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Fracture analysis of through-wall longitudinal cracks in thin walled tubes

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ABSTRACT: This paper is concerned with the determination of elastic and elastic-plastic crack driving forces created by postulated axial flaws of different lengths in the thin internally pressurised pressure tubes of Indian Pressurised Heavy Water Reactors,using 3-D finite element techniques.The pressure exerted by the escaping fluid on to the crack faces has been included in the analyses.The Critical Crack Length required to create an unstable condition for the operating conditions of the reactor has been evaluated.The effect of irradiation on the pressure tube material has not been considered.The analysis is,therefore,valid only for a fresh tube.

1 INTRODUCTION

Indian Pressurised Heavy Water Reactors(PHWR's) are pressure tube type reactors.These reactors use natural uranium as fuel and heavy water as a coolant and moderator.The pressure tubes(PT's)house the reactor fuel and direct the flow of the coolant.They are surrounded by a concentric Calendria tube and the annulus between the two tubes is maintained by garter springs. The pressure tubes are made of Zirconium alloys because of their low thermal neutron capture cross-section.Most of the Indian PHWR's have pressure tubes of Zircalloy-2.Some recent reactors have pressure tubes made of Zr-2.5% Nb.

In the present work,3-D Finite Element Techniques have been employed to determine the elastic and elastic-plastic Crack Driving Forces(CDF's) created by the presence of postulated axial through-wall flaws in thin walled internally pressurised pressure tubes.The escaping fluid exerts a pressure on the crack faces.The effect of the crack face pressure on the CDF values has been brought out.The 3-D finite element results have been compared with analytical solutions from the literature and the limitations of these closed form equations have been brought out.

Based on these studies,the Critical Crack Length (CCL) required to generate an unstable condition umder the design pressure and temperature have been determined. Knowledge of the CCL will help in a safe and orderly shutdown of a reactor ,when a leak is detected.

2 THE GEOMETRY AND LOADING

A pressure tube of an Indian 220MW(e) PHWR is 83mm in diameter and has a wall thickness of 4 mm. It operates at 573 degree K with a coolant pressure of 9.5 MPa. The pressure tube is made of Zr-2. The young's modulus of the tube material is 78.8 GPa and the flow stress is 400 Mpa. The poissons's ratio of Zr-2 is 0.43 (Anantharaman et.al, 1994).

The effect of irradiation and material degradation due to hydriding has not been considered. The analysis is therefore valid for a fresh tube only. The CCL for an irradiated tube will thus be smaller compared to an unirradiated and fresh tube.

3 FRACTURE PARAMETERS BY ANALYTICAL FORMULAE

Various formulae are available in the literature to compute the elastic and elastic-plastic crack driving forces for a thin internally pressurised cylinder with a through-wall axial flaw. A compilation of these formulae is given in Zahoor's handbook (1989)

a) The linear elastic stress intensity factor KI is found from

$$KI = M \sigma \sqrt{\pi c}$$

where

$M = (1+7.2449E\text{-}2\lambda + 0.64856\lambda^2 - 0.2327\lambda^3 + 3.815E\text{-}2\lambda^4 - 2.3487E\text{-}3\lambda^5)$
σ = p*R/t (Hoop stress)
R = mean radius of the cylinder
c = crack half length.
$\lambda = c/\sqrt{Rt}$
t = thickness of the tube.
p = internal pressure

b) The elastic-plastic J-Integral is found from the formula

$$J = [8c\sigma_f^2 \ln\{\sec(M\pi\sigma/2\sigma_f\}] / \pi E$$

where

$M = [1+1.29987\lambda^2 - 0.026905\lambda^4 + 5.3549E\text{-}4\lambda^6]$
σ = p*R/t
E = young's modulus
σ_f = flow stress.

The above formula is valid for $0 < \lambda \geq 5$ and $\sigma < \sigma_f/M$

Similar Formulae have also been given by Folias (1969). However these formulae ignore the pressure force exerted by the leaking fluid onto the crack faces.

4.FINITE ELEMENT ANALYSIS

The finite element computer code 'ABAQUS' was used for the analysis.A 3-D finite element mesh of the cylindrical tube was made as shown in Fig.1.20 noded quarter-point elements with reduced integration option have been employed in the analysis.Only one element across the thickness has been used.To simulate the axial stress induced by the pressure acting on the closed ends of the tube,an equivalent end pressure load was applied,along with the internal pressure.

The J-Integral values were obtained for 5 sets of concentric contour paths.For each contour path,the J-Integral values were obtained at the outer surface,mid surface and inner surface of the tube.The average value of J was found using the following formula

$$JaVg = 1/6\ J_{inn} + 2/3\ J_{mid} + 1/6\ J_{outer}$$

A reasonable degree of path independence was observed in the J-Integral values.This gives a check on the mesh accuracy.

Fig.3.shows a comparison of the linear elastic stress intensity factors obtained from closed form solutions (Zahoor,1989)and finite element analysis.The results are in reasonable agreement with each other.The effect of inclusion of crack face pressure in the linear elastic analysis has been brought out in Table.1.It is observed that the J-Integral values increased by about 20% when the pressure on the cracked faces was considered.

