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High Temperature Structural Integrity Evaluation Method and Application Studies by ASME-NH for the Next Generation Reactor Design

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The main purpose of this paper is to establish the high temperature structural integrity evaluating procedures for the next generation reactors, which are to be operated at over 500℃ and for 60 years. To do this, comparison studies of the high temperature structural design codes and assessment procedures such as the ASME-NH (USA), RCC-MR (France), DDS (Japan), and R5 (UK) are carried out in view of the accumulated inelastic strain and the creep-fatigue damage evaluations. Also the application procedures of the ASME-NH rules with the actual thermal and structural analysis results are described in detail. To overcome the complexity and the engineering costs arising from a real application of the ASME-NH rules by hand, all the procedures established in this study such as the time-dependent primary stress limits, total accumulated creep ratcheting strain limits, and the creep-fatigue damage limits are computerized and implemented into the SIE ASME-NH program. Using this program, the selected high temperature structures subjected to two cycle types are evaluated and the parametric studies for the effects of the time step size, primary load, number of cycles, normal temperature for the creep damage evaluations and the effects of the load history on the creep ratcheting strain calculations are investigated.

Key Words : ASME-NH, Elevated Temperature, Inelastic Strain, Creep-Fatigue, Liquid Metal Reactor, Ratcheting, SIE ASME-NH, Structural Integrity

Nomenclature

j : j-th cycle type
K_t : Bending stress reduction factor due to creep
K_ε, K_e' : Strain concentration factor
K, K_L, K_T : Stress concentration factor
K_ν : Multiaxial plasticity and Poisson ratio adjustment factor
N : Number of cycle type
P_1 : Effective primary membrane stress intensity
P_3 : Effective primary stress intensity with creep effect
P_b : Primary bending stress intensity
P_L : Local primary membrane stress intensity
P_m : Primary membrane stress intensity
$(Q_R)_{\max}$: The maximum range of the secondary stress intensity
$S^*, \bar{S}$: Stress indicators
S_y : Averaged yield stress for the max. and the min. temp.
S_a : Min $[1.25 S_{t|T\max, 10^4 hr}$, averaged $S_y]$
t : Time
T : Temperature

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V : Efficiency index
X, Y : Stress parameters
ε_p : Plastic strain
ε_c : Creep strain
ε_{EC} : Enhanced creep strain
ε_{mR} : Ratchet strain (membrane)
ε_{bR} : Ratchet strain (bending)
ε_{mEF} : Elastic followup strain by long term secondary bending stress (membrane)
ε_{bEF} : Elastic followup strain by long term secondary bending stress (bending)
ε_t : Total strain range
σ_b : Corrected primary bending stress intensity
σ_c : Effective creep stress
σ_L : Corrected local primary membrane stress intensity
σ_m : Corrected primary membrane stress intensity
Φ : Bending stress reduction factor due to creep

1. Introduction

In most LMR (Liquid Metal Reactor) designs, the operating temperature is very high at over 500℃ and the design lifetime is generally 60 years. Therefore, a time-dependent creep rupture, excessive creep deformation, cyclic creep ratcheting, creep-fatigue, creep crack growth and a creep buckling become very important for a reactor structural design. Unlike with a conventional PWR, the normal operating conditions can basically be a dominant design loading because the hold time at an elevated temperature condition is long enough to result in a severe creep damage during a total service lifetime. To accomplish the elevated temperature design or an assessment for the liquid metal reactors, the codes such as ASME-NH (USA) (2004), RCC-MR (France) (1987, 1993, 2002), R5 (United Kingdom) (2003), and DDS (Japan) (1984) have been developed and many efforts are being made to extend and modify the material database and a reduction of the conservatism contained in the codes. Recently, these have been reviewed and compared for an application to the high temperature gas-cooled reactor components (Shah et al., 2003). However the application procedures for these codes or assessments are very complicate to carry out by hand, especially when the design load history is resolved into several kinds of cycle types and the elastic approach is to be used. For the R-5 application, a computerized calculation program such as the DFA R5-Code (2003) has been developed to resolve the complicate assessment procedures of the R5. Likewise the R5, the ASME-NH rules are too complicate to completely apply to the high temperature structural design by hand (Koo and Yoo, 2000; 2001), especially when there are multi-transient cycle types for a whole design lifetime. As an example for the creep ratcheting limit evaluations by using simplified inelastic analysis rules, the creep ratcheting strain should be calculated for each temperature-time block throughout the entire service life time. To do this the isochronous stress and strain curves for the initial strain accumulated throughout the prior load history have to be regenerated by an appropriate curve fitting method (Penny, 1962) corresponding to the time block period and the temperature. And for the creep damage evaluations for the multi-transient operating conditions the envelop of the stress/temperature-time histories for each cycle type and the integrations of a creep damage for each time interval can be very complicated work when doing the calculations by hand. Therefore it is rather obvious that numerical code is needed for future design and assessmen, which can efficiently use the ASME-NH rules and produce detailed results of the structural integrity evaluations with all the calculation procedures.

In this paper, comparison studies of the design codes and the assessment procedures developed throughout the world are carried out to investigate the theoretical background contained in the rules of the inelastic strain limit and the creep-fatigue damage limit.

From the establishment of concrete application procedures of the ASME-NH rules, the SIE ASME-NH (Structural Integrity Evaluations by ASME-NH code), which has a computerized implementation of the ASME Pressure Vessels and Piping Code Section III Subsection NH rules, is developed to be used as a general purpose program for the next generation reactor design subjected to elevated temperature operations (Koo and Lee, 2006). Using the developed SIE ASME-NH program, the examples of an application are performed for the shell to head junction structures operating at a maximum of 650℃ with two representative cycle types during a total design life time. The parameteric studies of the evaluation parameters such as the weldment, the effects of the time step size, primary load, and number of cycles for a creep evaluation, and the load history effects on the creep ratcheting strain evaluation are carried out by using the SIE ASME-NH program.

2. Intercomparison of Codes and Assessment Procedure

2.1 Inelastic strain limits

The main purpose of the inelastic strain limit rules in the codes is to prevent a progressive deformation by the cyclic loads with a consideration of the creep effect. The limit rules for the accumulated inelastic stain during a total design life time are as follows;

ASME-NH

(a) Elastic Analysis Method:

$$X+Y \leq S_a/S_y \text{ or } 1.0 \tag{1}$$

where

$$X=\left(P_m+\frac{P_b}{K_t}\right)_{\max} \div S_y \tag{2}$$

$$Y=\frac{(Q_R)_{\max}}{S_y} \tag{3}$$

(b) Simplified Inelastic Analysis Method:

No ratcheting cycle:

$$\sum_{j=1}^{N} \varepsilon(1.25\sigma_c, T)_j \leq 1.0 \tag{4}$$

With ratcheting cycle:

$$\sum \varepsilon=\sum \nu+\sum \eta+\sum \delta \tag{5}$$

where

$\sum \nu$=the inelastic strains obtained from the isochronous curves

$\sum \eta$=the plastic ratchet strain increments

$\sum \delta$=the enhanced creep strain increments

RCC-MR

$$(\varepsilon_p+\varepsilon_c)|_{(1.25P_1)} \leq 1.0\% \tag{6}$$

$$(\varepsilon_p+\varepsilon_c)|_{(1.25P_3)} \leq 2.0\% \tag{7}$$

where

$P_1=\text{Max}(\sigma_m)/V_1$
: Effective primary membrane stress intensity (8)

$P_3=\text{Max}(\sigma_L+\Phi\sigma_b)/V_3$
: Effective primary stress intensity with creep effect (9)

DDS

$$\varepsilon=\varepsilon_{EC}+\varepsilon_{mR}+\varepsilon_{mEF} \leq 1.0\% \tag{10}$$

$$\varepsilon=\varepsilon_{EC}+\varepsilon_{mR}+\varepsilon_{bR}+\varepsilon_{mEF}+\varepsilon_{bEF} \leq 2.0\% \tag{11}$$

The symbols used in all the equations are listed in the nomenclature. As shown in the above limit rules for the inelastic strain, the rule of the RCC-MR is almost the same concept as the simplified inelastic analysis method in the case of no ratcheting region in the ASME-NH. This rule was recently modified while the previous rule was based on the use-fraction sum (RCC-MR, 1987, 1993, 2002). While the ASME-NH introduces an effective creep stress σ_c, which is related to the Bree diagram (Bree, 1967) corresponding to the effective creep stress parameter Z, the RCC-MR uses the effective primary stress intensities related to the efficiency diagram. Actually, when we transform the bree diagram to the efficiency diagram coordinate system, we can see that the general trends of both are the same and the Bree diagram provides a lower bound for the efficiency diagram. Finally, the accumulated inelastic strain is sequentially determined for each temperature-time block from the isochronous curves in the ASME-NH. However, in the RCC-MR, a plastic deformation should be determined from the minimum or average tensile curves and the total creep strain from the creep-strain law provided in the RCC-MR by considering a period covering all the events for which the loadings must meet the service level A criteria and the maximum temperature during this period. For the weld metal evaluation in the RCC-MR, the limit values should be half of the case of the base metal as in the ASME-NH rules.

