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Division I

CREEP FATIGUE DAMAGE ASSESSMENT OF HIGH TEMPERATURE PIPING IN FAST BREEDER REACTORS-COMPARISON WITH RCC-MR, ASME-NH AND CEGB-R5

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ABSTRACT

This paper discusses the creep fatigue damage assessment of high temperature piping in fast breeder reactors, when assessed according to RCC-MR, ASME Subsection NH and CEGB-R5 procedures (EDF-R5). RCC-MR has specific rules for high temperature piping for insignificant and significant creep for both the primary and secondary stresses, whereas ASME-NH and R5 refer to procedures related to vessels that are to be used for piping. Failure modes considered, failure theories used, creep deformation, creep rupture, creep deformation enhanced by cyclic loading, creep ratcheting (non linear interaction of primary and secondary stresses), combining cycles for fatigue analysis, fatigue strength reduction factors with significant creep effects, creep fatigue interaction and large strains induced by dynamic events such as seismic on subsequent creep response related to high temperature piping have been compared with respect to RCC-MR, ASME-NH and R5 assessment procedures. The effect of creep and fatigue rules in RCC-MR, ASME-NH and R5 assessment procedures, when different materials are used have also been discussed. The advantages and disadvantages of linear damage rule (cycle fraction / time fraction) used in NH with that of the strain fraction used by RCC-MR and R5 has also been discussed. The effect of elastic and inelastic analysis on creep and fatigue life of piping with respect to RCC-MR, ASME-NH and R5 procedures are also discussed.

INTRODUCTION

ASME NH, RCC-MR and CEGB R5 specify rules for the high temperature design of components, but RCC-MR gives specific rules for high temperature design of piping also. ASME NH and R5 have been developed for general high temperature components, whereas RCC-MR has been developed for fast breeder reactor components and piping. This paper compares the high temperature design methods that are available in the above mentioned three codes for piping.

FAILURE MODES AND THEORIES

The failure modes associated with elevated temperature design are based on Section III failure modes and supplemented by time dependent (creep) failure modes, which are but not restricted to ductile rupture from short term loadings, creep rupture from long term loadings, Creep fatigue failure, Gross distortion due to incremental collapse and ratcheting, loss of function due to excessive deformation, buckling due to short term loadings and creep buckling due to long term loadings.

For elastic analysis, ASME NH follows the maximum shear stress theory and for inelastic analysis, multi axial stress strain relationships and associated flow rules are to be used.

CREEP USAGE FRACTION: ΔU_A

For significant creep, RCC-MR uses the creep usage fraction rule both for primary membrane (P_m) and primary membrane and bending ($P_m + P_b$). The creep usage fraction U for the time interval 'j' is equal to the ratio of application time tj to the maximum allowable time Tj. The cumulative creep usage fraction U is the sum for the N intervals of the usage fraction calculated for each interval.

$U = \Sigma_{J=1}N (tj/Tj)$

This is applicable for Level A and C. For Level-D loadings under P-Type loadings creep rupture usage fraction (W) for the primary membrane, and primary membrane and bending stresses should be less than 1.

The same concept is applicable in CEGB R5 where a single value of creep usage fraction 'U' is obtained for each structural feature and it should be shown that

$U \leq 1.$

Creep usage fraction, $U = \Sigma[t_h/t_f (\sigma_{ref}, T_{ref})]j$

t_f – allowable time from SR curves for reference stress σ_{ref} at reference temperature T_{ref}. The time't' for each cycle 'j' may be further subdivided into blocks of steady load, when the loads or temperatures vary slightly with time during continuous operation. The summation should be made over all such blocks for each cycle type.

CREEP ENHANCED BY PROGRESSIVE DEFORMATION (RATCHETTING)

To prevent ratchetting, RCC-MR uses either the 3Sm rule (RB 3661.15) or a rule based on efficiency index (RB 3661.11 to RB 3661.14). It uses the efficiency index method to calculate the effective primary stress intensities, which are again used to calculate the plastic strain and associated creep strain. Initially, secondary ratios are calculated based on thermal, primary membrane and primary membrane and bending stresses, which are as given below:

$SR1 = \Delta Q / Max.(P_m)$

$SR2 = \Delta Q / Max.(P_L + P_b))$

Now entering the efficiency diagram (Figure.1), efficiency indices are calculated based on secondary ratios.