In Fig.4.,a comparison has been made between the J-Integral values averaged over the thickness Zahoor's closed form solutions for the elastic-plastic case.The agreement between the results is satisfactory.Again,a reasonable degree of path-independence was observed in the J-Integral values.When the effect of crack face pressure was included in the elastic-plastic analysis,the results were 25-30% higher.(Table.2.)

The J1c for the material is about 84 N/mm(Anantharaman et.al,1994). From Fig.5.it can be seen that the initiation of cracking may take place when crack length is about 50mm.

5.EVALUATION OF J-INTEGRAL FROM CMOD VALUES

The crack driving force is experimentally determined by carrying out a slit burst test.Axial through-wall slits are made at the centre of a tube and a clip gage is attached to each specimen at the mid-point of the slit to monitor the crack opening displacement (CMOD).The J-Integral value is obtained from the following equation(Asada et al,1991)

$$J = 2 \int \sigma \ d\delta$$

Here σ = hoop stress in the tube.
δ = crack opening displacement.

The J-Integral was again evaluated separately using CMOD values from 3-D F.E.analyses.The results compare well with FEM results.(Fig.4.)

6.CRITICAL CRACK LENGTH

The critical crack length (CCL) is that length of the crack which leads to an unstable condition.An unstable (critical) condition occurs when the energy generated by the extending flaw overcomes the material's resistive properties .If the size of the crack is less than CCL,sudden rupture of the pressure tube is avoided.Therefore value of the CCL is important in determining a safe and orderly shutdown procedure for the reactor.

The tearing modulus approach is used here to determine the critical crack length.From the material J-R curve(Anantharaman et al,1994),the tearing modulus of the material is determined.The point of intersection of the extrapolated J-Tmat curve with the applied J-T curve gives the the J-value at the onset of instability(Fig.6.). Thus the critical crack length for the internal pressure loading of 9.5 Mpa at the operating temperature is 88 mm.

7 CONCLUSIONS

The inclusion of crack-face pressure has a significant effect on the values of J-Integral.For linear elastic behaviour the increase is approximately 20% , while in the elastic-plastic analysis the increase is around 25-30%.

The closed-form solutions give a fairly accurate value of J-Integral in both cases.However,they ignore the effect of crack face load.

For the same J-R curve the inclusion of crack face loading predicts a smaller value of CCL.It is unconservative to exclude the pressure loading on the crack face.When the effect of irradiation and hydriding are included,the CCL values will be lower.

9.ACKNOWLEDGEMENTS

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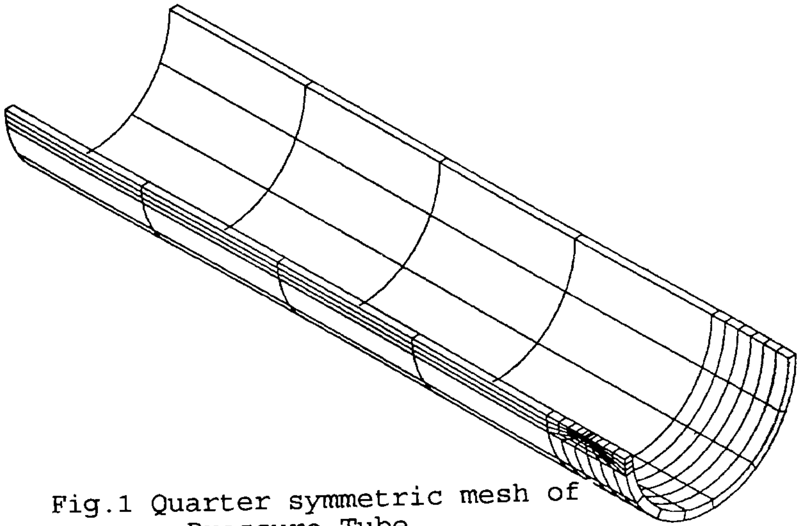
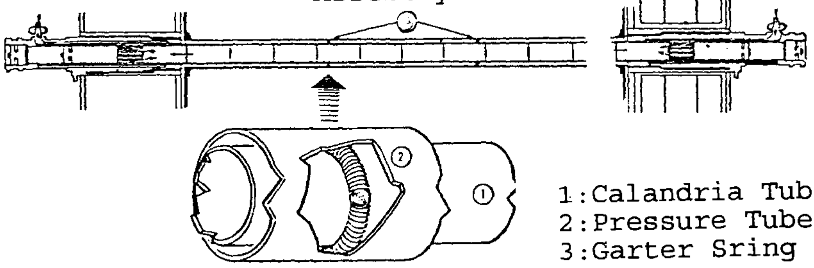


Fig.1 Quarter symmetric mesh of a Pressure Tube

Fig.2 Pressure Tube-Calandria Tube Assembly



1:Calandria Tube
2:Pressure Tube
3:Garter Sring

TABLE 1

Linear Elastic Fracture Mechanics Effect of Crack face pressure.

