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COMPARISON OF THE REQUIREMENTS OF THE BRITISH R5, FRENCH RCC-MRx, PROPOSED NEW RULES IN ASME SECTION VIII, AND API 579 CODES IN THE DESIGN OF A CYLINDER SUBJECTED TO PRESSURE WITH THERMAL GRADIENT AT ELEVATED CREEP TEMPERATURES.

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ABSTRACT

The authors analyze two sample problems using four different international codes in the evaluation. The first is the British R5 code, the second is the French RCC-MRx code, third is the ASME Section VIII, Division 2, code using proposed new simplified rules taken from the ASME nuclear code section NH, and the fourth is the API 579 code. The requirements, assumptions, and limitations of each of the four codes as they pertain to the sample problems are presented.

The first sample problem is for creep-fatigue analysis of a cylindrical shell subjected to internal pressure with a linear thermal gradient through the wall. The second sample problem is evaluating the critical buckling strength of the cylindrical shell under external pressure in accordance with proposed new rules in ASME Section VIII, Division 2, API 579, and a finite element analysis.

PART A. PREMISE OF SAMPLE PROBLEM 1

A pressure vessel cylindrical shell has in inside radius, R, of 30 inches (1524 mm), a thickness, t, of 1.25 inches (31.8 mm) and an effective length, L, of 180 inches (4572 mm). The design temperature is 1000°F (538°C) and the design pressure, P, is 315 psi (2172 KPa). Operating temperature is 950°F (510°C) and operating pressure is 300 psi (2068 KPa).The shell material is 2.25Cr -1Mo annealed steel (SA 387 Gr.22 CL1). A stress concentration factor of $K_{sc} = 1.10$ is used. During operation the metal temperature at the inside surface of the shell is 950°F (510°C) and at the outside surface is 850°F (454°C). The operating cycle of the vessel is as follows:

- Pressure: the pressure increases from 0 psi to 300 psi (2068 KPa) in 24 hours. It remains at 300 psi (2068 KPa) for about 18 months (13,000 hours), and is then reduced to zero in one hour. The same cycle is then repeated after a shutdown of two weeks for maintenance.
- Temperature: the temperature increases from an ambient 100°F (38°C) to 950°F (510°C) in 24 hours. It remains at 950°F (510°C) for about 18 months (13,000 hours), and is then reduced to ambient in four days. The same cycle is

then repeated after a shutdown of two weeks for maintenance.

The cylindrical shell is to be evaluated for a life of 300,000 hours at an operating inside temperature of 950°F (510°C).

1. SAMPLE PROBLEM 1. ASSESSMENT USING THE BRITISH R5 CODE.

The objective of the R5 development was to provide a comprehensive creep assessment document that could be easily used and is based on expert knowledge in structural mechanics and materials science. It is intended to augment and replace, where necessary, the provisions of other design codes. It also extends the design codes to facilitate the assessment of defects. The R5 procedure is different from a design code in that it is an assessment procedure and so does not contain design margins that are inherent in design codes.

Volume 2/3 "Creep-Fatigue Crack Initiation Procedure for Defect Free Structures" [1] is used for this comparative study. R5 gives, in Figures 4.1(a), (b), (c), and (d), flow diagrams for sequence of creep-fatigue analysis.

The procedures use simplified methods of inelastic analysis, not relying on a conservative interpretation of an elastic analysis or requiring a costly and complex cyclic inelastic computational model. The procedure tests for behavior sufficiently near to true shakedown in the steady cyclic state to ensure freedom from ratcheting. The procedure then progresses to obtaining parameters from the shakedown analysis for the assessment of combined creep and fatigue damage. Whilst the procedure includes some conservatism it does not preclude the use of more detailed analysis as a way of demonstrating component integrity.

The procedure provides a method of assessing the integrity of a component when the operating life may be limited by one of five mechanisms:

- Excessive plastic deformation.
- Creep rupture.
- Ratcheting or incremental collapse.
- Initiation of cracking due to combined creep-fatigue damage.
- Creep deformation enhanced by cyclic loading.