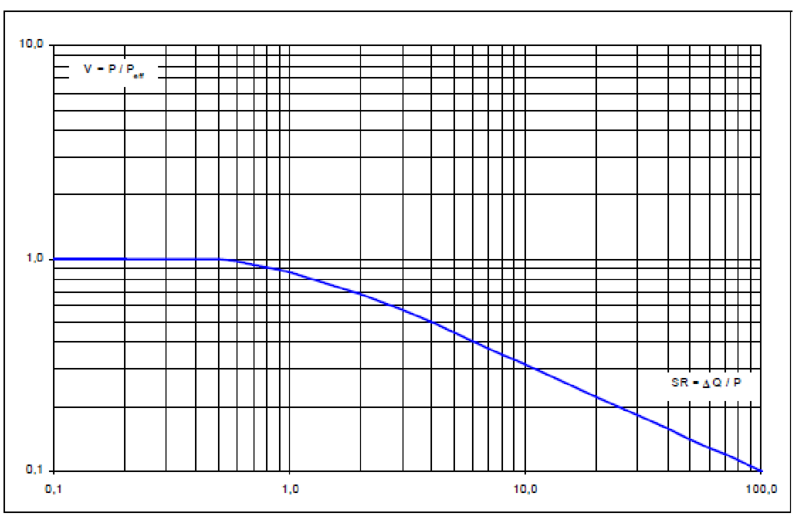

Figure 1. Efficiency diagram

V = 1 for $SR \leq 0.46$

$1.093-0.926SR^2 / (1+SR)^2$ for $0.46 \leq SR \leq 4$

$1/\sqrt{SR}$ for $SR \geq 4$

These efficiency indices are used to calculate effective primary stress intensities.

$P1 = Max. P_m/V1$

$P2 = Max.(P_L + P_b) / V2$

The efficiency diagram has been developed on the basis of experimental data on a large variety of specimen geometry and loading.

ASME NH says that until specific rules are developed for elevated temperature service for piping the rules for components are to be followed. For components, ASME NH uses the O'Donnell and Porowski method based on the Bree diagram (Figure.2). It was intended by Bree to represent the conditions in the wall of a pressurised tube subjected to transient thermal gradients.

Creep deformation can be enhanced because of the non linear interaction of primary and secondary stresses known as enhanced creep. ASME NH gives calculation for enhanced creep strain increment due to stress relaxation.

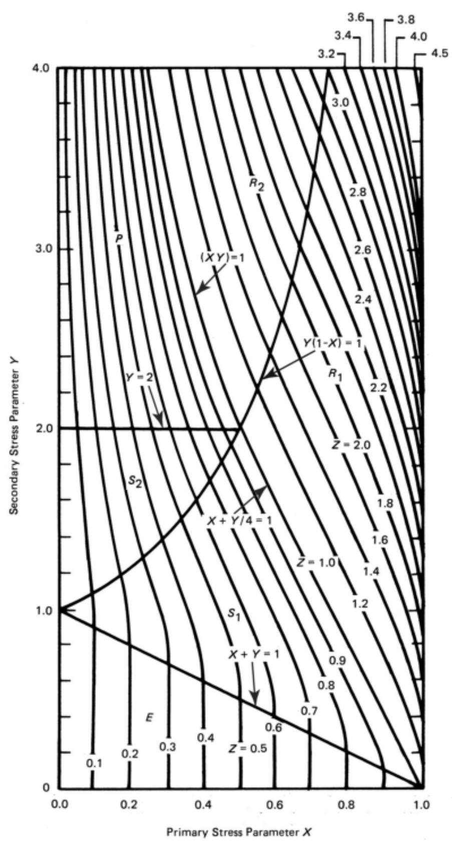

Figure 2. Bree diagram

Bree diagram has an elastic shakedown region, a plasticity region with high thermal gradients & low primary stresses and a region of ratcheting when thermal and mechanical stresses are both high. Creep is controlled by the core stress, z. First, Pm and Q are calculated as fractions of the yield stress, Sy.

$X = Pm/Sy$

$Y = Q/Sy$

The X,Y coordinates are plotted on the Bree diagram and the corresponding value of Z is picked. This value is then used to calculate creep deformation.

