Crack Instability for LBB at High Temperature Condition

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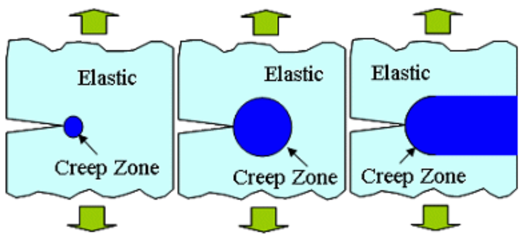
1. Introduction

The high temperature leak before break (LBB) approach is supposed to be applied to the design of KALIMER-600[1]. While the assessment of a crack instability is a essential element for an LBB application, solid methods for evaluation of a crack instability at high temperature condition are yet to be established even though it is well provided for in a PWR application[2-3]. In this study, US BS7910[4], UK R5/R6[5], and French RCC-MR A16[6] were examined and a tentative procedure was presented for an LBB application to sodium cooled fast reactor KALIMER-600.

2. Evaluation of Instability

At a low temperature operation where a creep deformation is not credible, it is enough to consider elastic fracture mechanics or elasto-plastic fracture mechanics to judge a crack instability and methodologies using such as tearing modulus and J-resistance are well established. When a crack grows to a certain size which is called as a critical crack size, a crack instability occurs to generate a abrupt structural failure. However, at a high temperature, this is not enough to judge an instability. As shown in Figure 1, a small scale creep zone is generated near a crack front due to a stress concentration and a creep zone grows to a steady state creep zone through a transient stage. Further, a creep crack growth needs to be combined with a fatigue crack growth at a high temperature condition. Therefore, two cases need to be considered for a fracture condition. The first case is a crack front instability and the second is the remaining ligament creep rupture.

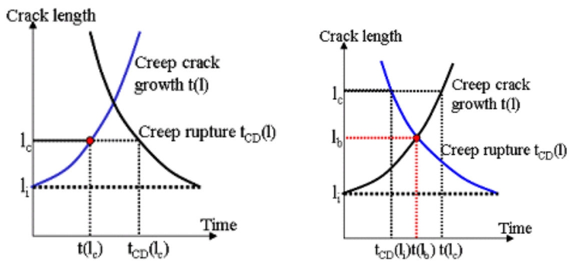


Small scale creep   Transient   Steady state creep

Figure 1. Crack growth phenomena at high temperature

French RCC-MR A16 presents the crack instability assessment methodologies as either the J_{sin} method at a negligible creep temperature or a creep usage fraction method for the remaining ligament at an appreciable creep temperature. BS7910 proposed a similar concept for a ligament creep rupture but with different details.

Figure 2(a) shows a case where a crack grows to a critical size (l_c) before the remaining ligament creep rupture and Figure 2(b) shows a case where the remaining ligament creep rupture occurs before the crack front instability. In this study, a tentative procedure is presented by combining the above two cases based upon French and UK methods. That is, one needs to evaluate both a crack front instability and the remaining ligament creep rupture condition and then choose the precedence condition. Finally, the corresponding crack size can be considered as a critical crack size for an LBB application.



(a) Instable growth   (b) Ligament creep rupture

Figure 2. Crack instability conditions at high temperature

2.1 Instability of crack front

Next certain conditions should be satisfied to avoid a crack front instability at the negligible creep condition.

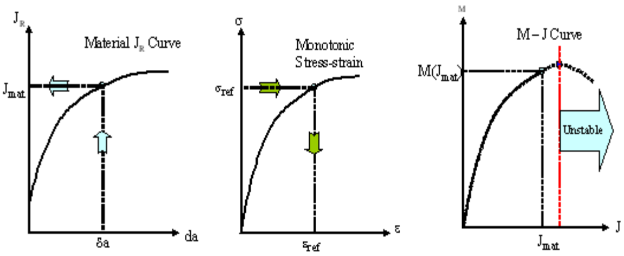
- Service condition A, B : $C_A \leq C_{Ainst}$
- Service condition C : $C_C \leq C_{Cinst}$
- Service condition D : $C_D \leq C_{Dinst}$

where C_A, C_C, and C_D are specified loadings for an instability analysis of crack at service conditions A, C, and D, respectively. And C_{Ainst}, C_{Cinst}, and C_{Dinst} are loadings producing a crack instability under a loading proportional to C_A, C_C, and C_D, respectively. To determine a loading (C_{inst}) yielding crack instability by considering material properties, the geometry of the structure including a crack, and loading condition, J_{sin} method utilizing J_R-da curve shall be applied as follows.