An elastic stress analysis forms the starting point for the procedure.

To ensure resistance to excessive plastic deformation the elastic stress levels from primary loading is compared with the allowable stress derived from the material yield stress. Additionally a limit is applied to the elastic range of primary + secondary stress to restrict plastic deformation from cyclic loading.

Creep rupture is assessed by use of a reference stress method and is adjusted according to the variation of the material creep ductility.

Shakedown analysis is used to ensure resistance to ratcheting. Peak stresses are excluded, which permits some local cyclic plasticity; however excessive deformation is prevented by ensuring these regions are constrained by elastic regions of the component.

Creep-fatigue cracking is initiated when a defect of a certain size is exceeded. The fatigue damage is then calculated based on the strain range modified for the effects of both plasticity and creep. The total damage being the summation of the two parts.

The effect of creep deformation which is enhanced by cyclic loading is assessed by limiting the creep strains to restrict the localized levels of creep damage.

To utilize this procedure material data is required that supports the analysis techniques being used. This can be found in a variety of sources. The main source is R66 “Materials Data Handbook” [2] but other sources, such as ASME Section III, RCC-MR or ECCC Data Sheets. Having collected the required material data the following procedure is followed.

1.1 Resolve Load History into Different Service Cycles.

1.2 Perform Elastic Stress Analysis

1.3 Demonstrate Sufficient Margin Against Plastic Collapse

The following inequalities must be met:

Inequality	Design	Operation
$P_m \le 0.67S_y$	16.6 ksi (114.3MPa)	17.6 ksi (120.9MPa)
$P_L + P_b \le S_y$	24.7 ksi (170.6 MPa).	26.2 ksi (180.5 MPa)
$\Delta(P_L + P_b + Q) \le 2.0S_y$	49.5 ksi (341.2 MPa)	52.4 ksi (361.0 MPa)

Inequality	Design	Operation
P_m	7.6 ksi (52.1 MPa)	7.2 ksi (49.7 MPa)
$P_L + P_B$	3.8 ksi (26.1 MPa)	3.6 ksi (24.8 MPa)
$\Delta(P_L+P_B+Q)$	18.2 ksi (125.5 MPa)	18.0 (124.2MPa)

inequalities are all met demonstrating sufficient margin against plastic collapse.

1.4 Determine Whether Creep is Significant

For the required design and operating temperature the maximum permitted duration is obtained from Figure (1) (Figure 5.3(b) of R5). By observation the test for insignificant creep is failed so the creep design checks must be calculated.

Figure 1.Insignificant Creep Curves for Ferritic Steels [1]

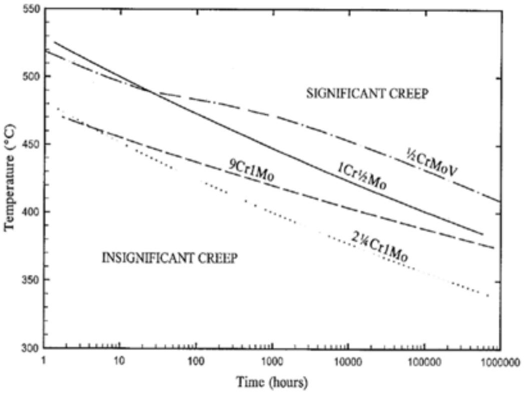


Figure 5.3(b) Insignificant creep curves for ferritic steels

1.5 Demonstrate that Creep Rupture Endurance is Satisfactory

By calculating the creep rupture reference stress and considering the allowable time from the creep rupture curve the creep usage factor can be determined.

$$\sigma_{ref} = \frac{P_B}{3} + \left[\left(\frac{P_B}{3}\right)^2 + P_L^2\right]^{\frac{1}{2}} \qquad (1)$$

$$\sigma_{ref}^{R} = \{1 + 0.13[\chi - 1]\}\sigma_{ref} \qquad (2)$$

From the creep rupture curve it can be seen that the creep allowable time, t_f = > $5x10^5$ hours for both design and operation cases.

$$U = \sum_j n_j \left[\frac{t}{t_f(\sigma^R_{ref}, T_{ref})} \right]_j < 1 \tag{3}$$

