analysis methods and data.

The key deliverable will be the largest initial flaw size for each case that satisfies the specified transient operating conditions (temperature, pressure, time, cycles).

This information will then be used in developing rational flaw acceptance criteria for equipment operating in the creep regime and is a necessary extension to the current Section I Code Case 2235 for using ultrasonic test methods in lieu of radiography, and directly supports Section I modernization.

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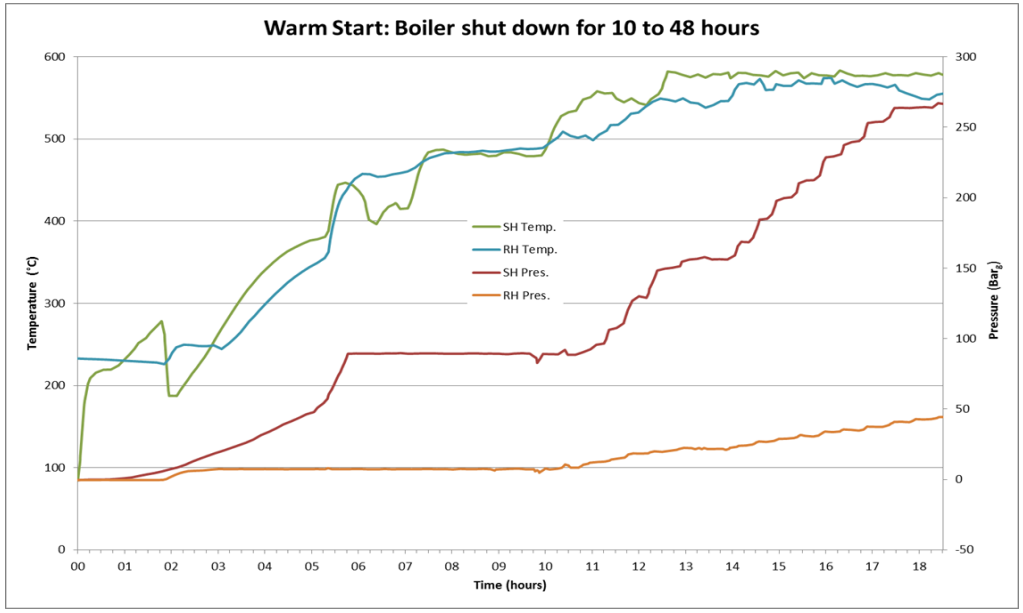
Creep-Fatigue Flaw Growth Analysis to Support Elevated Temperature Flaw Size Acceptance Criteria.

Specified Inputs:

- Operating Duration: 200,000 hours (22.8 years)
- Operating Conditions:
  - Cold Starts (> 48 hours shutdown) = 100
  - Warm Start (8 to 48 hours shutdown) = 1,000
  - Hot Start (<8 hours shutdown) = 6,000
- Stresses:
  - Pressure-induced
  - Welding residual equal to 35% of average 0.2% yield strength
  - Thermal



Transient conditions have been included (start-up, shutdown curves) intended to be representative of a typical ultra-supercritical (USC) power plant.

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Analysis Methods:

API 579-1/ASME FFS-1 Part 10 (including Annex F material models and data)
EDF Recommended Procedure R5 V4/5 (including R66 material models and date)
Electric Power Research Institute BLESS Code (including embedded material models and data)

Configurations:
To be girth welds (Superheater and Reheater tube, Superheater and Reheater header)

Materials :
To be Grade 22, Grade 91, Type 304H, Grade 23

Flaw Orientations to be:
Circumferential and Longitudinal

Flaw Locations to be Inside surface, Outside surface, Mid-wall (subsurface)

Flaw Geometries: to be Infinite length/full circumferential and 6:1 (2c vs. a) semi-elliptical

This creates 192 flaw analysis cases (per analysis method).

Acceptance criteria should be consistent with the given analysis method. If no acceptance criteria are given, then failure shall be defined as either a flaw growing to 75% through-wall at its deepest point or gross rupture due to loss of section.

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Thank You

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