The rule of the DDS is the same concept as the simplified inelastic analysis method of the ASME-NH but the consideration of an elastic followup is different. The elastic followup such as a pressure induced membrane and bending stresses and the thermal induced membrane stresses are classified as primary stresses in the ASME-NH and included in calculating the stress parameters of X and Y. On the other hand, as shown in Eqs. (10) and (11), the elastic followup strain is directly summed to the total inelastic strain with an enhanced creep strain and a ratcheting strain in the DDS.

2.2 Creep-fatigue limits

In elevated temperatures, fatigue damage is mainly induced by a strain-controlled low cycle fatigue mechanism and it interacts with the creep damage. Therefore, in all the design codes, the evaluation rules of a creep-fatigue limit are based on the calculation of a total strain range. The rules of a total strain range calculation are compared as follows ;

ASME-NH

$$\begin{aligned}\varepsilon_t &= K_v \Delta\varepsilon_{\mathrm{mod}} + K\Delta\varepsilon_c \\ &= K_v\left(\frac{S^*}{\bar{S}}\right)K^2\Delta\varepsilon_{max} + K\Delta\varepsilon_c\end{aligned} \tag{12}$$

RCC-MR

$$\begin{aligned}\varepsilon_t &= (\Delta\varepsilon)_{e+p} + \Delta\varepsilon_c \\ &= (\overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2} + \overline{\Delta\varepsilon_3} + \overline{\Delta\varepsilon_4}) + \Delta\varepsilon_c\end{aligned} \tag{13}$$

DDS

$$\begin{aligned}\varepsilon_t &= K_e\varepsilon_n + K_L\varepsilon_c + K_T\varepsilon_F \\ &= K_e'\left(\frac{S^*}{\bar{S}}\right)K^2\varepsilon_n + K_L\varepsilon_c + K_T\varepsilon_F\end{aligned} \tag{14}$$

R5

$$\varepsilon_t = \Delta\bar{\varepsilon}_{el} + (\Delta\sigma_{rD})/\bar{E} + \Delta\bar{\varepsilon}_{pl} + \Delta\bar{\varepsilon}_{vol} \tag{15}$$

Figure 1 to Fig. 4 demonstrate Eq. (12) to Eq. (15) above, which are for calculating the total elastic-plastic strain range from the elastic structural analysis. As shown in the figures and the equations, all the code rules have the same basic concept by using Neuber's rule to consider the local geometric stress concentration. For the ASME-NH, the monotonic isochronous curves modified with the stress relaxation strength S_{rH}, which may be determined by performing a pure uniaxial relaxation analysis starting with an initial stress of 1.5 S_m and holding the initial strain throughout the time interval equal to the time of service are used in obtaining the total strain range while the RCC-MR and the R5 use the cyclic material curves. The concept of the RCC-MR is based on the total equivalent stress range obtained from the elastic structural analysis and the cyclic material curves modified with the modified elastic modulus.

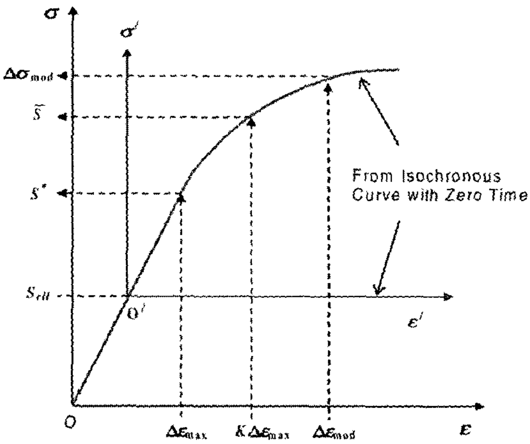

Fig. 1 Concept of the total strain range calculation by ASME-NH

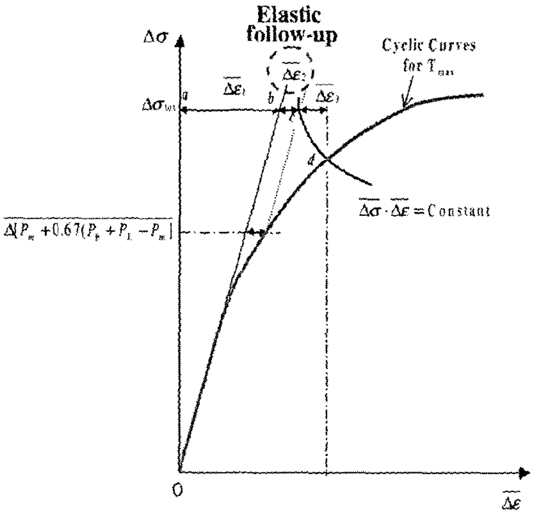

Fig. 2 Concept of the total strain range calculation by RCC-MR

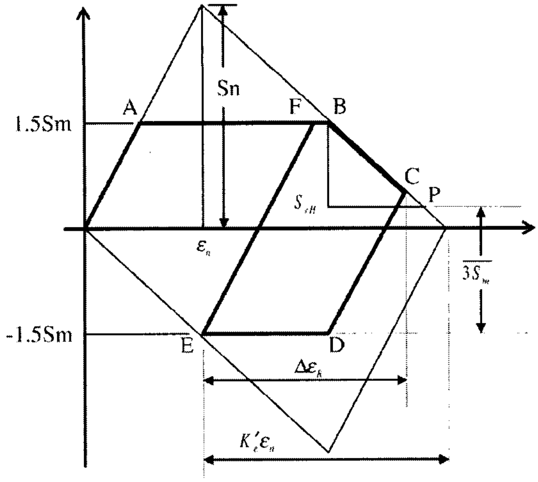

Fig. 3 Concept of the total strain range calculation by DDS

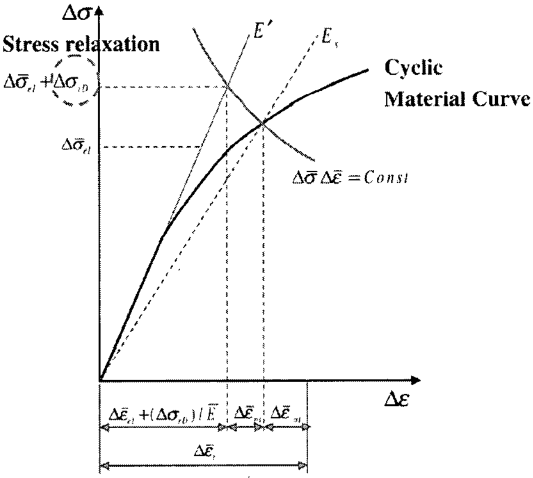

Fig. 4 Concept of the total strain range calculation by R5

This rule includes an elastic followup by the primary stress and the creep strain increment by a given creep equation. The rules of a DDS for a total strain range determination are almost the same as the ASME-NH but they include the peak thermal strain range multiplied by the elastic stress concentration factor. The R5 has two approaches for the calculation. One is a simplified calculation method of the elastic-plastic strain range and the other one is the detailed construction method of the hysteresis loop. Eq. (15) above is for the former case when a creep is significant and the dwell is at the peak of the cycle. Like the RCC-MR, R5 is based on the total equivalent stress range calculated by the elastic structural analysis. This method uses the modified cyclic material curve or an isochronous curve.