Total creep usage factor, U = 0.6

1.6 Perform Simple Test for Shakedown and Check for Insignificant Cyclic Loading

By calculating the following inequalities the check to ensure shakedown is achieved.

$$\overline{\sigma}_{el,lin}(x,t) \le K_s S_y$$

$$\overline{\sigma}_{el}(x,t) \ge K_s S_y$$

$$(r_p)_i + (r_p)_o \le 0.2w \tag{4}$$

1.7 Perform Global Shakedown Check and Calculate Cyclic Plastic Zone Size

Not required as Step 6 met.

1.8 Calculate the Shakedown Reference Stress, Reference Temperature and Start of Dwell Stress

The start of dwell stress is calculated at the point where the temperature cycle becomes constant. With a constant dwell temperature the shakedown reference temperature, T^s_{ref} = 538^OC, thus the shakedown reference stress, σ^s_{ref} = 125.5 MPa and the start of dwell stress can be conservatively taken as σ_o = 86 MPa from:

$$\sigma_0 = \Delta\overline{\sigma}_{el,max} - (K_s S_y)_{nc} \tag{5}$$

1.9 Estimate the Elastic Follow-up Factor and Associated Stress Drop During the Creep Dwell

Option 1 neglects any stress relaxation that may occur during a dwell period and is conservative in the calculation of creep damage.

Using option 2 with a start of dwell stress, σ_o of 86 MPa.

The elastic follow-up factor approximates to Z = 3.

1.10 Calculate the Total Strain Range

Solving the following equation gives the total strain range of 0.129%.

$$\Delta\bar{\varepsilon}_t = \left[\frac{\Delta\bar{\sigma}}{\bar{E}} + \left(\frac{\Delta\bar{\sigma}}{A} \right)^{1/\beta} \right] + \Delta\bar{\varepsilon}_{vol} \tag{6}$$

1.11 Check Limits on Cyclically Enhanced Creep

Solving the following equation checks the creep usage factor at the shakedown reference stress.

$$W = \sum_j n_j \left[\frac{t_.}{t_f(\sigma^s_{ref}, T^s_{ref})} \right]_j \tag{7}$$

1.12 Summarize the Assessment Parameters

σ_o = 12.5 ksi (86 MPa).

$\Delta\sigma$ = 18.0 ksi (124.2 MPa).

$\Delta\varepsilon$ = 0.00129

Z = 3

1.13 The Treatment of Weldments

Not required for this assessment.

1.14 Calculate the Fatigue Damage per Cycle

Based on experimental data the first part of the assessment is related to the formation of initial defect and the second stage is the growth of this defect to a specified (acceptable) depth.

For this example the fatigue damage is not critical.

1.15 Calculate the Creep Damage per Cycle

Calculating the creep damage for the start of the dwell stress gives a damage per cycle of 0.0013.

$$d_c = \frac{Z\Delta\bar{\sigma}'}{\bar{E}\varepsilon_U} \qquad (8)$$

1.16 Calculate the Total Damage

The total damage gives a total number of cycles of 769 which is in excess of the required number of 23.

2. SAMPLE PROBLEM 1. ASSESSMENT USING THE FRENCH RCC-MRx CODE.

The RCC-MRx (edition 2012) is a code used for fast breeder and experimental reactors. Its main specificities are to take into account the creep phenomenon and the irradiation effects. The chapters RB3200 give a set of criteria in order to cover the following damage for level 1 components:

- Excessive deformation (with or without creep),
- Ratcheting (with or without creep),
- Creep-Fatigue rupture,
- Fast fracture.

For this problem, only the three first points will be analyzed, considering successively negligible creep and significant creep criteria. The material data used for the 2.25Cr-1Mo come from the Appendix A3.16AS of the RCC-MRx.

2.1 Significant Creep Test

The chapter A3.16AS.311 of the Appendix A3 of the RCC-MRx indicates that the situation is to be considered in significant creep if its temperature is higher than 707°F (375°C). In the case of the problem 1, the temperature is equal to 950°F (510°C) for the internal skin and 850°F (454°C) for the external skin. So the operating situation is in significant creep domain. At this time there is no negligible creep curve for A16S material, meaning that no refined possibility to determine significant creep domain is allowed.