Similar to ASME NH, there are no specific rules for piping in R5 approach also. The rules of components are to be followed. The R5 procedure assumes that creep relaxation is slow within a single cycle. The maximum stress will relax toward a stationary state in successive cycles. The creep deformations accumulated will be identical to those for a steady load solution and can be estimated by the conventional reference stress method.

CREEP FATIGUE INTERACTION

RCC-MR uses a creep fatigue interaction diagram (Figure.3) depending on the material being used. Based on the material, fatigue usage fraction and creep rupture usage fraction are calculated. Crack initiation by creep fatigue mechanisms is avoided in R5, ASME and RCC-MR by calculating fatigue usage fraction (V), creep rupture usage fraction (W) and then demonstrating that the points lies within an allowable area in the interaction diagram. The same approach is used in ASME NH.

Both RCC-MR and R5 follow the same methodology as ASME NH except when it comes to computing relaxation stresses. Both recognise that stress relaxation at constant strain is virtual impossibility. They assume that a certain amount of elastic follow up accompanies the relaxation process. RCC-MR and ASME NH offer an elastic route as an alternative to inelastic analysis. R5 permits ductility exhaustion to be used if the material data are available. If appropriate data are not available, a linear damage summation similar to that recommended in ASME NH is used. The R5 procedure does not consider the end of creep fatigue life to be indicative of component failure but merely the initiation of a macroscopic crack. It then assesses the time for the crack to grow to a critical size.

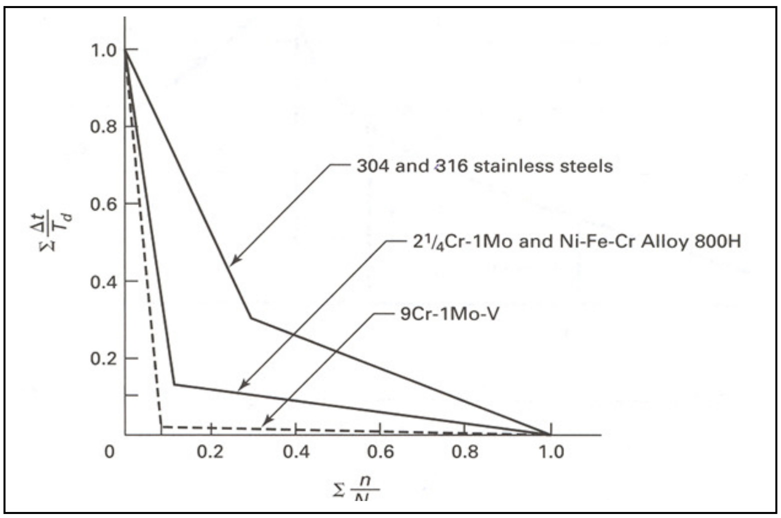

Figure 3. Creep Fatigue interaction diagram

CREEP BUCKLING

ASME NH-T-1522 gives time dependent load controlled buckling factors that are to be multiplied with service loadings to get a load history and to be demonstrated that instability will not occur during the specified lifetime of the component and to protect against load controlled time dependent creep buckling. Rules for buckling under significant creep for components are given in RCC-MR RB 3272. RCC-MR at present does not address creep buckling for piping.

CREEP FATIGUE CRACK GROWTH

ASME NH and RCC-MR does not address creep cracking explicitly which is important for residual life assessment. R5 presents the use of ductility exhaustion as an alternative to the life fraction rule for calculating the creep component of damage. Volume 4/5 and 7 of CEGB R5 provide rules for structural integrity assessment of plant containing defects to be performed under Creep and Creep-Fatigue loadings.

RCC-MR gives creep crack growth curves (Figure.4) expressed as $da/dt=A \cdot (C^*)^q$
with
da/dt – crack growth rate in mm/h
C^* in $(kj/m^2)/h$ or (N/mm)/h
A and q – value of coefficients (experimentally determined material constants).

The same equation is given in R5 for creep crack growth assessment.

