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Numerical simulation of crack behaviour under PTS based on experimental observation

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ABSTRACT: In recent years, pressurised thermal shock accidents have attracted the attention of fracture mechanics researchers to investigate presence of flaws in the pressure vessels. The research work is being done in both the aspects, numerical investigation as well as experimental simulations. Large scale experiments on components with flaws under PTS loading is recently reported in literature. The present work is carried out to numerically investigate crack growth and crack arrest behaviour under PTS loading.

A thermo-elastic-plastic analysis is performed using in-house computer codes based on finite element technique. The computed parameters are compared with the measured values and/ or other published results. The crack propagation and crack arrest phenomena is shown on Failure Assessment Diagram and integrity of the component is assessed.

1 INTRODUCTION

The integrity of the components subjected to pressurised thermal shock (PTS) loading is a major issue before the plant designers. In nuclear plants, chemical process industries and aerospace applications, structures may be subjected to severe mechanical and thermal transients under emergency conditions. Assessment of the integrity of the components in the presence of a flaw is of great importance from safety point of view under such scenario.

To investigate the crack growth and crack arrest behaviour of materials, large scale experiments were conducted on components under PTS loading (Bass 1991; Stumpfrock 1993). One of the experiments conducted by Stumpfrock et al, at MPA Stuttgart, Germany, under the project designated NKS-6, consisted of a thick cylinder with circumferential prefatigued crack under PTS loading. The specimens showed both cleavage and stable crack growth during the thermal transient.

In this present paper, efforts have been made to numerically simulate the crack growth and arrest phenomena using finite element method. The structural integrity is evaluated using failure assessment diagram (FAD).

2 BRIEF DESCRIPTION OF NKS6 EXPERIMENT

The test set up consisted of a thick walled hollow cylinder (D_i= 400mm, t= 200 mm), welded to the grip of a tensile testing machine. The cylinder, made up of three different materials, has a prefatigued crack at the inner surface. The low toughness material 17 MoV 84 is backed up by a high toughness material S3 NiMo 1. The cylinder is subjected to a constant axial pull of 25 MN and pressurised internally. The cylinder is initially heated by an external heater. Thermal shock is applied by spraying cold water on the inside surface. The test set up, material properties are provided in literature (Stumpfrock 1993). The crack growth, crack mouth opening displacement (CMOD) and strain away from the crack plane are the parameters recorded during the transient. Table I provides the observed crack growth with time.

Table I: Observed crack growth Data

Initial crack length (a)= 34 mm. At 35-th sec. crack jumps to 54 mm and remains standstill for next 17 sec.

Time(s)	a (mm)	Time(s)	a (mm)	Time(s)	a (mm)
52	54	62	74	72	91
54	58	64	78	74	93
56	62	66	82	76	95
58	66	68	86		
60	70	70	89		

3 CODE DETAILS

The analysis has been performed using in-house computer codes WELTEM (Dutta 1981) and THESIS (Dutta 1983). The WELTEM is a code for computing temperature transients based on finite element formulations. The code is capable of considering nonlinear material properties, constant temperature/ convective/ radiative boundary conditions and phase change. The temperature transient equations are solved using explicit or implicit solution procedure. The THESIS is a 2-D/ axisymmetric finite element code for thermal-elastic-plastic analysis. This code is capable of considering material properties as a function of temperature, hardening/ nonhardening materials, material creep etc. The code can compute SIF at the crack tip using displacement extrapolation method/ crack-closure integral/ J-integral method. Accurate pointwise values of energy release rate J(s) along a crack front is obtained using domain integral technique developed by Shih et al (1986). For a 2-D structure with a crack, the formulation of energy release rate is expressed by the following equation.

$$J= \int_A [(\sigma_{ij}\, u_{j,1} - W\, \delta_{1i})\, q_{1,i} + (\alpha\, \sigma_{ii}\, \theta_{,1} - f_i u_{i,1})\, q_1]\, dA - \int_{c^+ + c^-} t_i\, u_{i,1}\, q_1\, dC \quad .....(1)$$

