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# Rules of Structural Integrity Evaluation for Class-A Components of High Temperature Reactors

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## 1. Introduction

Recently, non-PWRs such as molten salt reactor, sodium cooled-reactor, lead cooled-reactor, and gas-cooled reactor, etc. are on development for various applications worldwide. Most of these reactors are designed to be operating at elevated temperature services, which can invoke creep or creep rupture failures. There are many rules for high temperature reactor design [1~4]. And some studies have been done for application of these rules for an actual design [5~7]. In this paper, the procedures for high temperature structural integrity evaluation by ASME Section III Division 5[1] are discussed and an example is described in a practical design point of view.

## 2. Rules of High Temperature Structural Integrity Evaluations and Exampled Application

### *2.1 Load-Controlled Limits*

The primary stress intensity limits shall be satisfied for base metal and at weldments. To assure the high temperature structural integrity for the base metal, allowable stress limit values are defined: time-independent limit ($S_m$), long-time service at elevated temperature ($S_{mt}$), and a temperature and time-dependent limit obtained from long-term, constant load, and uniaxial tests ($S_t$).

The priority work to carry out the structural integrity evaluation when using the elastic analysis is to derive the stress intensities from the results of the elastic stress analysis. This shall be calculated by the rules of ASME HBB-3215, which requires the six scalar quantities of the stress components for each type of loading at critical locations cross the thickness of the structural section. The selection of the critical location and the cross section will mostly depend on the stress analysis results and the engineering experience. That means there are no precise rules in selecting the critical locations, therefore the designer should do it carefully with his own responsibility.

When the evaluation points are at weldments, $S_{mt}$ shall be taken as the lower of the $S_{mt}$ values or 0.8Sr x R, where Sr is the value obtained from the expected minimum stress-to-rupture strength and R is the appropriate ratio of the weld metal creep rupture strength to the base metal creep rupture strength). The values of $S_t$ should be taken as the same way of $S_{mt}$.

### *2.2 Deformation and Strain-Controlled Limits*

In regions expecting elevated temperatures the maximum accumulated inelastic strain shall not exceed the following values.

- Strains averaged through the thickness, 1%: Membrane strain $\varepsilon_m < 1.0\%$
- Strains at the surface, due to an equivalent linear distribution of strain through the thickness, 2%: Bending strain $\varepsilon_b < 2.0\%$
- Local strains at any point, 5%: Local strain $\varepsilon_L < 5.0\%$

Actually when creep effects are presumed significant, the above inelastic strain limits are required to be checked by the detail inelastic analysis. However, in order to reduce the number of evaluation points in a structure subjecting the elevated temperature, the elastic and simplified inelastic methods of analysis are provided in ASME-Division 5 Nonmandatory Appendix HBB-T with conservative bounds.

#### *2.2.1 Elastic Analysis Method*

The strain limits of HBB-T-1310 are considered to have been satisfied if the limits of any one of Test No. A-1, Test No. A-2, or Test No. A-3 are satisfied. The metal temperatures used in this rule are the wall averaged temperatures, which can give more conservative results.

To establish the appropriate cycle to be evaluated in Test Nos. A-1 and A-2, an individual cycle, as defined in the DS(Design Specification) can not be split into subcycles to satisfy these requirements because the maximum range of the secondary stress intensity during the cycle may not be selected in the split subcycles. And at least one cycle must be defined that includes the maximum value of ($P_m$ + $P_b/K_t$) which occur during all level A, B, and C Service Loadings.

The limits for inelastic strains are considered to have been satisfied if the limits of any one of the following Test No.B-1 or Test No.B-2 are satisfied. The metal temperatures used in this rule are the hot and cold temperatures corresponding to the extremes of the stress cycle, which can reflect more realistic metal temperature conditions during the stress cycle.

Test No.B-1 can be used only for structures in which the peak stress is negligible. Test No.B-2, which is more conservative, is applicable to any structure and loadings.

Note that in calculating the primary stress parameter *X*, the secondary stresses with elastic follow-up (i.e., pressure-induced membrane and bending stresses and thermal-induced membrane stresses) are classified as primary stresses for purposes of this evaluation. In calculating the stress parameters of $X$ and $Y$, the $S_{yL}$ value shall be used instead of $S_y$ for Test Nos, B-1 and B-2.

