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FRACTURE MECHANICS STUDIES ON ELBOW

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1. INTRODUCTION

With the advent of Leak-Before-Break (LBB) concept in the design of piping system, the role of fracture mechanics is becoming more and more important in nuclear industry. The LBB approach requires the application of fracture mechanics to demonstrate that pipings are very unlikely to experience Double Ended Guillotine Break (DEGB). Stress analysis of primary heat transport (PHT) piping in nuclear power plant shows that highly stressed piping components are normally elbows and tees. The use of LBB concept requires the postulation of the largest credible flaw at highly stressed points and the demonstration of its stability under the most severe loading. This necessiates detailed fracture mechanics evaluation of piping components by computing stress intensity factor and/or J-integral. Simple analytical solutions for SIF and J-integral are available for straight pipes [Ref.1]. However, the same type of solutions are not available for elbows and tees in open literature. Hence, a computational method e.g. finite element method is adopted to evaluate the solutions for elbows and tees. In the present work, a database is generated for stress intensity factors for various sizes of elbows with flaws under different types of loadings.

2.EVALUATION OF STRESS INTENSITY FACTOR

As a part of the present work, a finite element code 'FABS' (Fracture mechanics Analysis of Bending Structures) has been developed. It uses nine noded heterosis/ eight noded degenerate shell bending elements. Stresses along the thickness has been considered using the layered approach. The capability of the code has further been enhanced by adding subroutines to calculate J-integral at different layers of thickness in a three dimension body. The code has been tested for a number of problems e.g centre cracked plate under tension and bending, axially and circumferentially cracked cylinder under internal pressure etc. The details of the code are available in Ref.2. Considering a large number of case studies to be done to generate the database, a versatile pre-processor is developed which generates element topology, nodal coordinates, boundary conditions and loading data. The ouput of the program 'FABS' is then further processed to get the SIF values in terms of a non-dimensional parameter 'Ae'. Ae is expressed as

$$Ae = K_{mid} / \sigma_r \sqrt{\pi a} \quad ; \quad \sigma_r = (pr/2t) + (M/\pi r^2 t)$$

where, K_{mid} is the SIF at mid surface, σ_r is the reference stress, 'p' is the internal pressure, 'M' is the remote bending moment and 'a' is the semi crack length.

There are number of methods to evaluate SIF. However, SIF values computed through displacement correlation method have been reported here. It has been evaluated by considering the crack face nodes only. However, normal procedure of evaluating SIF by extrapolating a curve is more of an art where uniqueness is lost. Hence, in the present work, a best fit straight line equation is used for number of nodes and then extrapolated to the crack tip to get a unique solution of SIF. The equations used are:

$$(SIF)_c = \Sigma(K_i - \beta r_i)/n$$

$$\beta = [n \Sigma K_i r_i - \Sigma K_i \Sigma r_i] / [n \Sigma r_i^2 - (\Sigma r_i)^2]$$

where, K_i is the SIF computed at radial distance 'r_i' and n is the total number of nodal points considered.

3. PARAMETRIC STUDY OF ELBOW WITH CIRCUMFERENTIAL CRACK

A detailed parametric study of elbows with circumferential throughwall flaws under combined internal pressure and closing remote bending moment has been carried out. The crack has been postulated at the extrados of the elbow (fig.1). One fourth of the elbow is modelled due to symmetry. The finite element model consists of 552 eight noded thick shell elements and 1751 nodes. The crack tip singularity is modelled by using quarter-point crack tip elements. The structure is assumed to be in elastic condition where SIF can characterise the stress and strain field around the crcak tip. Three parameters are chosen to characterise an elbow with a circumferential crack, namely, r/t , ϕ_c and the pipe factor ($h=tR/r^2$). Here, t is the pipe thickness, r is the mean pipe radius, R is the mean pipe bend radius and ϕ_c is the semi crack angle. Another parameter is chosen to consider the relative magnitude of stresses due to internal pressure and bending moment. It is expresed as:

$$\rho = (2/\pi).(M/pr^3)$$

$\rho = 0$ indicates internal pressure only and $\rho = \infty$ indicates pure bending moment. The parametric study involves the evaluation of 'Ae' for different pipe factors(h), crack angles (ϕ_c), r/t and load ratios (ρ). Since, 'h' is given by tR/r^2, this may be written as (R/r)(t/r). The mean pipe bend radius (R) should always be greater than mean pipe radius (r), R/r > 1, hence, hr/t > 1. This concludes that the minimum value of h is limited by t/r. Therefore, the minimum possible values of 'h' for r/t = 20, 10 and 5 are 0.05, 0.1 and 0.2 respectively. In the present study, the minimum values of 'h' are chosen as 0.075, 0.15 and 0.35 for r/t=20, 10 and 5 respectively. It has been seen that pure closing bending moment cannot fully open up small crack .