Here, f_i is the body force per unit volume, t_i is the traction on the crack faces, u and σ denote displacement and stress. The function q_1 within an element is expressed by the eqn.,

$$q_1 = \sum_{I=1}^{nnode} N_I \, Q_{1I} \qquad .....(2)$$

where Q_{1I} are the nodal values of the I-th node, N denotes the shape function and 'nnode' denotes total number of nodes. The finite element formulation can be derived for 2-D and axisymmetric structures (Shih 1986).

A new type of q_1 function is developed in the present work which is a combination of pyramid and plateau functions. This function is equal to 1 at the crack tip and at the edge of the first ring surrounding the crack tip. This function is equal to 0 on the edge of the domain and varies linearly between the inner most edge surrounding the crack tip and the outer most ring. It is felt that this new function has advantages of both the pyramid and the plateau functions. The code THESIS has been modified to compute the J-integral using the above equations. Further calculations are performed using the q_1 function.

4 NUMERICAL INVESTIGATION

A nonlinear transient thermal analysis is performed for the experiment NKS6 to find out the temperature transient during the cooling using the code WELTEM. The transient temperature distribution is shown in Fig.1. A thermo-elastic-plastic analysis is carried out using the code THESIS. The crack growth is simulated based on data given in Table-I. The computed CMOD is plotted along with the measured CMOD in Fig.2. The computed SIF with crack tip temperature is plotted in Fig.3.

A number of methods are available for assessing the integrity of structures containing flaws. One such method is R-6 method for establishing the integrity of a structure with defects (Milne 1988). The limiting condition for a structure in R-6 method is evaluated by using fracture load and plastic collapse load. Structural integrity in relation to these two limiting conditions is evaluated by means of a Failure Assessment Diagram (FAD). The crack propagation and arrest phenomena as observed during the experiment is plotted on FAD. The FAD is drawn using Option I and Option II (Milne 1988). The collapse load is calculated on the basis of the collapse of the remaining ligament. Ligament is assumed to collapse when the induced stress exceeds the flow stress. The thermal load is converted into equivalent primary load (Shih 1986) and added with the primary mechanical load to compute the total applied load on the structure. The crack propagation and crack arrest on the FAD is shown in Fig.4. The factor of safety with time in stable and unstable crack propagation based on FAD is shown in Fig.5.

5 DISCUSSION AND CONCLUSIONS

The computed temperature transients along the wall thickness have excellent agreement with the measured temperature values (Stumpfrock