For the creep-fatigue damage limit evaluation, the ASME-NH, the RCC-MR, and the DDS have the same concept of a linear damage summation rule with criteria by using the creep-fatigue interaction diagram. However, the R5 procedure permits the use of the ductility exhaustion method for a creep-fatigue evaluation if the material data is available, which can consider a metal surface creep crack initiation. If appropriate data is not available, a linear damage summation similar to that of the ASME-NH can be used.

3. Structural Integrity Evaluation by ASME-NH

3.1 Basic concept of the ASME-NH rules

At temperatures and loading conditions where the creep effects are significant, the design by analysis should consider the time-dependent material properties and the structural behavior by guarding against failure modes such as a ductile rupture from short-term loadings, a creep rupture from long-term loadings, creep-fatigue damage, a gross distortion due to an incremental collapse and a ratcheting.

In evaluating the structural integrity for an elevated temperature, it can be broadly checked by four-quantities such as 1) the load-controlled stress, 2) the total accumulated inelastic strain, 3) creep-fatigue damage, and 4) a buckling instability.

In this section, the contents and the application procedures of the ASME-NH to be implemented as the basis of the SIE ASME-NH program will be investigated.

3..1.1 Limits for load-controlled stresses

The primary stress intensity limits should be satisfied for a base metal and at the weldments. To assure a high temperature structural integrity for the base metal, allowable stress limit values are defined : time-independent limit (S_m), long-time service at an elevated temperature (S_{mt}), and a temperature and time-dependent limit obtained from the 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 should be calculated by the rules of ASME NH-3215(b), which requires the six scalar quantities of the stress components for each type of loading at critical locations across 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. This means that there are no precise rules in selecting the critical locations, therefore the designer should select them carefully.

When the evaluation points are at the weldments, S_{mt} should be taken as the lower of the S_{mt} values or $0.8S_r \times R$, where S_r is the value obtained from the expected minimum stress-to-rupture strength (Table I-14.6) (2004) and R is the appropriate ratio of the weld metal creep rupture strength to the base metal creep rupture strength (Table I-14.10) (2004). The values of S_t should be taken in the same way as S_{mt}.

Since ASME-NH does not provide the inelastic analysis rules for satisfying the primary stress limits, these rules are basically carried out by the elastic analysis method. Table 1 shows a summary of the primary stress limit rules in the ASME-NH.

3.1.2 Limits for a deformation and strain

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

(a) Strains averaged through the thickness (Membrane strain): $\varepsilon_m \leq 1.0\%$

(b) Strains at the surface due to an equivalent linear distribution of a strain through the thickness (Bending strain): $\varepsilon_b \leq 2.0\%$

(c) Local strains at any point (Local strain): $\varepsilon_L \leq 5.0\%$

Actually when creep effects are presumed to be significant, the above inelastic strain limits need to be checked by a detailed inelastic analysis. However, in order to reduce the number of evaluation points in a structure subjected to an elevated temperature, the elastic and simplified inelastic methods of an analysis are provided in ASME NH Nonmandatory Appendix T (2004) with conservative bounds.

Elastic Analysis Method

The maximum accumulated inelastic strain limits mentioned in the above paragraph 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 defined in the ASME-NH rules are satisfied. These tests are based on the concept of the Bree Diagram which uses the stress parameters of X and Y. Actually, this method is developed to be applicable to axisymmetric shell structures subjected to an internal pressure and thermal stresses caused by a linear through-thickness temperature

Table 1 Load-controlled stress limits in ASME-NH

Design Condition	Service Level A & B	Service Level C	Service Level D
Membrane	Membrane	Membrane	Membrane
$P_m \leq S_o$	$P_m \leq S_{mt}$	$P_m \leq \mathrm{Min}[1.2S_m, S_t]$ $\sum_i \left(\frac{t_i}{t_{im}}\right) \leq B$	$P_m \leq \mathrm{Min}[0.67S_r,$ $0.8S_rR$, Appendix $F]$ $\sum_i \left(\frac{t_i}{t_{ir}}\right) \leq B_r$
Membrane+Bending	Membrane+Bending	Membrane+Bending	Membrane+Bending
$P_L + P_b \leq (1.5)\,S_o$	$P_L + P_b \leq K\,S_m$ $P_L + P_b/K_t \leq S_t$	$P_L + P_b \leq 1.2K\,S_m$ $P_L + P_b/K_t \leq S_t$ $\sum_i \left(\frac{t_i}{t_{ib}}\right) \leq 1.0$	$P_L + P_b$ $\leq \mathrm{Min}[3.6S_m, 1.05S_u]$ $P_L + P_b/K_t$ $\leq \mathrm{Min}[0.67S_r, 0.8S_rR]$

gradient,. The stress parameters are defined as the maximum local primary membrane and bending stress intensities and the maximum range of a secondary stress intensity divided by the average of the yield strength value at the maximum and minimum wall averaged temperatures during the cycle as follows ;

$$X = (P_m + P_b/K_t)_{\max} \div S_y \tag{16}$$

$$Y = (Q_R)_{\max} \div S_y \tag{17}$$

The value of $(X+Y)$ should not be greater than 1.0 or (S_a/S_y), where S_a is the lesser of 1.25 $S_t|_{t=10^4hr}$ and S_y.

Simplified Inelastic Analysis Method

The elastic analysis method might be very conservative for the inelastic strain limit rules. When the limits are not satisfied by the elastic analysis method, the simplified inelastic analysis method provided in ASME-NH could be used with a lesser conservatism. 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.

The main concept of this rule is almost the same as that of the elastic analysis method using the stress parameters but in calculating the primary stress parameter X, the secondary stresses with an elastic followup (i.e., pressure-induced membrane and bending stresses and thermal-induced membrane stresses) are classified as primary stresses for the purposes of this evaluation and in calculating the stress parameters of X and Y, the S_{yL} value will be used instead of S_y.

The creep ratcheting strain is determined from the isochronous stress and the strain curves corresponding to each effective creep ratcheting strain of the temperature-time blocks calculated by $\sigma_e = 1.25\sigma_c = 1.25Z \cdot S_{yL}$, where Z is an effective creep stress parameter determined by the Bree Diagram corresponding to the stress parameters of X and Y.

One important thing to keep in mind when using this rule is that the time to enter the isochronous curves for individual time blocks should always sum to the entire life regardless of whether all or only a 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 it may be subdivided into the appropriate temperature-time blocks. For each block, the isochronous curves can be entered at the initial strain accumulated throughout the prior load history as shown in Fig. 5. To do this, some complicated procedures to regenerate the isochronous curves

