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°C 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
\( K_e, K_e' \) : Strain concentration factor
\( K, K_e, K_T \) : Stress concentration factor
\( K_v \) : 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
\( (Q_{el})_{max} \) : The maximum range of the secondary stress intensity

\( S^*, S \) : Stress indicators
\( S_y \) : Averaged yield stress for the max. and the min. temp.

\( S_a \) : \( \text{Min } [1.25S_{(t_{max},10^4}, \text{averaged } S_y] \)
\( t \) : Time

\( T \) : Temperature
\( V \) : Efficiency index
\( X, Y \) : Stress parameters
\( \varepsilon_p \) : Plastic strain
\( \varepsilon_c \) : Creep strain
\( \varepsilon_{EC} \) : Enhanced creep strain
\( \varepsilon_{MR} \) : Ratchet strain (membrane)
\( \varepsilon_{BR} \) : Ratchet strain (bending)
\( \varepsilon_{MEF} \) : Elastic followup strain by long term secondary bending stress (membrane)
\( \varepsilon_{LEF} \) : Elastic followup strain by long term secondary bending stress (bending)
\( \varepsilon_t \) : Total strain range
\( \sigma_b \) : Corrected primary bending stress intensity
\( \sigma_c \) : Effective creep stress
\( \sigma_L \) : Corrected local primary membrane stress intensity
\( \sigma_m \) : Corrected primary membrane stress intensity
\( \Phi \) : 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°C 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 lifetime. 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 assessments, 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