2.2 Excessive Deformation

The criteria used for this damage comes from the chapter RB3251 (negligible creep) and RB3252 (significant creep).

In negligible creep, the criteria are:

$$\overline{P_m} \le S_m$$

$$\overline{P_l + P_b} \le 1.5 \cdot S_m$$

For the operating conditions, the results are the following:

$\overline{P_m}$	6.4 43.9	Ksi MPa
$\overline{P_l + P_b}$	6.6 45.7	Ksi MPa
$S_m(482°C)$	17.3 119	Ksi MPa
$1.5 \cdot S_m(482°C)$	25.9 178.5	Ksi MPa

** 900°F (482°C) corresponds to the average temperature between 850°F (454°C) and 950°F (510°C).

For the negligible creep, the criteria are verified.

In significant creep, the criteria are:

$$U\left(\overline{P_m}\right) \leq 1 \qquad \text{with } \Phi = 0.88$$
$$U\left(\overline{P_l + \Phi P_b}\right) \leq 1$$

For the operating conditions, the results are the following:

$\overline{P_m}$	6.4 43.9	Ksi MPa
$\overline{P_l + \Phi P_b}$	6.6 45.5	Ksi MPa
Allowable time for $\overline{P_m}$	$4.16\text{x}10^6$	Hours
Allowable time for $\overline{P_l + \Phi P_b}$	$3.25\text{x}10^6$	Hours

For an operating time of 300 000 hours, the usage factors are the following:

$$U\left(\overline{P_m}\right) = 0.07$$
$$U\left(\overline{P_l + \Phi P_b}\right) = 0.09$$

For the significant creep, the criteria are verified.

2.3 Ratcheting

The chapters RB3261.111 presents the rules for the ratcheting evaluation in negligible creep domain:

- The efficiency diagram
- Or the alternative rule
  $$Max\left(\overline{P_l + P_b}\right) + \overline{\Delta Q} \leq 3 \cdot S_m$$

For the others material than austenitic stainless steels, only the alternative rule can be applied:

$Max\left(\overline{P_l + P_b}\right)$	6.6 45.5	Ksi MPa
$\overline{\Delta Q}$	5.9 40.4	Ksi MPa
$Max\left(\overline{P_l + P_b}\right) + \overline{\Delta Q}$	13.9 95.9	Ksi MPa
$S_m(482°C)$	17.3 119	Ksi MPa
$3 \cdot S_m(482°C)$	51.8 357	Ksi MPa

For the ratcheting damage in negligible creep domain, the criterion is verified.

In significant domain, only the efficiency diagram can be used in RCC-MRx but this diagram is for the present time limited to the austenitic stainless steels. So the material 2.25Cr-1Mo cannot be analyzed in significant creep domain, using the efficiency diagram, as the applicability of the diagram to this alloy is not demonstrated yet.

2.4 Creep-Fatigue

In order to evaluate the creep-fatigue damage, it is necessary to calculate the fatigue usage factor and the creep usage factor. For the first usage factor, we must determine the strain variation $\overline{\Delta\varepsilon}$ which is equal to $\overline{\Delta\varepsilon} = \overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2} + \overline{\Delta\varepsilon_3} + \overline{\Delta\varepsilon_4} + \overline{\Delta\varepsilon_{cr}}$:

- $\overline{\Delta\varepsilon_1}$: strain range given by elastic analysis
- $\overline{\Delta\varepsilon_2}$: plastic increase in strain due to the primary strain range equal to $\overline{\Delta\left[P_m + 0.67 \cdot \left(P_l + P_b - P_m\right)\right]}$
- $\overline{\Delta\varepsilon_3}$: plastic increase in local strains due to the elastic follow-up

- $\overline{\Delta\varepsilon_4}$: plastic increase in strain due to triaxiality
- $\overline{\Delta\varepsilon_{crl}}$: plastic increase due to creep

The appendix A3.16AS gives all the data in order to calculate the four first strain range but the creep strain law is not given. So the last strain range cannot be calculated.