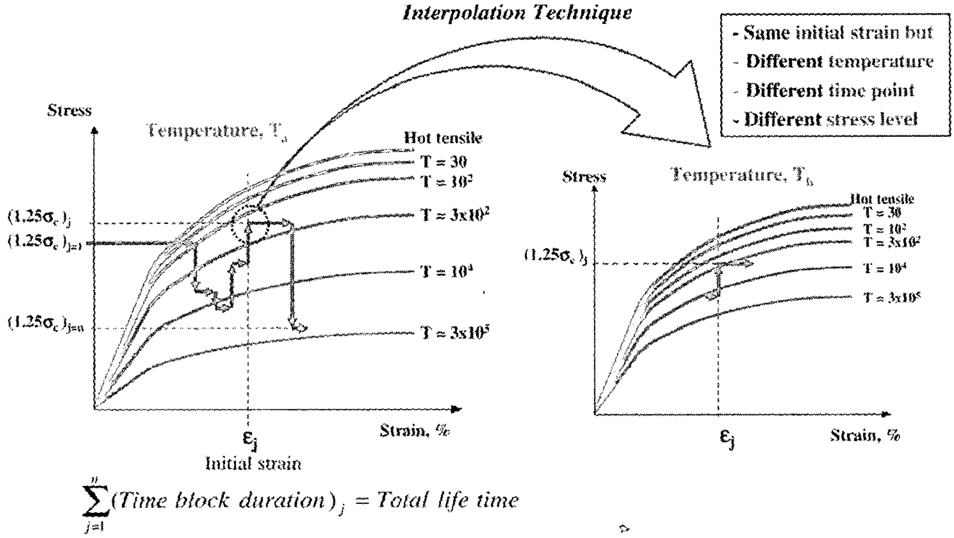

Fig. 5 Concept of the accumulated creep ratcheting strain calculation from the isochronous curves

corresponding to the temperature-time block by the interpolation technique are required. After regenerating the isochronous curves, the next step is to find the time point corresponding to the initial strain accumulated throughout the prior temperature-time blocks on the isochronous curve and to determine the creep ratcheting strain increment for the next temperature-time block duration. The procedure should be continued for a whole load history to determine the total accumulated creep ratcheting strain throughout the total design lifetime. The individual cycles or time blocks may differ from those for the creep-fatigue evaluations.

Inelastic Analysis Method

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

3.1.3 Limits for a creep-fatigue damage

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

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j+\sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k\leq D \qquad (18)$$

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 design 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

The total damage, D, should not exceed the creep-fatigue damage envelope curves given in Fig. 6. The detail evaluation procedures are described in the next section.

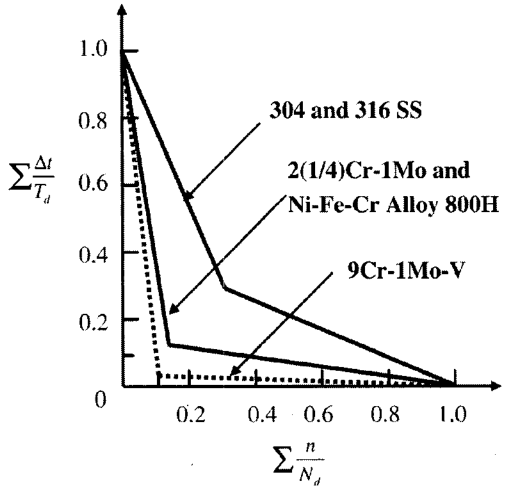

Fig. 6 Creep-fatigue interaction diagram of ASME-NH

3.2 Development of the SIE ASME-NH program

3.2.1 List of the program modules

The rules of the ASME-NH are computerized and implemented into the SIE ASME-NH computer program. This program is coded by using the Fortran language with module types, which can be easily upgraded as the evaluation rules are changed. The main program modules consist of the following ;

- SIE-ASME-NH.f : Main program for the overall procedures
- INPUT-DATA.f : Input data control module
- P-LIMITS.f : Primary stress limits evaluation module
- S-LIMITS.f : Inelastic strain limits evaluation module
- CF-LIMITS.f : Creep-fatigue by an elastic analysis
- CF-INELASTIC.f : Creep-fatigue by an inelastic analysis
- MAT-*.f : Material database

Figire 7 shows the overall contents of the SIE ASME-NH code. The input data file required in the SIE ASME-NH can be easily prepared with command based control cards, which are independently used for any required evaluation item.

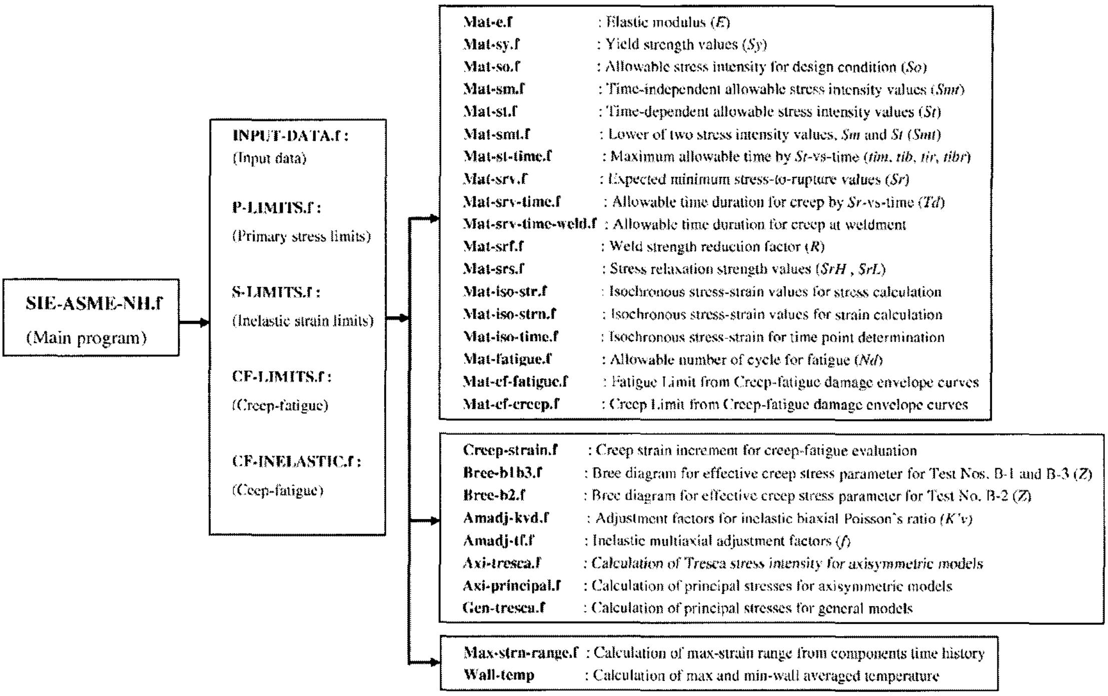

Fig. 7 Contents of the SIE ASME-NH code

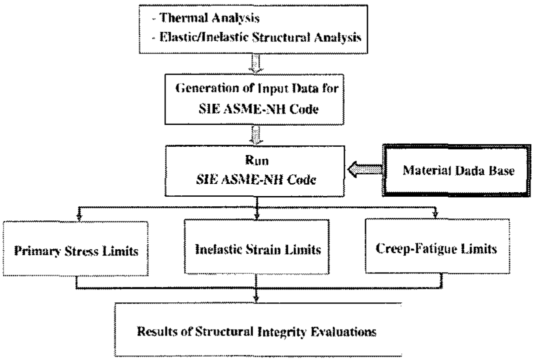

Fig. 8 General procedures of the SIE ASME-NH code

3.2.1 General evaluation procedures

Figure 8 shows the general procedures of the structural integrity evaluations performed by the SIE ASME-NH code. More detailed procedures for the high-temperature structural integrity evaluations by using the SIE ASME-NH code are as follows ;

[Step 1] Determine the representative primary loads for the specified service levels

[Step 2] Primary stress analyses

[Step 3] Determine the representative thermal cycle types for the structural design

[Step 4] Transient temperature distribution analyses for each specified cycle type

[Step 5] Thermal stress analysis for each cycle type

[Step 6] Determine the stress cycle indicating the extreme stress and strain time points during the cycle

[Step 7] Determine the evaluation sections at a time corresponding to the maximum stress time point

[Step 8] Extract the input data required in the program for the evaluation points at the time corresponding to the extreme stress and the strain time points from the analysis results

[Step 9] Perform the evaluation by using the SIE ASME-NH

[Step 10] Review the evaluation results of the output files

In step 7 above, the total stress intensity contour is very helpful to determine which locations can be taken as the critical evaluation sections. The recommendation notices to be considered in selecting the critical locations are as follows ;

- Weld zone
- Maximum stress level
- Maximum stress range
- Maximum temperature level
- Hold time at maximum temperature level

In step 8 above, the basic input data required in the SIE ASME-NH is the stress components and the metal temperatures at extreme stresses during a stress cycle, the maximum and the minimum wall averaged temperatures, the strain components at extreme strains during a strain cycle, and the maximum metal temperature during a cycle. In most cases, to extract the maximum elastic strain range in step 8 above, a user can look for the strain cycle and determine the extreme strain time points. By using the elastic strain components at these two extreme time points the maximum strain range may be extracted easily instead of following the complex procedure of ASME-NH T-1413 Step 2 and Step 3.

