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Crack arrest prediction in reactor pressure vessel under PTS

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ABSTRACT: Pressurized thermal shock may cause extension of small cracks existing in the reactor pressure vessel. A study is performed to predict the growth of crack with time and the arrest of crack due to temperature transient in a pressurized cylinder. The paper deals with the finite element modelling, the crack growth and arrest methodology. The predicted crack extension is compared with observed.

1 INTRODUCTION

The emergency core cooling system injection is one of the most severe load cases to be analyzed in the integretity assessment of Reactor Pressure Vessels (RPV). As a result of severe pressure temperature shock (PTS), the large tensile stresses at the inside wall may lead to the rapid crack extension at the reactor belt line region where irradiation embrittlement is severe. Fortunately, crack may arrest after penetrating into hot region due to increased toughness and reduced stress level. The crack growth and arrest predictions require reliable material properties in irradiated conditions, which may be difficult and time consuming to obtain. Moreover, the scatter in the experimental data forces one to use the lower bound or reference properties. Further, the elasto-plastic calculations using 3-D finite element models is very expensive. Therefore, a fracture mechanics study for a cylindrical pressure vessel with axial surface crack was planned to assess the effect of various uncertainties. The finite element thermoelastic procedure with reference fracture toughness recommended by ASME section III is adopted to assess the methodology. The crack growth and arrest results are compared with observed ones.

2 GEOMETRY, LOADING AND MODELLING

The cylinder with circumferential weld at midlength contains one axial elliptical surface crack at outer surface (Fig.1). The crack length and depth considered is

350 mm and 38 mm respectively (Keinanen 1993). The internal pressure transient and sudden thermal shock from outside is the loading considered in the analysis. The geometry of the vessel with axial surface crack and loading permits exploitation of symmetry and half of the vessel is used for three dimensional modelling. The mixture of eight noded and twenty noded solid elements are used for economy. At interface multi point constraints are used. Singularity elements are used at crack tip. Fine mesh with twenty noded elements is used in the crack neighbourhood to capture the steep stress gradient. The model is shown in figure 2. Excepting the regions constrained by free surface and weld boundary, the orthogonality of element edges was maintained with reasonable accuracy.

3 CRACK GROWTH AND ARREST PREDICTIONS

The finite element computer package (ABAQUS) is used for computations. The transient linear elastic solution is computed based on load history. Initial analysis is carried out without allowing the crack growth. For predicting the crack propogation and arrest, a methodology is developed in the frame work of finite element model as follows.

The three dimensional model with moving mesh technique is employed. A computer program is developed for moving the mesh as required. The transient stress intensity factor (SIF) distribution along the crack front is computed. When SIF (K1) becomes more than K1c (fracture toughness), the crack growth or extension will occur and crack arrest will depend on K1a (material arrest toughness). The initiation fracture toughness data corresponding to 95 percent confidence level is used. In the absence of reliable data, the lower bound crack arrest toughness data is assumed as reference data recommended by ASME (PVRC).

$$K1a = 27.018 + 1.234\mathrm{Exp}\{0.0145\ [T - (Tnd - 71.1)]\} \qquad (1)$$

Where Tnd = Nil ductility temperature in degree centigrade
= 64 deg C for weld and 159 deg C for base metal
K1a = Material toughness in MPa(m**0.5)

The equation (1) is useful for many pressure vessel steels. When K1 exceeds K1c, the crack growth along the crack front is estimated based on K1c and K1a. Accordignly, the crack front is shifted and mesh is modified. Analysis is repeated and new SIF (K1) along the crack front is computed and compared with K1a. The crack growth is recalculated and supplied to the model. The procedure is repeated till the computed K1 along the crack front is almost equal to K1c. The crack growth and arrest analysis is repeated at next time step.

The comparision of computed crack mouth opening displacement (CMOD) with experimentally measured (Torronen 1993) is presented in figure 3. The agreement seems to be satisfactory. The experiment curve shows rapid growth while computed growth is gradual up to 160 seconds. As the crack arrest values used are lower bound, crack growth is slightly overestimated. While the CMOD without considering crack growth is lower bound.

Due to high K1c for weld material, no crack growth occurs in weld region up to 160 seconds. The crack grows only in base material. Due to the absence of growth in weld, stresses, SIF and triaxility shows peak values in weld zone at 150-160 seconds while in base material these parameters exhibit relaxation due to crack growth (figure 4 to 7). The triaxility distributionn in the ligament shows the extent to which the stress distribution approximates to plane stress or plane strain state. Triaxility should reduce as the end of crack is approached near free surface while it must peak at centre as plane strain stress distribution. The triaxility shows near plane strain value 2.16 up to t=60 seconds and a large increase around t=150 seconds for weld locaiton B.

The J-integral history at location A,B and C is shown in figure 8. J-integral value rise in weld zone when crack growth is allowed. This is caused by growth only in base meterial. The SIF distribution along the crack is shown in figure 9. Peaking of SIF at weld region can be seen. Figure 10 shows the SIF variation with crack tip temperature.