The creep-fatigue cannot be evaluated for this material.

3. SAMPLE PROBLEM 1. ASSESSMENT USING THE PROPOSED NEW RULES IN ASME SECTION VIII-2 CODE [3].

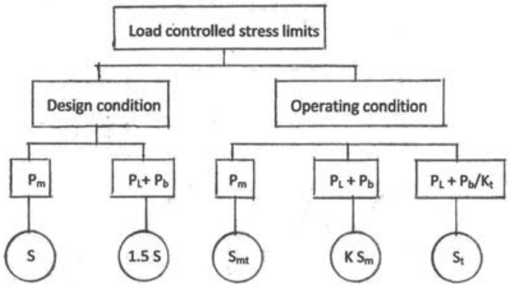
The new proposed rules in the ASME VIII-2 code [4] are a simplification of the rules in the ASME nuclear code, Section III-NH. The procedure for evaluating creep fatigue consists of three parts

1. Evaluating load controlled limits
2. Evaluating strain controlled limits
3. Performing creep-fatigue analysis.

3.1 Load Controlled Limits

The requirements for load controlled limits are shown in Figure 2. The purpose of these requirements is to assure thickness adequacy of the component. Accordingly, only primary membrane and primary bending stresses are considered.

Figure 2. Flow diagram for Load controlled stress limits [4]



The calculations for the design conditions resulted in $(P_m/S) = 0.84$ and $[(P_m + P_b)/1.5S] = 0.56$

The calculations for the operating condition resulted in $(P_m/S_{mt}) = 0.66$, $[(P_m + P_b)/KS_m] = 0.29$, and $(P_m + P_b/K_t)/S_t = 0.44$.

3.2 Strain Controlled Limits

The requirements of strain controlled limits may be satisfied using elastic analysis, simplified inelastic analysis, or inelastic analysis. The purpose of these analyses and their limits is to prevent excessive strain during the life of the component. In this paper the elastic analysis will be used. The criterion for the example problem is

$$X + Y \leq 1.0 \qquad (9)$$

Where, $X = (P_L + P_b/K_t)_{max} \div S_y$

$Y = Q_{max} / S_y$

S_y = the average of the S_y values at the maximum and minimum wall averaged temperatures during the cycle being considered.

The calculations for this condition show that $X = (P_L + P_b/K_t)/S_y = 0.229$ and $Y = Q/S_y = 0.512$.

Thus, Equation (9) is satisfied.

3.3 Creep-Fatigue Evaluation

The rules for creep fatigue evaluation for this example are applicable when the strain limits of Section 3.2 are met and the stress levels given by the following equation are satisfied.

$$(P_L + P_b + Q) < 3S'_m \tag{10}$$

Where, $3S'_m$ is the lesser of $3S_m$ or $3\overline{S}_m$ at the temperature at a point. For this problem, the value of $3\overline{S}_m = 1.5S_m + 0.5S_t$.

S_t = 7.3 ksi (50.3 MPa) at 950°F (510°C) and 12.3 ksi (84.7 MPa) at 850°F (454°C) for 300,000 hours.

The requirement of Equation (10) is satisfied since $(P_m + P_b + Q)/3S'_m$ is equal to 0.30 for the inside surface and 0.58 at the outside surface.

The creep-fatigue interaction equation is given by

$$\sum (\Delta t/T_d) + \sum (n/N_d) \leq D \tag{11}$$

The first part of this equation satisfies the creep criterion and the second part satisfies the fatigue criterion.

3.3.1 Creep Evaluation

The creep evaluation is performed in two steps. The first step is to calculate the total strain including stress concentration factors. Total strain, ε_t, consists of creep strain, ε_c, obtained from the appropriate isochronous stress-strain diagram for the material at a given temperature, plus an elastic strain, $\Delta\varepsilon_{mod}$. The second step is to calculate stress creep relaxation from isochronous stress-strain curves and then determine a usage factor to be used in satisfying the first part of Eq.(11). Calculations for both the inside and outside surfaces show that creep damage at the outside surface with a temperature of 850°F (454°C) is insignificant. Hence, only the inside surface calculations are shown.