3.2.2 Creep-fatigue evaluation by elastic analysis method

The general procedures to evaluate the fatigue damage term in Eq. (18) by using the elastic analysis method are as follows ;

[Step 1] Calculate the elastic strain time history for each cycle type, j

[Step 2] Select one of the extreme time points for the cycle (set subscript o)

[Step 3] Calculate strain ranges for all the components at each time point as

$$\Delta\varepsilon_{xi}=\varepsilon_{xi}-\varepsilon_{xo},\ \Delta\varepsilon_{yi}=\varepsilon_{yi}-\varepsilon_{yo},\ \text{etc..}$$

[Step 4] Calculate the equivalent strain range for each point in time as

$$\Delta\varepsilon_{equi,i}=\frac{\sqrt{2}}{2(1+\nu^{*})}\Big[(\Delta\varepsilon_{xi}-\Delta\varepsilon_{yi})^{2}+(\Delta\varepsilon_{xi}-\Delta\varepsilon_{yi})^{2}+(\Delta\varepsilon_{xi}-\Delta\varepsilon_{yi})^{2}+\frac{3}{2}(\Delta\gamma_{xyi}^{2}+\Delta\gamma_{yzi}^{2}+\Delta\gamma_{zxi}^{2})\Big]^{1/2}$$

[Step 5] Define $\Delta\varepsilon_{\max}=\mathrm{Max}(\Delta\varepsilon_{equiv,i})$

[Step 6] Modify $\Delta\varepsilon_{\max}$ with a local geometric stress concentration and the multiaxial effects

[Step 7] Calculate the total strain range as

$$\varepsilon_t=K_v\Delta\varepsilon_{\mathrm{mod}}+K\Delta\varepsilon_c$$

[Step 8] Find the allowable number of cycles, N_d from the design fatigue curves corresponding to ε_t

[Step 9] Calculate the fatigue damage by

$$\sum_{j}^{p}\left(\frac{n}{N_d}\right)_j$$

For the weldment evaluations, the obtained allowable number of design cycles N_d should be one-half the value permitted for the parent material.

The general procedures to evaluate the creep damage term in Eq. (18) of the creep-fatigue damage rules are as follows ;

[Step 1] Define the total number of hours expended at an elevated temperature, t_H

[Step 2] Define the hold temperature, T_{HT}

[Step 3] Define the average cycle time, $\bar{t}_j=t_H/n_j$

[Step 4] Determine the stress level, $S_j|\varepsilon_t$ from time independent isochronous stress-strain curve corresponding to T_{HT}

[Step 5] Obtain the stress relaxation time history curve at dwell stress S_j and a hold temperature, T_{HT}

[Step 6] Modify the stress relaxation time history curve by considering the load-controlled transient effect

[Step 7] Define the cycle transient temperature

[Step 8] Repeat Step3 through to Step 7 to make $j=1$ for the P sets of the stress relaxation time histories and superimpose these onto the results in the envelope stress-time history

[Step 9] Determine the integration time step size, $(\Delta t)_k$, the stress, $(S)_k/K'$, and the temperature, $(T)_k$

[Step 10] Obtain the allowable time duration, $(T_d)_k$ for each time interval from the expected minimum stress-to-rupture curve

For the multi-cycle types, the individual stress relaxation time histories should be generated for each cycle type and these should be superimposed to make a single representative enveloped history as shown in Fig. 9.

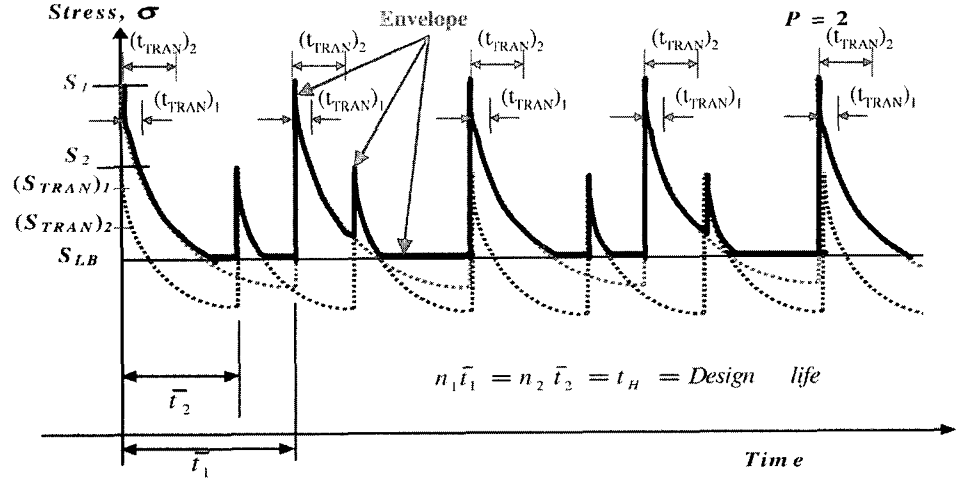

Fig. 9 Concept of the envelop stress-time history for a creep damage evaluation

For the weldment evaluations, the allowable time duration T_d should be determined from a stress-to-rupture curve obtained by multiplying the parent material stress-to-rupture values by the weld strength reduction factors (2004).

3.2.3 Creep-fatigue evaluation by the inelastic analysis method

The general procedures of the inelastic analysis method are basically the same as the elastic analysis method, which is based on well-defined cycle types. As the effects of a local geometric stress concentration and a multiaxial behavior are included in the inelastic analysis, additional modification procedures of the maximum strain range, which are required in the elastic analysis method, are not necessary.

The fatigue damage can be directly evaluated by using a design fatigue curve at the total strain range ε_t which is defined as $\varepsilon_t = \Delta\varepsilon_{\max}$ obtained by the same procedures of the elastic method. The maximum metal temperature during the cycle should be used in selecting the design fatigue curve.

The general procedures to evaluate the fatigue damage by the inelastic analysis method are as follows ;

[Step 1] Define the complete load cycle types

[Step 2] Perform an inelastic analysis with well-proven constitutive equations for each cycle type

[Step 3] Find the maximum strain range $\varepsilon_t = \Delta\varepsilon_{\max}$ with the same procedures of step 1 through to step 5 in elastic analysis method

[Step 4] Find an allowable number of cycles, N_d from the design fatigue curves corresponding to ε_t and the maximum metal temperature during each cycle

[Step 5] Calculate the accumulated fatigue damage by $\sum_j^p \left(\frac{n}{N_d}\right)_j$

To evaluate the creep damage term in Eq. (18), the stress-time history corresponding to the load history should be calculated for a whole service lifetime by an inelastic analysis with well-proven constitutive equations.

The general procedures for the creep damage evaluation by the inelastic analysis method are as follows ;

[Step 1] Define the load history for the entire design life time

[Step 2] Perform an inelastic analysis with well-proven constitutive equations

[Step 3] Calculate the equivalent stress-time history by the given equations

[Step 4] Obtain an allowable time duration for the maximum stress divided by the safety factor, K' during each time interval by using the expected minimum stress-to-rupture curves

[Step 5] Calculate the creep damage by using the integral form

3.3 Metal temperature data

For an evaluation of the high-temperature structural integrity by the rules of ASME-NH, several kinds of metal temperature data at selected evaluation points, obtained by a thermal analysis, are required as follows ;

- Maximum and Minimum Wall Averaged Metal Temperatures During the Cycle :

These temperatures are used in the rules of the inelastic strain limit by using the elastic analysis method with a consideration of a conservatism. The values such as the yield strength (S_y), time-independent and time-dependent allowable stress intensities (S_m, S_t), stress-to-rupture time (S_r-vs-time), and isochronous stress-strain curve are determined with this temperature data.