a mm	Japp1 N/mm	Japp2 N/mm	% Increase
10	6.807	8.198	20.434
15	15.420	18.575	20.460
20	29.666	35.669	20.235
25	50.481	60.775	20.392
30	78.900	95.400	20.913
35	116.260	139.960	20.385
40	162.192	195.267	20.393

TABLE 2

Elastic Plastic Fracture Mechanics Effect of Crack face Pressure.

a mm	Japp1 N/mm	Japp2 N/mm	% Increase
10	7.700	8.962	16.400
15	18.100	21.032	16.200
20	43.278	34.914	23.956
25	82.520	65.130	26.700
28	119.455	91.058	31.185
30	152.331	114.84	32.647
35	282.523	197.88	42.76

Japp1 = without crack face pressure
Japp2 = with crack face pressure
a = Crack Half Length

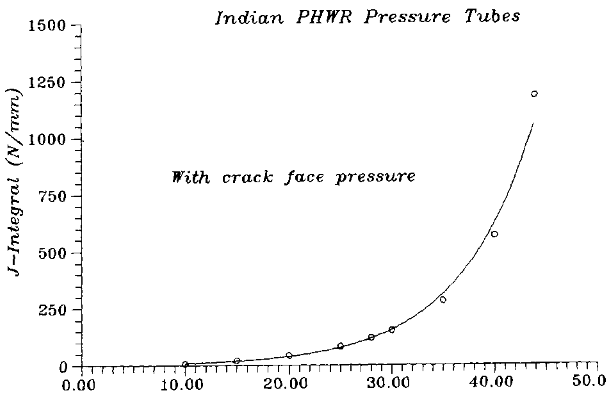


Fig.No.5 Plot of Applied J-integral V/s. Crack Half Length.
Crack Driving Force Curve

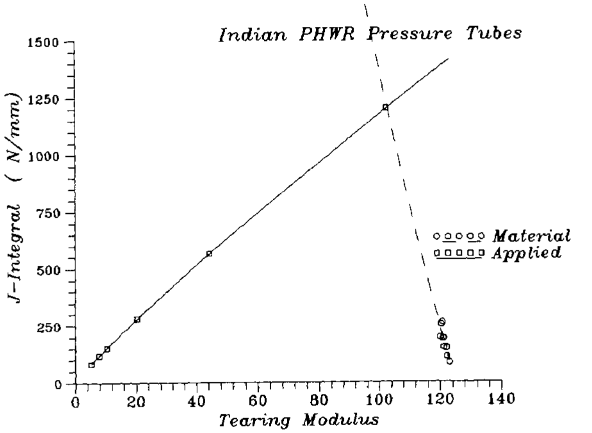


Fig.No.6 Plot of J-integral V/s. Tearing Modulus
Elastic-Plastic Fracture Mechanics

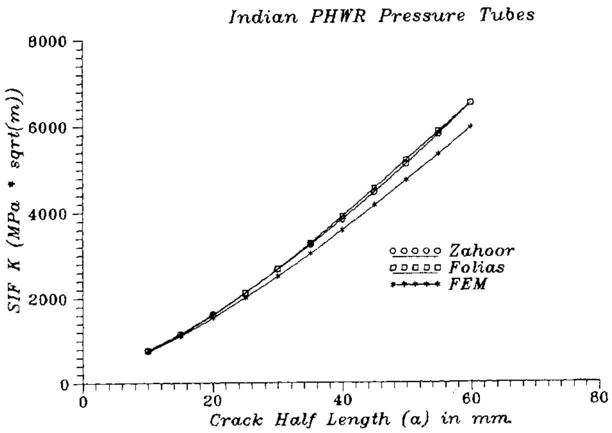


Fig.No.3 Plot of SIF V/s.Crack Length
Linear Elastic Fracture Mechanics

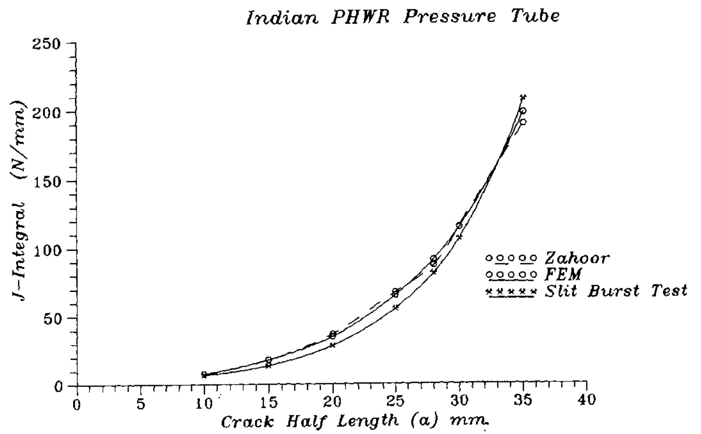


Fig.No.4 Plot of J-integral V/s. Crack length
EPFM Crack face pressure not considered