3.3.1.1 Strain Calculations

The elastic strain calculated with a stress concentration factor or 1.1 is $\Delta\varepsilon_{mod} = 0.000416$.

The creep strain, calculated from the Bree diagram, is $\Delta\varepsilon_c = 0.000338$. Thus the total strain used in the creep fatigue analysis = 0.00083.

3.3.1.2. Creep Relaxation Calculations

Creep relaxation is obtained by entering the appropriate isochronous stress strain diagram with the strains obtained above. Values of stress at various times are then obtained while holding the strain constant. Time increments are then used to obtain stress versus time duration values. Rations of duration time over time to rupture are obtained and summed up to give a total value of $(\Delta t/T_d)$ in Eq. (11). The total sum calculated was $(\Delta t/T_d) = 0.69$.

3.3.2 Fatigue Evaluation

Figure T-1420-1D of ASME Section III-NH [5] shows the relationship between strain and hours.

At the inside surface with $\varepsilon_t = 0.00083$, the allowable number of cycles > 1,000,000 hours

At the outside surface with $\varepsilon_t = 0.00116$, the allowable number of cycles > 1,000,000 hours.

The fatigue interaction is calculated in accordance with the second part of Eq.(25).

$\sum(n/N_d) = 23/1{,}000{,}000 \approx 0$

3.3.3 Creep-Fatigue Evaluation

From the D diagram in Figure 8, the thickness of 1.25 inch is adequate for 300,000 hours under the loading condition specified.

Entering the creep fatigue damage envelope in III-NH, with $(\Delta T/T_d) = 0.69$ and $(n_c/N_d) = 0$, shows that the expected life of 300,000 hours is well within the acceptable limits.

4. SAMPLE PROBLEM 1. ASSESSMENT USING THE API 579 CODE [6].

Assuming thin shell theory, hoop stress and longitudinal stress is calculated using the mean diameter which is 61.25 inches (1556 mm). The stress values are , assuming negligible radial stress, $\sigma_1 = 7.35$ ksi (50.6 MPa) and $\sigma_2 = 3.675$ ksi (25.3 MPa).

4.1 Creep Damage Using OMEGA Parameters

The strain rate and Omega parameters are obtained from Table F.30 of API579. The following parameters are used for this problem

$T = 950^oF$, $\beta_\Omega = 0.33$, $\alpha_\Omega = 2.0$,

$\Delta_{SR} = -0.5$, $\Delta_{cd} = 0$, and Time = 13,000 hrs

Calculated time to rupture, in hours, $L = 6.695 \times 10^6$.

Damage per cycle = $13{,}000/L = 1.92 \times 10^{-3}$.

Damage in 23 cycles = $D_c = 0.045$

4.2 Fatigue Calculations

In this step the thermal stress is added to the pressure stress. The equivalent von-Mises stress becomes $\Delta S_{PK} = 20.137$ ksi (138.8 MPa). The alternating stress, using $K_{ek} = 1.0$ and $K_{sc} = 1.1$, is 11.1 ksi (76.5 MPa). For this stress level, the fatigue life from ASME III-NH is $.10^7$ cycles. Hence, $D_f = 23/10^7 = 2.3 \times 10^{-7}$.

It is seen from API's creep-fatigue damage interaction diagram that a life of 300,000 hours is acceptable.