- Hot and Cold Temperatures During the Cycle :

These temperatures are used to determine the stress relaxation strength (S_{rH}, S_{rL}). The hot and the cold temperatures are defined as the temperatures corresponding to the two stress extremes in the stress cycle respectively. These are not wall averaged values but at local points, therefore different from that of the hot and cold end temperature.

- Wall Averaged Metal Temperatures for the Stress Extremes Defining the Maximum Secondary Stress Range, $(Q_R)_{\max}$:

These temperatures are used in the rules of the strain limits by using the simplified inelastic analysis method. As the purpose of this rule is to reduce the conservatism of the code rules, more realistic temperature data is used. The yield strengths (S_{yL}, S_{yH}) and elastic modulus (E_H, E_L) are determined with this temperature data. These are called the hot and the cold end temperature.

- Maximum Metal Temperature During the Cycle :

This temperature is used in the rules of the fatigue damage evaluation. Values such as the stress relaxation strengths (S_{rH}), time-independent allowable stress intensities (S_m), elastic modulus (E), isochronous stress-strain, allowable number of cycles for a fatigue are determined with this temperature data.

- Hold Temperature :

This temperature is used in the rules of the creep damage evaluation.

- Transient Temperature :

This temperature is used in the rules of the creep damage calculation to consider the maximum transient metal temperature during the cycle. This value is to be equal to the maximum metal temperature during the cycle type.

3.4 Load history concepts

The complete load history of a component should be defined to evaluate the design integrity for a whole service lifetime. Actually the whole load history may be complicated and it can be difficult to delimit each operating cycle type. Therefore, it is necessary to simplify the load history to apply the structural integrity evaluations. To do this, a user should resolve the load history into well-defined cycle types in the same way as the R5 code before the structural integrity evaluations. The representative cycle types with the number of occurrences, which can cover all kinds of design operating conditions for a design life time, should be clearly defined.

Actually, the concepts of the load history required in the creep ratcheting stain limit evaluation and the creep-fatigue evaluation are different in the ASME-NH code. In the strain limit evaluation, the temperature-time block concepts are introduced to be able to evaluate the cyclic creep ratcheting strain accumulation for each cycle of the time block. However, in the creep-fatigue damage evaluations, the representative cycle types are required to calculate the maximum elastic-plastic strain ranges and the creep strain increments for each cycle type. The creep strain increment for each cycle type should be obtained by the same rules used in the inelastic strain limit evaluation.

To avoid any confusion and maintain a consistency with the ASME-NH in using the defined load cycle types, the procedures in the SIE ASME-NH are used to construct the load history by using a combination of the representative cycle types. The total time durations used in the load history generation should not be less than the design life time.

3.5 Weldments evaluation

When the evaluation points are in the vicinity of a weld (defined by ±3 times the thickness to either side of the weld centerline), the rules for a weldment have to be applied. In the SIE ASME-NH program, the command *WELDMENT is provided to support this rule.

4. Examples of an Application

4.1 Thermal and elastic stress analyses

As an example of an application, the shell to head junction type structure with a gross structural discontinuity is selected. Fig. 10 shows the axisymmetric finite element analysis model and the applied boundary conditions by ANSYS program. The radius of the fillet size at the junction part is assumed to be the same as the vessel thickness. It is expected that the stress and the strain concentrations might occur at this part. The used structural material is a Type 316 austenitic stainless steel with a required design lifetime of 240,000 hours (about 28 years) at an elevated temperature operation.

As shown in the boundary conditions of Fig. 10, the bulk temperature of the outer side of the cylindrical vessel is assumed to remain constant at 300℃ during all the transient operating cycles. The inner surface of the cylindrical vessel is subjected to the transient bulk temperature and a constant pressure of 10 bar. For the stress analysis, the vertical displacement degree of freedom is only constrained at the upper end of the cylindrical vessel, therefore the structure can be freely expanded in the radial and vertical directions.

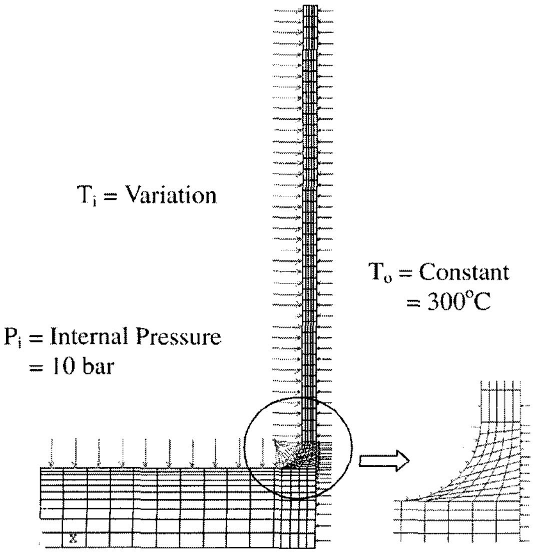

Fig. 10 Used axisymmetric finite element model with thermal B.C.

4.2 Thermal transient operating cycles

For an example of the multi-transient cycle types, two representative cycle types are assumed during the total design lifetime as shown in Fig. 11. For cycle type 1, the coolant temperature starts to decrease down to $T_1=500$℃ from the normal operating temperature, $T_{ss}=550$℃ for 5 hours and next it gradually increases to $T_2=650$℃ for 5 hours and then it recovers the normal operating temperature again after 5 hours. Therefore, the total transient duration is 15 hours. For cycle type 2, the coolant temperature starts to decrease down to $T_1=400$℃ from the normal operating temperature, $T_{ss}=550$℃ for 5 hours and next it increases up to $T_2=600$℃ for 5 hours and then it recovers the normal operating temperature again after 5 hours. The total transient duration is 15 hours, the same as that of cycle type 1.

To define the load history for the total creep ratcheting strain calculation, it is assumed that the two cycle types are uniformly distributed over the design life time and that they have the same hold temperature duration, then the two cycles repeatedly occur 10 times with 12000 hours each. Therefore, the total temperature-time block used in the evaluation is 20 time blocks and the total times used in selecting the isochronous curves exactly sum to the total service life. The number of each

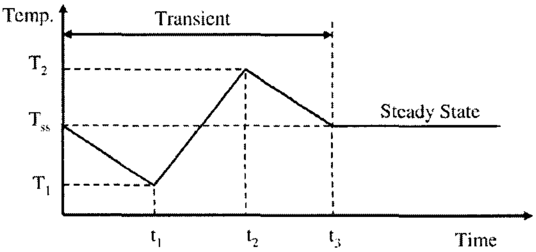

Fig. 11 Used representative cycle type

cycle type for the creep-fatigue damage evaluations are defined to be 10 for cycle type 1 and 15 for cycle type 2.

The primary cycle types are assumed to be the same in both cycle types with an internal pressure of 1.0 MPa.

4.3 Define critical locations

Not to miss or underestimate the structural integrity, the establishment of the exact locations of the critical points in the analysis model is very important. To determine the critical locations, the analysis results of the primary stress and the secondary stress intensities are analyzed in detail. As shown in Fig. 12 the maximum primary stress occurs at the junction part and also the maximum secondary stress intensity occurs at almost the same location to that of the primary stress at the extreme time points. Therefore, the evaluation section is selected between the inner surface node number 200 (evaluation point 1) and the outer surface node number 186 (evaluation point 2), which is expected to provide the maximum membrane stress intensity value.

4.4 Results of the creep ratcheting evaluation

When using the elastic analysis rules, the calculated sum of the stress parameters $(X+Y)$ at evaluation point 1 is 0.6985 for cycle type 1 and 0.9709 for cycle type 2. These satisfy the limit value of $S_a/S_y=0.9495$ for cycle type 1 and $S_a/S_y=1.0$ for cycle type 2 in Test No A-1. The evaluation point 2 also satisfies the creep ratcheting limit rules with large enough margins.