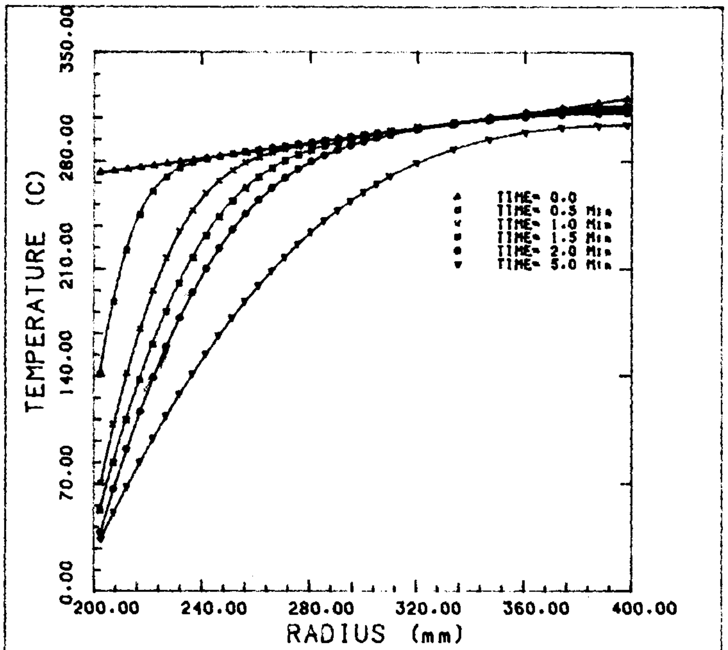

FIG.1 TRANSIENT TEMPERATURE VARIATION WITH TIME

1993). The good agreement of the computed CMOD with the measured value shows that numerically crack growth can be simulated using gradual release of nodes. During cleavage event there is a sharp drop in SIF due to decrease in thermal load. During stable crack growth, the SIF is nearly constant. The increase in SIF due to crack extension is neutralised by reduction in thermal load.

Fig.4 shows that the cleavage occurred before the assessment point reached the FAD boundary. The steady state crack propagation is not found to initiate immediately after the point reached the assessment line. It is rather found to start beyond the boundary of FAD. During the entire stable crack propagation period the assessment points are outside the area on FAD. After the stable propagation is over, the assessment point is again within the FAD concluding the arrest of the crack at the outer tough material. It is observed that crack propagation occurs within a factor of safety of ± 0.1. This zone may be treated as an uncertain zone on R-6 plane for the present experiment and crack propagation/ arrest is expected at any point in this zone. It is also observed that both the Options produce identical results as the applied maximum L_r value is low.

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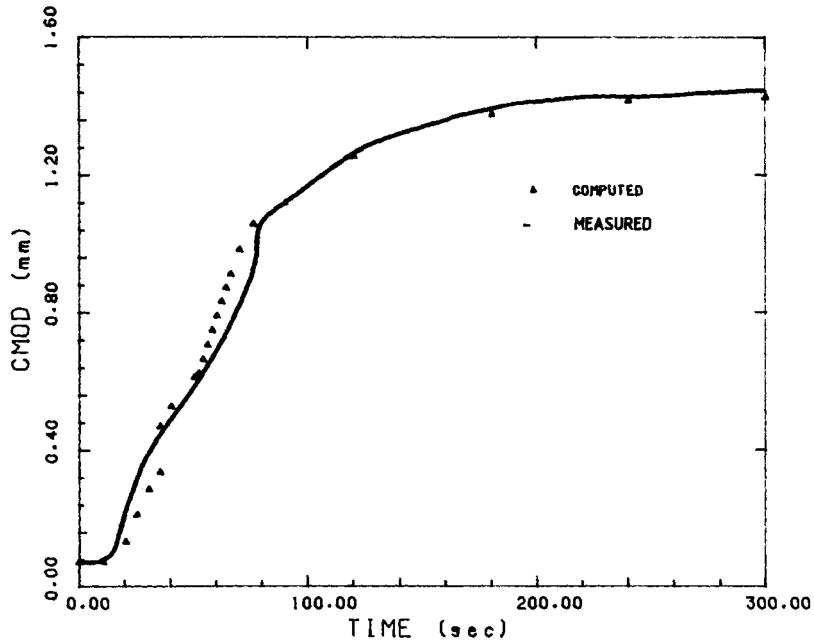