5. SUMMARY OF RESULTS

The rules in all four codes are capable of evaluating creep fatigue for the problem presented. All applicable codes showed ample margin for the 300,000 hour life. A summary of the requirement in each of the codes is shown in the table below

	R5	RCC-MRx	ASME, VIII-2	API 579
Checks for P_m plus P_b stress	Yes	Yes	yes	No.
Checks for negligible creep	Yes	Yes	Yes	No. Evaluates creep damage and plots the point on a creep-fatigue figure.
Checks for ratcheting	Yes	Yes	yes	No. Compares stress to fatigue curves for life.
Evaluates stress reduction at a given ε	Yes	Yes	yes	No
Creep fatigue interaction	Equation	Figure. But not for 2.25Cr-1Mo steel	Figure	Figure
External pressure and axial compression	No	Not for 2.25Cr-1Mo steel	Yes (with limits)	Yes
2.25 Cr-1Mo data base	Yes	No creep data base	Yes	Yes
304 stainless steel	Yes	Yes	Yes	Yes
Sample problem #1 meets requirements	Yes	Not applicable	Yes	yes

PART B. PREMISE OF SAMPLE PROBLEM 2

The cylinder in sample problem 1 is evaluated for external pressure at elevated temperature in the creep regime using API 579, ASME-VIII, and Finite Element analysis.

1. SAMPLE PROBLEM 2. ASSESSMENT USING THE PROPOSED NEW RULES IN ASME SECTION VIII-1 CODE (CODE CASE 2676).

Research published recently [7,8] by ASME indicates that external pressure charts for materials operating in the creep regime can be generated from isochronous stress-strain curves. One such chart is shown in Code case 2676 [9] for 2.25Cr-1Mo steel at 1000°F (538°C). Hence, for cylinder with a t = 1.25 inches (31.8mm), D_o = 62.5 inches (1588 mm), and L = 180 inches (4572 mm),

$D_o/t = 50$, $L/D_o = 2.88$, and A from Figure G of ASME Section II-D [10] = 0.0013

From the figure in code case 2676 for 300,000 hours, B ≈ 1700 psi (11.7 MPa). The allowable external pressure in accordance with ASME VIII-1 is given by

$$P_a = (4/3)[B/(D_o/t)]$$

$$= 45 \text{ psi } (310 \text{ KPa}).$$

ASME VIII-1 uses a factor of safety of 3.0 for external pressure. Hence, the critical buckling pressure for this cylinder is P_c = 135 psi (930KPa).

2. SAMPLE PROBLEM 2. ASSESSMENT USING THE API 579 CODE

For the creep buckling analysis the elastic buckling solution is first obtained. Using the procedure in ASME Section VIII, Division 2, Part 4, the critical buckling stress σ_{cr} is 9.09 ksi (62.3 MPa).

The creep buckling analysis per ASME/API-579 has to be done in an iterative procedure to determine the critical buckling pressure

Assume a hoop stress which is approximately half of the critical buckling stress 4.5 ksi. Hence, σ_1 = 4.5 ksi (31.0 MPa), σ_2 = 2.25 ksi (15.5 MPa), and σ_3 = 0 ksi. σ_e = 3.9 ksi (26.9 MPa), S_1 = 0.59, and η_{BN} = 5.757. Other factors are δ_Ω = 0.0, Ω = 125.68, A_{cd} = 0.0, Ω_n = 119.93, Ω_m = 131.44, Δ_{SR} = -0.5, ε_{co} = 3.413 x 10^{-10}, Q = 2.33, ε_{ce} = $9.813\text{x}10^{-5}$, and time = 285,698 hours.

Since the calculated time is less than 300,000 hrs, iterate again with a lower stress (σ_1). By iterating a few times the stress required to give 300,000 hours is 3.9 ksi (26.7 MPa).

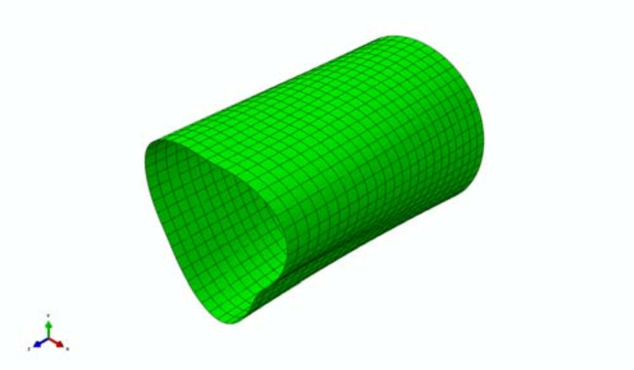
Using 3.9 ksi (26.7 MPa) critical creep buckling stress, the calculated creep buckling pressure is 156 psi (1075 KPa).