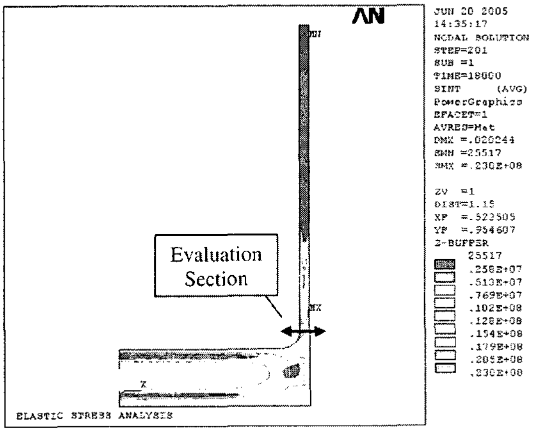

Fig. 12 Determined evaluation section

When using the simplified inelastic analysis rules, it is assumed that the peak through-the-wall thermal stresses are negligible and the obtained effective creep ratchet stresses for each evaluation point and cycle type are assumed to remain constant throughout each block service time defined in the evaluation. These are listed as follows ;

For Point No=1 and
Cycle Type=1 : 1.25Sc=56.59(MPa)
For Point No=1 and
Cycle Type=2 : 1.25Sc=56.52(MPa)
For Point No=2 and
Cycle Type=1 : 1.25Sc=36.45(MPa)
For Point No=2 and
Cycle Type=2 : 1.25Sc=55.82(MPa)

The above effective creep ratchet stresses are so small that a shake down might be expected. In the output lists, the inelastic strains occur during the first few time blocks but there are no more after that. The calculated total creep ratchet strains are 0.1544% for point 1 and 0.0375% for point 2, which are very small quantities when compared with the inelastic strain limits for the base metal 1.0% or 0.5% for the weldment.

When using Test No B-3 for the individual strain calculations, the total enhanced creep strain increments occur during the time blocks corresponding to cycle type 1, but it is very small to to 8.053e-6 for each time block and it can hardly affect the total inelastic strains.

4.5 Results of the creep-fatigue evaluation

Before performing the creep-fatigue damage evaluation, the ASME-NH requires the check of the modified $3S_m$ limit compatible with the NB-3222.2. In this example, the $3S_m$ limit satisfies the ASME-NH rule as follows ;

$$\Delta(P_L+P_b+Q)=88.833<3\bar{S}_m=269.693 : \text{OK}$$

The calculated fatigue damages are negligible for both cycle types at each evaluation point because the obtained total strain ranges are too small to invoke a fatigue damage.

To evaluate the creep damage, the enveloped stress relaxation time history should be generated for cycle type 1 and cycle type 2 during an entire life time. Fig. 13 shows the obtained envelope stress relaxation time history at evaluation point 1 including the safety factor $K'=0.67$.

As shown in the figure, the obtained envelope stress relaxation time history is very complicated and during the stress relaxation time of cycle type 1 the stress level of cycle type 2 makes the stress level increase enough to affect a creep damage occurrence. This stress envelop procedure of ASME-NH enables the designer to treat any kind of temperature and stress increment occurring in the intermediate operating time following a severe transient operation for the creep damage evaluations. In the figure, no further modification of the stress time history is done on the stress time history curve during the transient time of 15.0 hours due to a lesser primary stress than those in the stress curve, but the maximum transient metal temperature is included in compliance with the ASME-NH rules. As shown in the enveloped stress relaxation time history curve, the stresses are significantly relaxed at the initiating time of a dwell stress. This phenomenon will stop the creep damage from severely increasing during the maximum transient temperature operation. This is due to the low dwell stress level. However, when the initial stress level is much higher, then the trend of a significant reduction of the initial stress at the initiating stage will be reduced. Actually when we investigated the characteristics of the isochronous curves in detail, we can find that the slopes of the hot tensile stress-strain curves for the strains less than 0.2% and a stress less than 138 MPa are so steep for most temperature ranges. This means that the dwell stresses can be significantly reduced at the initiating stage of a relaxation for these stress and strain ranges. All the stress levels in the obtained stress time history are higher than that of the lower bound level, 56.6 MPa for point 1 and 55.8 MPa for point 2.

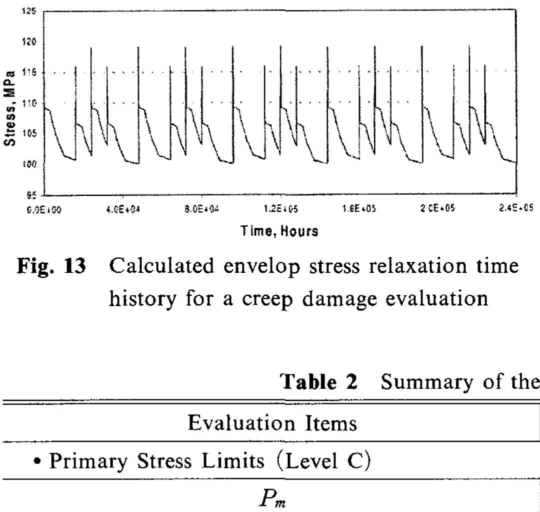

Fig. 13 Calculated envelop stress relaxation time history for a creep damage evaluation

The calculated creep damages are 0.4686 for point 1 and 0.3480 for point 2. For the case of point 1, the calculated creep damage from the enveloped stress relaxation time history is larger than 0.4588 for a single cycle type 1 or 0.4449 for

Table 2 Summary of the SIE ASME-NH evaluations

Evaluation Items	Calculated	Limit value	Check
• Primary Stress Limits (Level C)			
P_m	10.16 MPa	48.97MPa	OK
$\sum(t/t_m)$	0.23	1.0	OK
P_L+P_b/K_t	26.44 MPa	48.97 MPa	OK
$\sum(t/t_B)$	0.34	1.0	OK
• Inelastic Strain Limits			
Elastic Approach	0.9709	1.0	OK
Simplified Inelastic Approach	0.1544%	1.0%	OK
• Creep-Fatigue Limits			
Fatigue Damage	0.9E-5	0.2277	OK
Creep Damage	0.4686	1.0	OK

Note : The bending stress at the junction is classified as primary (Table NH-3217-1, Note 2) a single cycle type 2. From this result, the creep damage increases due to the effects of cycle type 2 during cycle type 1. Actually, it is expected that the higher the stress levels used for the expected minimum stress-to-rupture curve at the given hold temperature are, the larger the effect of the enveloped stress level will be on the creep damage.

Instead of the enveloped stress method provided in ASME-NH, if we calculate the creep damage individually for both cycle types and linearly sum these with an assumption that each cycle type is repeated throughout the entire design life time, then the creep damage at point 1 will be 0.4588 for cycle type 1 and 0.4449 for cycle type 2, which results in a total creep damage, of 0.9037. This estimation method is simple but results in a greatly overestimated creep damage. Therefore, one should be careful to define the cycle types and their time durations, which sum to the entire design life time.

Table 2 shows a summary of the structural integrity evaluation results for this example.

5. Parametric Studies Using SIE ASME-NH

All data such as the model and the operating cycle types used in these evaluations are based on the example above.

5.1 Evaluations for the weldment

When assuming that the evaluation points are the part welded with SFA-5.22 E 316T, then the input data corresponding to the command *WELDMENT can be used to evaluate the high temperature structural integrity evaluations. From the evaluation results, the calculated creep ratcheting strain of 0.1544% satisfies the limit value of 0.5% and the fatigue damage is still negligible. However, the creep damage is calculated to be 2.8467 for point 1 and 1.1535 for point 2, which is considerably over the limit value of 1.0. When we compare these results with those of the base metal case, the creep values significantly increase due to the stress rupture factors given in Table I-14.10 of ASME-NH.