It is observed that crack growth initiates near free surface and gradually spreads along the crack front, up to weld material boundary. The extension history of crack front shown in figure 11 compares well with the observed one (Keinanen 1993).

4 CONCLUDING REMARKS

The crack growth and arrest has been computed for a circumferentially welded cylinder with axial outer surface crack due to pressurized thermal shock. The methodology is developed to predict the crack initiation and its arrest. The crack growth predictions are satisfactory as compared with published results. The lower bound crack arrest toughness data given by ASME slightly overestimate the crack mouth opening displacement.

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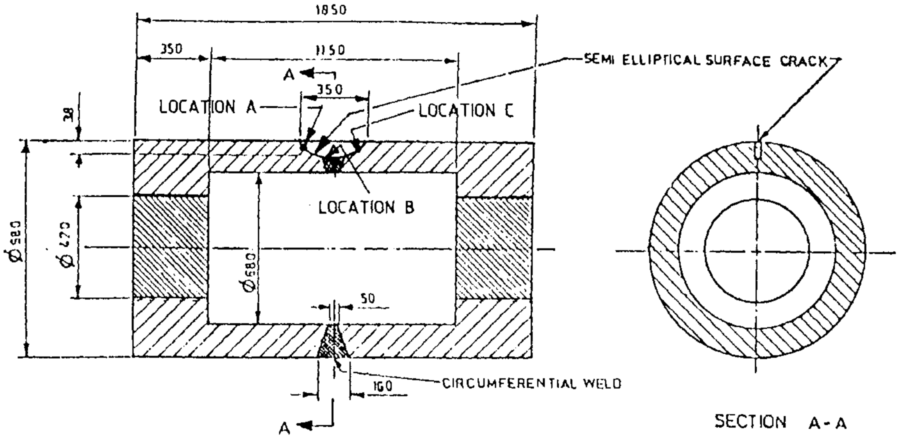

Fig. 1 Geometry of welded cylinder with axial surface crack.

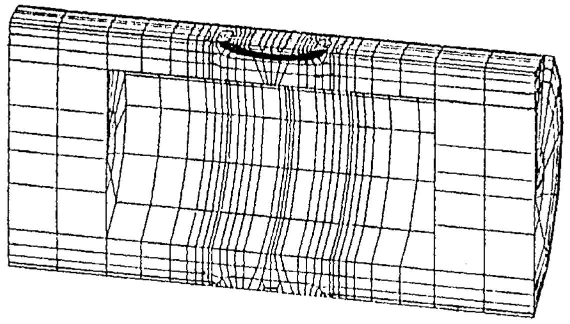

Fig. 2 Finite element model of cylinder with surface crack.

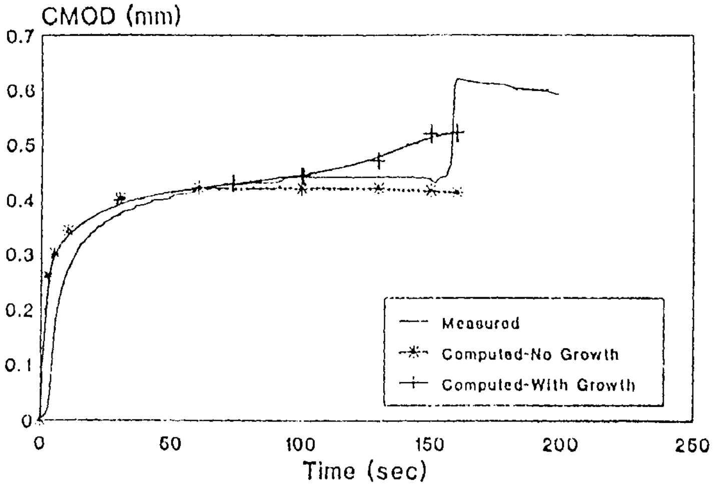

Fig. 3 Crack mouth Opening Displacement.

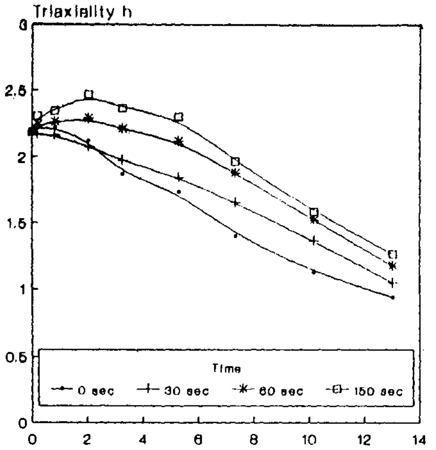

Fig. 4 Triaxiality at Location A
(Without Growth)

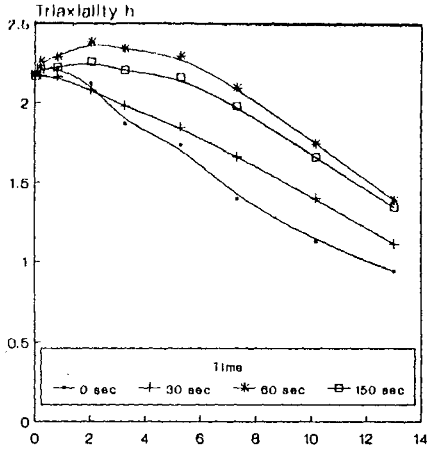

Fig. 5 Triaxiality at Location A
(With Growth)