3. SAMPLE PROBLEM 2. ASSESSMENT USING THE FINITE ELEMENT METHOD.

A creep buckling analysis of the cylindrical shell was done using finite element method. The cylindrical shell was modeled using eight nodded shell elements in ABAQUS. Only half the cylindrical shell was modeled with symmetric boundary condition on one edge and the other edge was kept perfectly cylindrical with appropriate boundary conditions. An Eigen value analysis was done to determine the appropriate buckling mode shape and this mode shapes were then used in the post buckling analysis via an imperfection on the model. The imperfection on the model was assumed to be 1% of the diameter of the shell.

For the post buckling analysis an isochronous curve was used. This curve was generated using Omega parameters and appropriate equations from API-579, Appendix F. The post buckling analysis predicted a collapse pressure of 90 psi (620 KPa). Figure 3 shows the buckled shape.

Figure 3. Deflection from Finite element program



4. COMPARISON OF RESULTS

The buckling pressure of 135 psi (930 KPa) in the ASME Section VIII code is obtained directly without iterations. The 156 psi (1075 KPa) external pressure obtained from API 579 requires a number of iterations. The difference between the two results is partially due to different data base used by the two codes. The result of 90 psi (620 KPa) from the finite element analysis is based on the amount of initial imperfection assumed in the model. For the post buckling analysis an initial imperfection of 1% of the diameter was assumed. The R5 and RCC-MRx codes do not have direct methods for solving buckling of cylindrical shells in the creep range at this time.

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NOMENCLATURE

A = constant in Ramberg-Osgood law for cyclic response
B = external pressure factor
β = constant in Ramberg-Osgood law for cyclic Response
d_c = creep damage per cycle
D = total creep fatigue damage
D_c = damage factor in API 579
D_f = cumulative fatigue damage in API 579
ε = strain
ε_U = upper shelf ductility
$\Delta\bar{\varepsilon}_t$ = total equivalent strain range
$\Delta\bar{\varepsilon}_{vol}$ = correction to strain range due to change to constant volume deformation in plasticity
E = Young's modulus
$\bar{E}$ = effective elastic modulus = $3E/(2(1+\nu)$
i, o = subscripts (i) and (o) refer to inside and outside.
K = plastic shape factor
$K_{e,k}$ = fatigue penalty factor in API 579
K_s = factor applied to Sy to obtain material ratchet limit
K_{sc} = stress concentration factor
K_t = creep shape factor
n = number of cycles
nc = non creep
n_j = number of service cycles of type j in R5
N_d = number of allowable cycles from fatigue curves.
ν = elastic Poisson's ratio
P_a = allowable external pressure
P_b = primary bending stress
P_L = local membrane stress
P_m = membrane stress
Q = secondary stress
r_p = cyclic plastic zone size
S = allowable stress
S_m = allowable stress using time independent criteria.
S_{mt} = the lower of S_m and S_t value
S_t = stress in the time dependent regime
S_y = yield stress
S_y = minimum 0.2% proof test in R5
σ_{el} = elastically calculated stress
σ_o = equivalent stress at beginning of dwell period
σ_{ref} = primary load reference stress
$\sigma^R{}_{ref}$ = rupture reference stress
$\sigma^S{}_{ref}$ = shakedown reference stress
$\Delta\bar{\sigma}$ = equivalent stress range
$\Delta\bar{\sigma}'$ = equivalent stress drop allowing for elastic follow-up
$\Delta\bar{\sigma}_{el,max}$ = maximum elastically calculated equivalent stress range
t = time
t = thickness in external pressure calculations
t_f = time to failure in a constant load creep rupture test
T, T_{ref} = temperature, reference temperature
$T^S{}_{ref}$ = shakedown reference temperature
T_d = allowable time
U = creep usage due to primary loads
w = section thickness in R5
W = creep usage enhanced by cyclic secondary loads
X = position within a structure
χ = adjustment factor for stress concentrations
Z = elastic follow up factor in R5.

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