Hence, different crack angles ($2\phi_c$) chosen are $50^\circ, 90^\circ, 120^\circ, 140^\circ$, 160° and 180°. Different load ratios (ρ) selected are α, 2, 1, 0.5 and 0. Fig.4 shows the variation of 'Ae' for different pipe factors, r/t and crack angles for ρ= 0 and 1.

4. PARAMETRIC STUDY OF ELBOW WITH LONGITUDINAL CRACK

A parametric study of elbows with longtudinal crack (fig.1) under combined internal pressure and remote closing bending moment has been done. It is seen that in case of pure bending moment, maximum hoop stress occurs at $\phi = 90^\circ$ and this location gradually shifts towards intrados with the application of internal pressure. In the present case, crack location has been chosen at $\phi = 90^\circ$. Half of the elbow has been modelled due to symmetry. Parameters chosen are same as before except that the crack length is expressed as $\lambda = a/\sqrt{(rt)}$. In case of longitudinal crack, crack length is a function of bend radius, $a = R.\theta_c$, where, a is the semicrack length, θ_c is the angle subtended by the semi crack at the elbow bend centre. The maximum value of θ_c is 45° for a 90° elbow. This has restricted the maximum value of λ to 2.5. Another point is that in case of pure bending moment, due to high local bending stresses, a throughwall longitudinal crack cannot fully open up. Hence, different load ratios considered are ρ = 2,1,0.5 and 0. Fig.2 shows a typical deformed plot of a longitudinally cracked elbow under internal pressure. Fig.5 shows the variation of 'Ae' values for different pipe factors, crack lengths and r/t for load ratio ρ = 1 and 0. Fig.3 shows the effect of load ratio on Ae.

5. DISCUSSION AND CONCLUSION

A database of stress intensity factors is generated for circumferentially and longitudinally throughwall cracked elbow under combined internal pressure and remote bending moment. Different parameters chosen to characterise a cracked elbow are pipe factor (h), r/t, load ratio (ρ) and crack length expressed in non-dimensional terms. SIF as expressed in a non-dimensional form (Ae) is evaluated for various values of the aforementioed parameters. The following conclusions can be drawn from the present study :

1) The effect of pipe factor becomes more pronounced for higher r/t ratios.
2) For the same reference stress, the value of 'Ae' for longitudinal flaw is more for internal presure alone,compared to the combined internal pressure and bending moment.
3) Pure closing bending moment cannot open a small throughwall circumferential flaw at the extrados.
4) Pure bending moment cannot open a throughwall longitudinal flaw due to high local bending stresses.

REFERENCES

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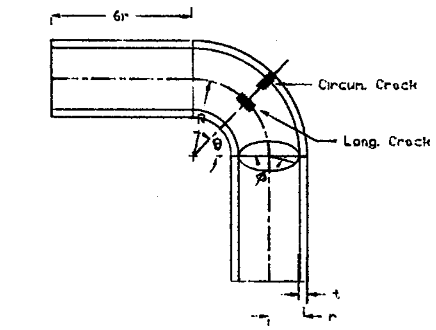