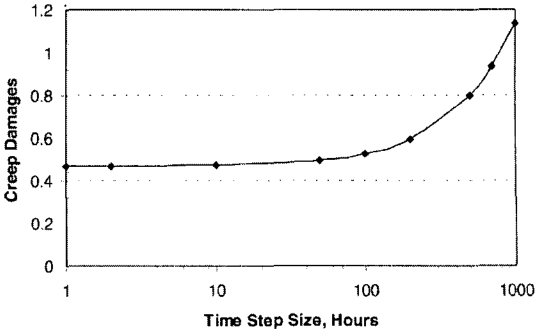

Fig. 14 Time step size effect on a creep calculation

5.2 Effects of the time step size for a creep calculation

In calculating the creep damage from the stress relaxation time history, it is important to select the time step size that will be used to integrate the time fraction. According to ASME-NH, the stress $(S)_k$ and Temperature $(T)_k$ are assumed to be constant during each time interval $(\Delta t)_k$.

Figure 14 shows the effects of the time step size on the creep damage calculation in the previous example. As shown in the result, the calculated creep damage increases from when the time step size is larger than 10 hours. This is due to the assumption that the maximum stress value is constant during the time step size. Especially when considering the transient time of 15 hours, which has higher temperature conditions, a larger time step size may result in very conservative or overestimated creep damage values in this time interval. Therefore, to minimize the conservatism in calculating the creep damage, it is recommended that the time step size should be less than the transient time interval at least.

5.3 Effects of the primary load on a creep damage

Actually the creep damage is primarily invoked by the load-controlled stresses under high temperature conditions. Fig. 15 shows the effects of the load-controlled stresses, which are calculated for a variation of the internal pressure in the example above, on the creep damages by using the ASME-NH rules. As shown in the figure, the creep damages start to increase significantly when the internal pressure reaches a certain level. From

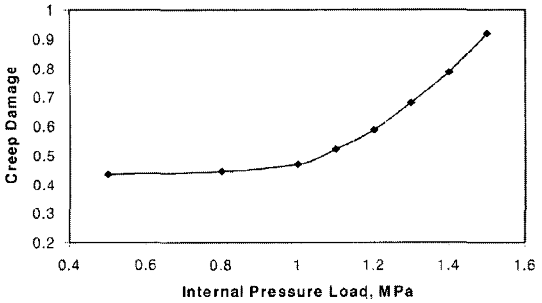

Fig. 15 Primary load effect on a creep damage

these results, we can see that even by slightly increasing the primary loads at a certain level subjected to an elevated temperature it may result in an unexpected severe creep damage rather than any other design factors.

5.4 Number of cycles effects on a creep damage

When there are several kinds of representative cycle types, the enveloped stress relaxation time history can be complicated and the occurrence numbers of the short period transient operations during the longer transient operating cycles can affect the total accumulated creep-fatigue damage. In this investigation, it is assumed that cycle type 1 is a long period transient cycle occurring 10 times and cycle type 2 is a short period transient cycle with varying cycle numbers but the individual operating cycle should sum to the total design life time of 240000 hours. Fig. 16 shows the results of the calculated creep damage versus the numbers of cycle type 2. As shown in the figure, as the numbers of cycle type 2 increase the creep damage becomes larger. This means that a lot of high transient temperature occurrences and an enhancement of the stress level by the following transient cycle types can significantly affect the creep damage.

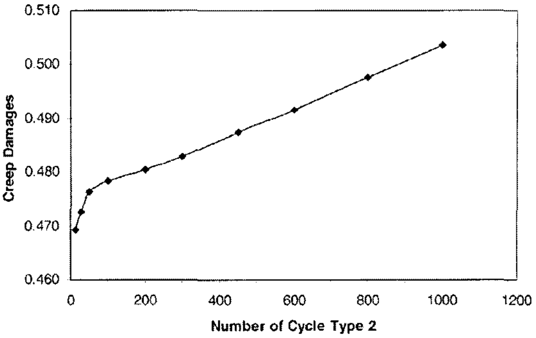

Fig. 16 Effect of the number of cycles on a creep damage

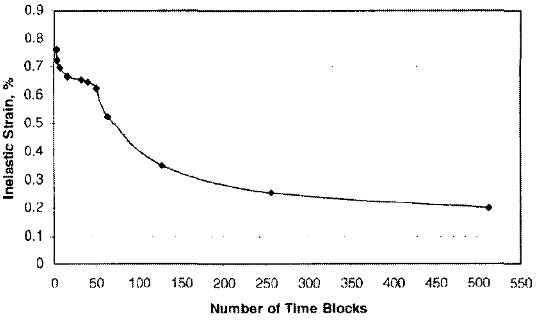

Fig. 17 Load history effect on a creep ratcheting strain

5.5 Load history effects on the creep ratchet strains

To investigate the load history effects on the creep ratchet strain, it is assumed that cycle type 1 and cycle type 2 repeatedly occur with the same time intervals. For an example of the two time blocks, cycle type 1 occurs for 1 cycle with 120000 hours and cycle type 2 with 120000 hours occurs for 1 cycle with the following cycle type 1. Then each time block is summed to the total design service life time of 240000 hours.

Figure 17 shows the results of this evaluation. As shown in the figure, the total accumulated creep ratchet strain decrease as the numbers of time blocks increases. This result provides the rational for the general requirements of the rule T-1331-(b) of the ASME-NH Code where the individual cycles or time blocks defined in the design specification can not be split into sub-cycles.

6. Conclusions

In this paper, an intercomparison of the high temperature structural integrity evaluation codes and assessment procedure is carried out. From this, it is found that all the fundamental concepts are basically similar and based on the ASME-NH rules. SIE ASME-NH program, which contains a computerized implementation of the ASME Pressure Vessels and Piping Code Section III, Subsection NH rules, is developed to be used for the next generation reactor design. From the selected applications and the parametric studies carried out in this paper, the following results are extracted ;

(1) Developed SIE ASME-NH program is very powerful and convenient tool to carry out the high temperature structural integrity evaluations.

(2) Defining the representative cycle types or the temperature-time blocks for a whole design life time is very important for an accurate structural integrity evaluation.

(3) Various metal temperature data required in the ASME-NH rules can significantly affect the results of the structural integrity evaluations.

(4) Stress rupture factors for the weldments significantly affect the creep damage calculations.

(5) Large integration time step size can result in an overestimated creep damage.

(6) When the primary load exceeds a certain level, the creep damage becomes very sensitive to it.

(7) Sequence of the cycle types in a load history is important in calculating the total creep ratcheting strain.

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References

1984, Elevated Temperature Structural Design Guide for Class 1 Components of Prototype Fast Breeder Reactor, PNC N241-84-08, PNC.

1987, 1993, 2002 RCC-MR, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, AFCEN.

2003, Assessment Procedure for the High Temperature Response of Structures, British Energy Generation Ltd.

2004, ASME Boiler and Pressure Vessel Code Section III, Subsection NH, ASME.

ANSYS User's Manual, Volume I and II.

Bree, J., 1967, "Elastic-Plastic Behavior of Thin Tubes Subjected to Internal Pressure and Intermittent High-Heat Fluxes with Application to Fast-Nuclear-Reactor Fuel Elements," *Journal of Strain Analysis*, Vol. 2, pp. 226~238.

Koo, G. H. and Yoo, B., 2000, "Elevated Temperature Design of KALIMER Reactor Internals Accounting for Creep and Stress Rupture Effects," *Journal of the Korean Nuclear Society*, Vol. 32, No. 6, pp. 566~594.

Koo, G. H. and Yoo, B., 2001, "Evaluation of Creep-Fatigue Damage of KALIMER Reactor Internals Using the Elastic Analysis Method in RCC-MR," *Journal of the Korean Nuclear Society*, Vol. 33, No. 6, pp. 566~594.

Koo, G. H. and Lee, J. H., 2006, Computer Program of SIE ASME-NH Code, KAERI/TR-3161/2006, KAERI.

Penny, S. K., 1962, A Fortran Subroutine for Table Generation by Data Interpolation, Oak Ridge national Laboratory, ORNL-3255.

Shah, V. N., Majumdar, S. and Natesan, K., 2003, Review and Assessment of Codes and Procedures for HTGR Components, NUREG/CR-6816, ANL-02/36, Argonne National Laboratory.