-Determine initial crack size a_o, $2c_o$.
-Obtain $J_R(da)$ corresponding to the increment da of initial crack (a_o) as shown in Figure 3(a).
-Calculate stress intensity factor (K_I).
-Calcualte reference stress (σ_{ref}) and obtain the corresponding reference strain (ε_{ref}) as shown in Figure 3(b).
-Determine J_{el} using stress intensity factor (K_I).
-Calculate J using next equation and record loading (F or M) when J_s=J_R.

$$J_s = \left[\frac{\sigma_{ref}^2}{2(\sigma_{ref}^2 + \sigma_y^2)} + \frac{E\varepsilon_{ref}}{\sigma_{ref}} \right] \left(\frac{K_I^2}{E^*} \right) \quad \textit{for mechnical load}$$

- Renew *da* and draw a loading-fracture toughness diagram repeating the above procedures as shown in Figure 3(c).
- Instable growth will occur when loading *M* and fracture toughness J_{mat} reaches their maximum value.



(a) Fracture toughness (b) Reference strain (c) Instability
Figure 3. Instability assessment using J_{sin} methods

2.2 Instability due to ligament creep rupture

At a high temperature condition for service levels A, B, C, and D where a creep plays important role, the failure requirement by primary stresses in the ligament excluding crack should be satisfied to avoid an abrupt creep rupture. The creep usage fraction and the creep rupture usage fraction in the remaining ligament calculated from the stress analysis are to be determined as follows for this evaluation.

The creep usage fraction (*U*) indicates the level of damage due to a creep deformation as defined by

$$U = \sum_{j=1}^{N} \frac{t_j}{T_j}$$

where *N* indicates the number of loading time segment, t_j indicates the hold time for the j^{th} loading segment, and T_j indicates the time to reach allowable stress (S_t). If the total creep usage fraction (*U*) for *N* segments becomes 1, one can conclude that the damage is generated to an extent that it yields the allowable stress intensity. The condition to determine the allowable stress intensity (S_t) is to select the minimum value among 2/3 of a creep rupture stress, 80% of a stress to induce tertiary creep, and the stress inducing a total strain of 1% which is determined from the isochronous curve. If the stress inducing a total strain of 1% is the lowest value and the creep usage fraction becomes 1, one can judge that the total inelastic strain for a structure reaches 1%.

The creep rupture usage fraction (*W*) shows the time fraction to a creep rupture of a structure as defined

$$W = \sum_{k=1} \frac{t_k}{T_k}$$

where t_k indicates time for the k^{th} segment and T_k indicates the corresponding creep rupture time determined from the material creep rupture stress (S_r) curve. When the value of *W* becomes 1, one can consider that the creep rupture failure occurred.

If the creep usage fraction *U* becomes larger than 1 for service conditions A, B, and C, an instability occurs and all the loadings should satisfy following condition.

- For primary membrane stresses,

$$U_{A,B,C}(\Omega \bar{P}_m) \le 1$$

where *Ω* is the correction factor.

- For primary membrane stress and bending stress,

$$U_{A,B,C}(\overline{P_L + \Phi P_b}) \le 1$$

where *Φ* is a factor depending upon the geometry of the cross section.

Under service condition D, an instability occurs if the value of *W* becomes larger than 1 and the next conditions should be satisfied to avoid an instability.

- For primary membrane stresses,

$$W_{A,B,C,D}(1.35\Omega \bar{P}_m) \le 1.$$

- For primary membrane stress and bending stress,

$$W_{A,B,C,D}(1.35(\overline{P_L + \Phi P_b})) \le 1.$$

3. Conclusion

Both a detectable crack size and a critical crack size are influenced by a creep condition and become smaller as the hold time becomes longer. To achieve an LBB applicability at a high temperature, a crack should be larger than the detectable crack size and smaller than a critical crack size. In this study, a tentative procedure is presented to determine a critical crack size by considering both a crack front instability and the remaining ligament creep rupture. This procedure can be implemented to an LBB application at a high temperature condition. The evaluation of the crack instability and LBB application for IHTS piping of KALIMER-600 is in progress.

ACKNOWLEDGMENT

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