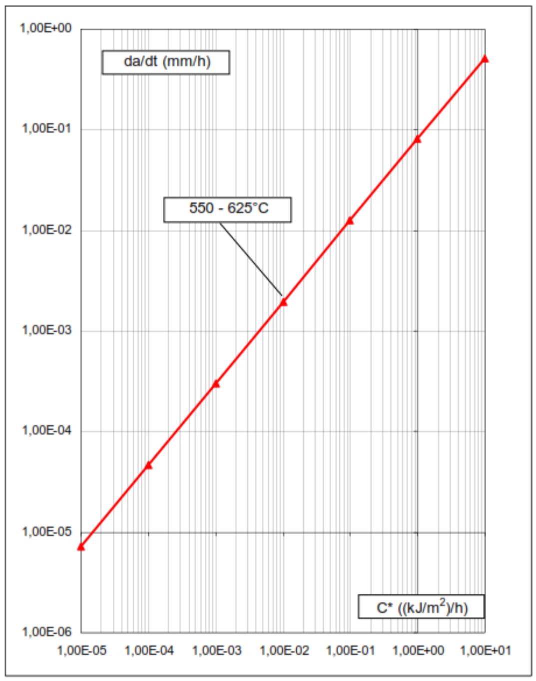

Figure 4. Creep crack growth law

EFFECT OF CREEP AND FATIGUE ON DIFFERENT MATERIALS

In ASME NH, isochronous curves are used for the calculation of total strain range and creep damage. The isochronous stress-strain curves are used to obtain the creep ratcheting strain. The total service life is divided into temperature time blocks. The creep strain increment for each block is evaluated separately. The times used in selecting the isochronous curves shall sum to the total service life. The creep strain increments for each time-temperature block shall be added to obtain the total ratcheting creep strain. The resulting value shall be limited to 1% for parent metal and ½% for weld metal.

In RCC-MR, creep laws are used for the calculation of total strain range and creep damage. RCC-MR takes into account effects of irradiation on materials, whereas ASME NH or R5 does not take into account the irradiation effect on materials.

The creep fatigue interaction diagram in Figure shows creep fatigue interaction for different materials like SS 316, 2 1/4 Cr 1 Mo and 9Cr 1 Mo V steels. It can be inferred from this figure that creep and fatigue damage allowable are more for SS316 and less for 9Cr 1Mo V steel.

INELASTIC ANALYSIS ON CREEP AND FATIGUE

ASME NH recommends using appropriate multi axial stress-strain relationship and associated flow rules to combine multi axial stresses and strains. Linearly elastic analysis methods may significantly underestimate the actual strain range incurred during plastic or creep deformation. ASME NH suggests methods to account for these increased strain ranges due to inelastic behaviour in the region under consideration.

RCC-MR Appendix 11 deals with the inelastic analysis with creep. However, for piping the details of inelastic analysis under significant creep are not given in RCC-MR.

FATIGUE STRENGTH REDUCTION FACTOR WITH SIGNIFICANT CREEP EFFECT

Fatigue strength reduction factor accounts for the effect of a local structural discontinuity (e.g. weld joint) on the fatigue strength. At present, ASME NH gives factors only for cycles that do not involve significant creep effects. RCC-MR multiplies a fatigue strength reduction factor which depends on the type of joint to calculate the stress range for both negligible creep and significant creep. The fatigue curve of the welded joint is given in Appendix-9 of RCC-MR. Different fatigue strength reduction factors are given based on volumetric or surface examinations.
ASME NH does not address crack growth under creep and creep fatigue interaction.

CREEP DEFORMATION ENHANCED BY CYCLIC LOADING

A material is subjected to deformation variations when the loading applied to a structure evolves with time, in particular in a cyclic fashion. If these variations are numerous and are of large amplitude they can cause cracking. When the temperature is sufficiently high, creep deformation occurs during each cycle thus accelerating the appearance of cracking. RCC-MR provides methods to calculate real deformation range by evaluating the strain amplification due to plasticity and creep.

CONCLUSION

ASME NH and CEGB R5 do not give specific rules for piping for elevated temperature design. They allow the rules of components to be followed for elevated temperature design of piping. RCC-MR having specific rules for elevated temperature design is the only choice if piping is to designed for creep and fatigue. It is expected that ASME comes with specific rules for piping in its later edition, when subsection NH is merged with Section III Division 5 – High temperature reactors.

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