One important thing kept in mind using this rule is that the time to enter the isochronous curves for individual time blocks shall always sum to the entire life regardless of whether all or only part of the cycles are evaluated under this rule. To do this the load history should be defined first for the entire design lifetime and they may be subdivided into the appropriate temperature-time blocks. The individual cycles or time blocks may differ from those for the creep-fatigue evaluations.

### *2.2.2 Inelastic Analysis Method*

The main intension of the ASME-Division 5 is to restrict the maximum accumulated inelastic strain averaged across a wall thickness to 1% or less during whole service lifetime. When the elastic method can not satisfy the design rules, the inelastic analysis can be used to demonstrate the deformation and strain limits for functional requirements.

### *2.3 Creep-Fatigue Limits*

The accumulated creep and fatigue damage shall satisfy the following relation for the combination of Levels A, B, and C Service Loadings.

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \le D$$

where

$D$ = total creep-fatigue damage
$P$ = number of different cycle types
$(n)_j$ = number of applied repetitions of cycle type, $j$
$(N_d)_j$ = number of allowable cycles for cycle type, $j$
$q$ = number of time intervals for the creep damage calculation
$(T_d)_k$ = allowable time duration determined from the stress-to-rupture curves

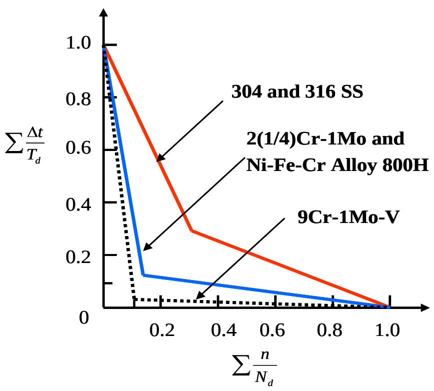


Fig. 1 Creep-Fatigue Damage Envelope

The total damage, D, shall not exceed the creep-fatigue damage envelope curves given in Fig. 1.

### *2.4 Exampled Application*

As an example of high temperature structural integrity evaluation by ASME-Division 5, the cladded reactor vessel for the molten salter reactor (MSR) application shown in Fig.2 is considered with four representative operating cycle types of Fig. 3. Table I presents the summary results of the structural integrity evaluations for load-controlled limits and Table II presents the summary results of strain limit by elastic analysis, and Table III is for strain limit by simplified inelastic analysis method and creep-fatigue limit.