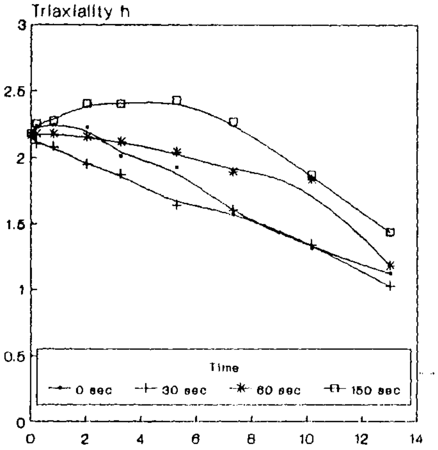

Fig. 6 Triaxiality at Location B
(Without Growth)

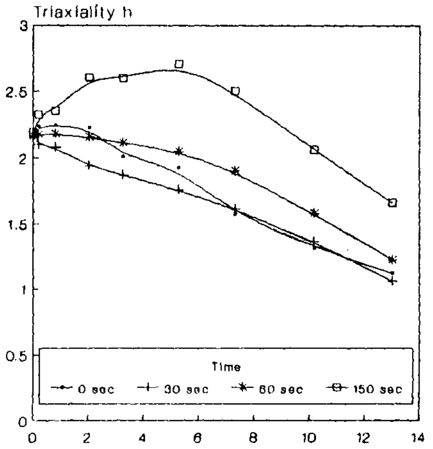

Fig. 7 Triaxiality at Location B
(With Growth)

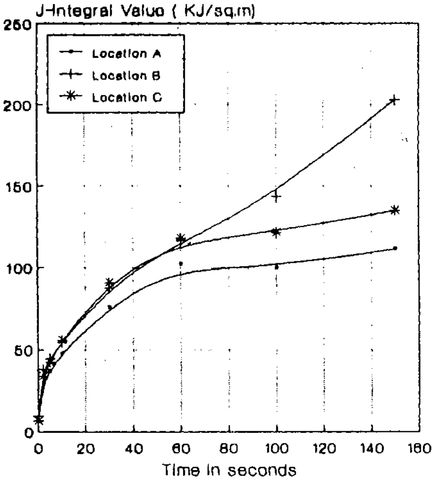

Fig. 8 J-Integral (With Crack Growth)

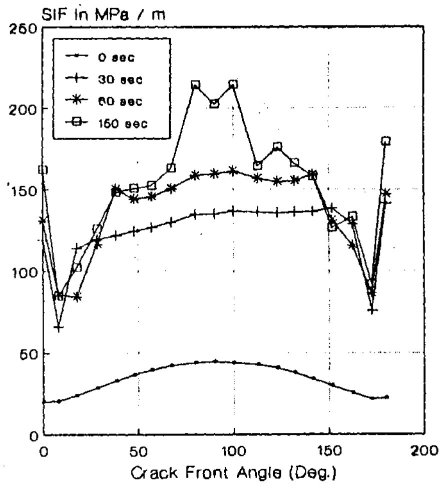

Fig. 9 SIF Distribution (With Growth)

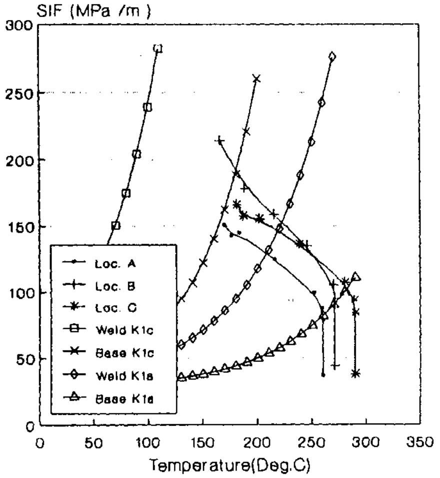

Fig. 10 SIF vs Crack tip temperature
and fracture toughness

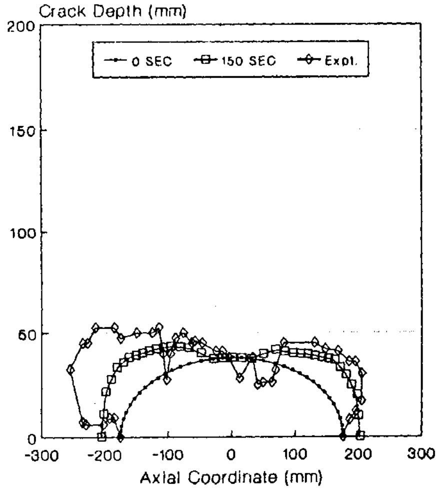

Fig. 11 Crack Growth History