FIG.2 COMPARISION OF COMPUTED & MEASURED CRACK MOUTH OPENING DISPLACEMENT

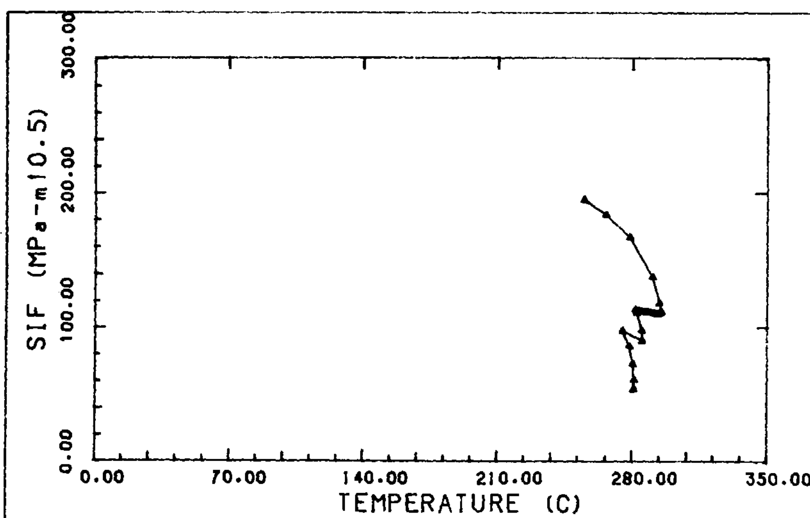

FIG.3 STRESS INTENSITY FACTOR VARIATION WITH CRACK TIP TEMPERATURE

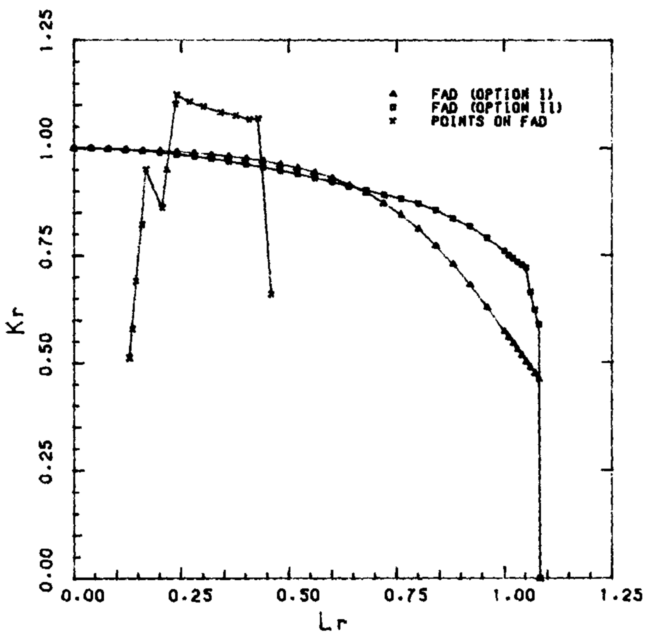

FIG.4 CRACK PROPAGATION & CRACK ARREST ON FRACTURE ASSESSMENT DIAGRAM

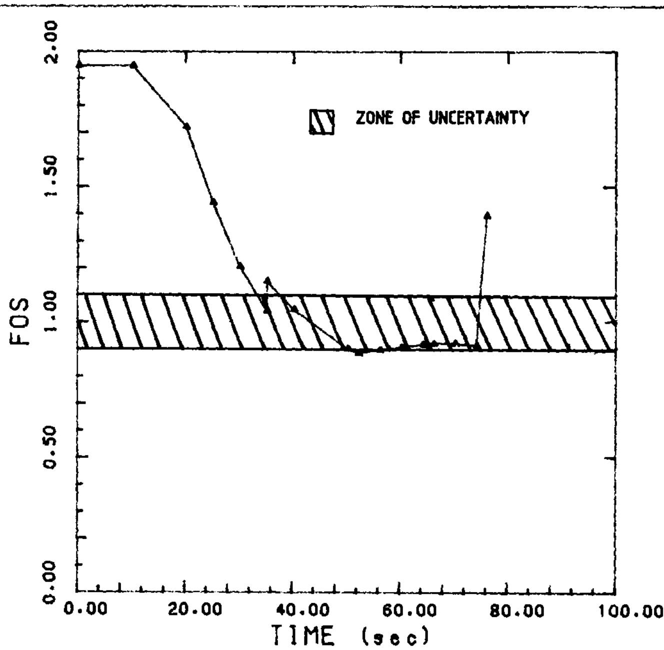

FIG.5 FACTOR OF SAFETY IN STABLE & UNSTABLE CRACK PROPAGATION BASED ON FAD