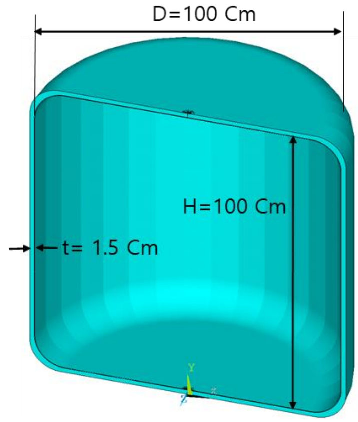


Fig. 2 Exampled Model of Reactor Vessel

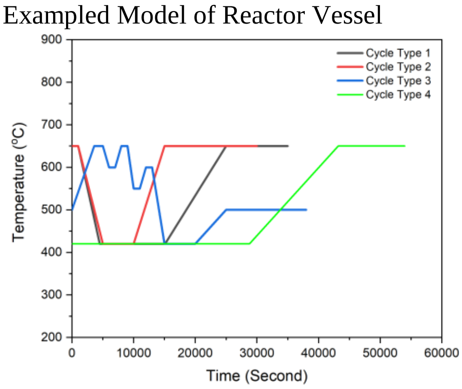


Fig. 3 Assumed Operation Cycle Types

Table I: Summary Results of Load-Controlled Limits

| Evaluation Items | Cycle Types | | | |
|---|---|---|---|---|
| | OCT-1 | OCT-2 | OCT-3 | OCT-4 |
| Service Level | A | B | C | B |
| $T_{max}$ (°C) | 650 | 650 | 650 | 650 |
| $S_{mt}$ Reduction Ratio (%) | 0.0 | 0.0 | 0.0 | 0.0 |
| $S_m$ Reduction Ratio (%) | 0.0 | 0.0 | 0.0 | 0.0 |
| $P_m$ (MPa) | 9.40 < $S_{mt}$ = 34.25 | 9.40 < $S_{mt}$ = 34.25 | 6.27 < $S_{mt}$ = 34.25 | 9.40 < $S_{mt}$ = 34.25 |
| $(P_L+P_b)$ (MPa) | 32.57 < $KS_m$ = 147.76 | 32.57 < $KS_m$ = 147.76 | 21.71 < $1.2KS_m$ = 177.31 | 32.57 < $KS_m$ = 147.76 |
| $(P_L+P_b/K_t)$ (MPa) | 25.59 < $S_t$ = 34.25 | 25.59 < $S_t$ = 34.25 | 17.06 < $S_t$ = 34.25 | 25.59 < $S_t$ = 34.25 |
| UFS($t_i/t_{im}$) | 0.19104 | 0.19104 | 0.17404 | 0.19104 |
| Total UFS($t_i/t_{im}$) | Total User Fraction Sum ($t_i/t_{im}$) = 0.74715 < 1.0 : Satisfied | | | |
| UFS($t_i/t_{ib}$) | 0.38540 | 0.38540 | 0.25090 | 0.38540 |
| Total UFS($t_i/t_{ib}$) | Total User Fraction Sum ($t_i/t_{ib}$) = 1.4071 > 1.0 : Not Satisfied | | | |

Table II: Summary Results of Strain-Controlled Limits by Elastic Analysis Method

| Evaluation Items | Cycle Types | | | |
|---|---|---|---|---|
| | OCT-1 | OCT-2 | OCT-3 | OCT-4 |
| TEST NO. A-1 | (X+Y) = 0.5414 > Sa/Sy= 0.6142 | (X+Y) = 0.5945 > Sa/Sy= 0.6142 | (X+Y) = 0.6155 > Sa/Sy= 0.6142 | (X+Y) = 0.2799 > Sa/Sy= 0.6142 |
| TEST NO. A-2 | (X+Y) = 0.5414 < 1.0 | (X+Y) = 0.5945 < 1.0 | (X+Y) = 0.6155 < 1.0 | (X+Y) = 0.799 < 1.0 |

Table III: Summary Results of Strain-Controlled Limits by Simplified Inelastic Analysis Method and Creep-Fatigue Limits

| Evaluation Items | | Cycle Types | | | |
|---|---|---|---|---|---|
| | | OCT-1 | OCT-2 | OCT-3 | OCT-4 |
| Max Primary SI (MPa) | $(P_L+P_b/K_t) + Q_m$ | 28.77 | 26.41 | 30.43 | 25.71 |
| Second. SI Range (MPa) | $(Q_R)_{max}$ | 13.67 | 15.71 | 19.60 | 2.46 |
| Yield Stress (MPa) | $S_{yL}$ | 122.00 | 122.00 | 122.00 | 122.00 |
| Primary Stress Parameter | X | 0.2359 | 0.2164 | 0.2494 | 0.2107 |
| Secondary Stress Parameter | Y | 0.1096 | 0.1288 | 0.1607 | 0.0202 |
| Creep Stress Parameter | Z | 0.2359 | 0.2164 | 0.2494 | 0.2107 |
| Effective Creep Ratchet Stress (MPa) | $\sigma_c$ | 28.77 | 26.41 | 0.25090 | 25.71 |
| Total creep Ratcheting Strain (%) | TEST NOS. B-1 or B-2 | Total Creep Ratcheting Strain = 0.06718 % < 1 % : Satisfied | | | |
| Fatigue Damage | Df | $0.1558 \times 10^{-6}$ < faigue Limit= 0.1654 | | | |
| Creep Damage | Dc | 0.6141 < Creep Limit= 1.0 | | | |

## 3. Conclusions

In this paper, the rules of high temperature structural integrity evaluation for Class A components of high temperature reactors are investigated and the related example is described. This rule will be practically used for the development of high temperature reactors.

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