Fig.1 GEOMETRY OF A CRACKED ELBOW

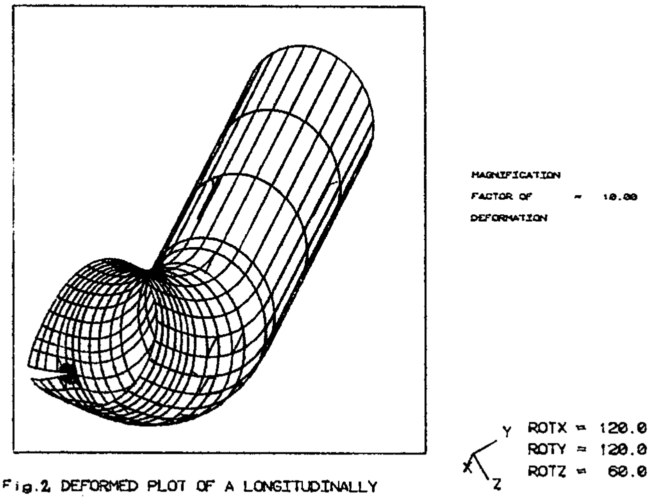

Fig.2 DEFORMED PLOT OF A LONGITUDINALLY CRACKED ELBOW UNDER INTERNAL PRESSURE

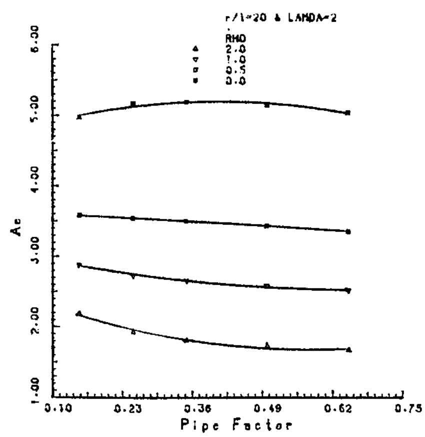

Fig.3 Ae VALUES FOR DIFFERENT LOAD RATIOS

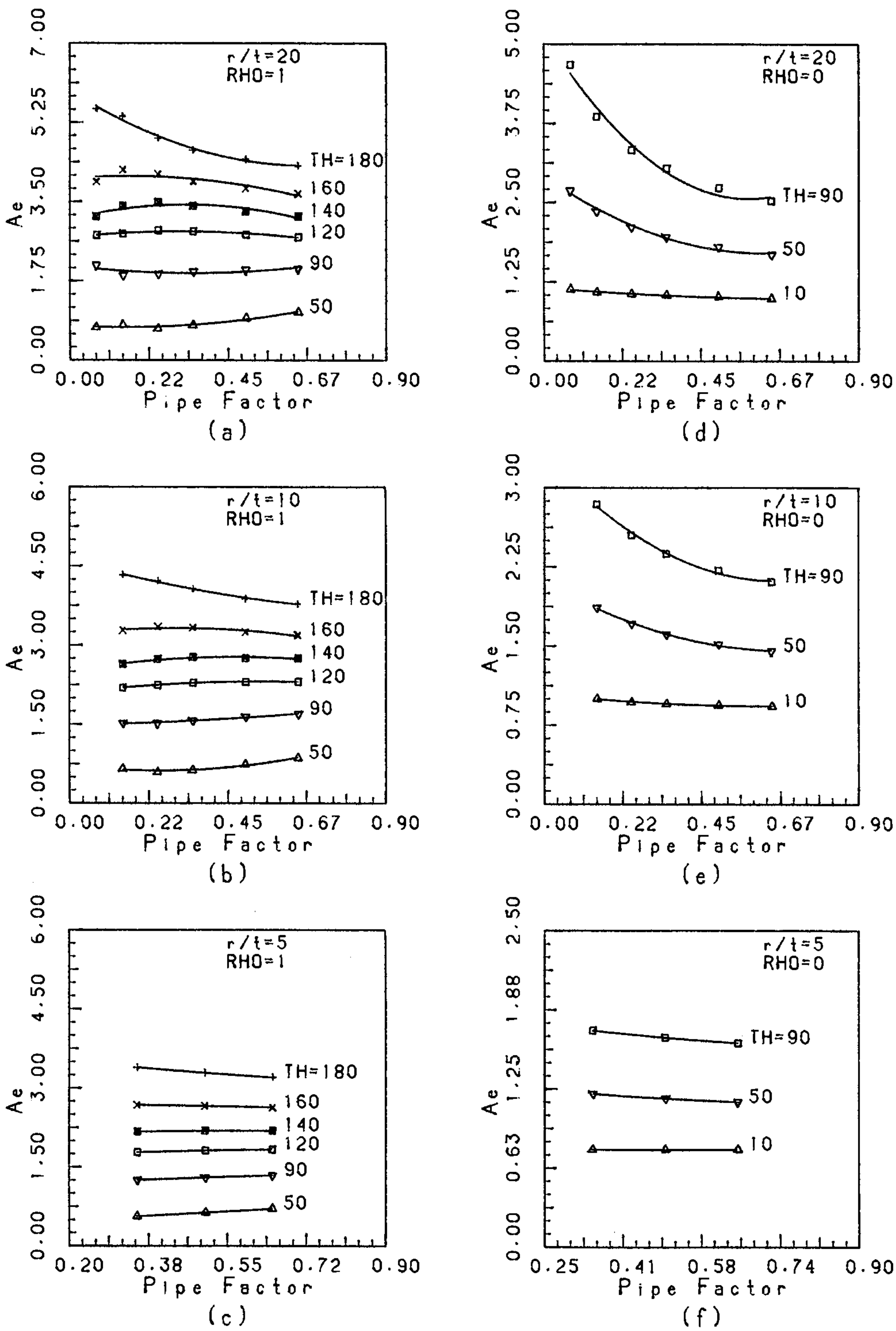

Fig.4 VARIATION OF Ae FOR CIRCUMFERENTIALLY CRACKED ELBOW UNDER INTERNAL PRESSURE & MOMENT

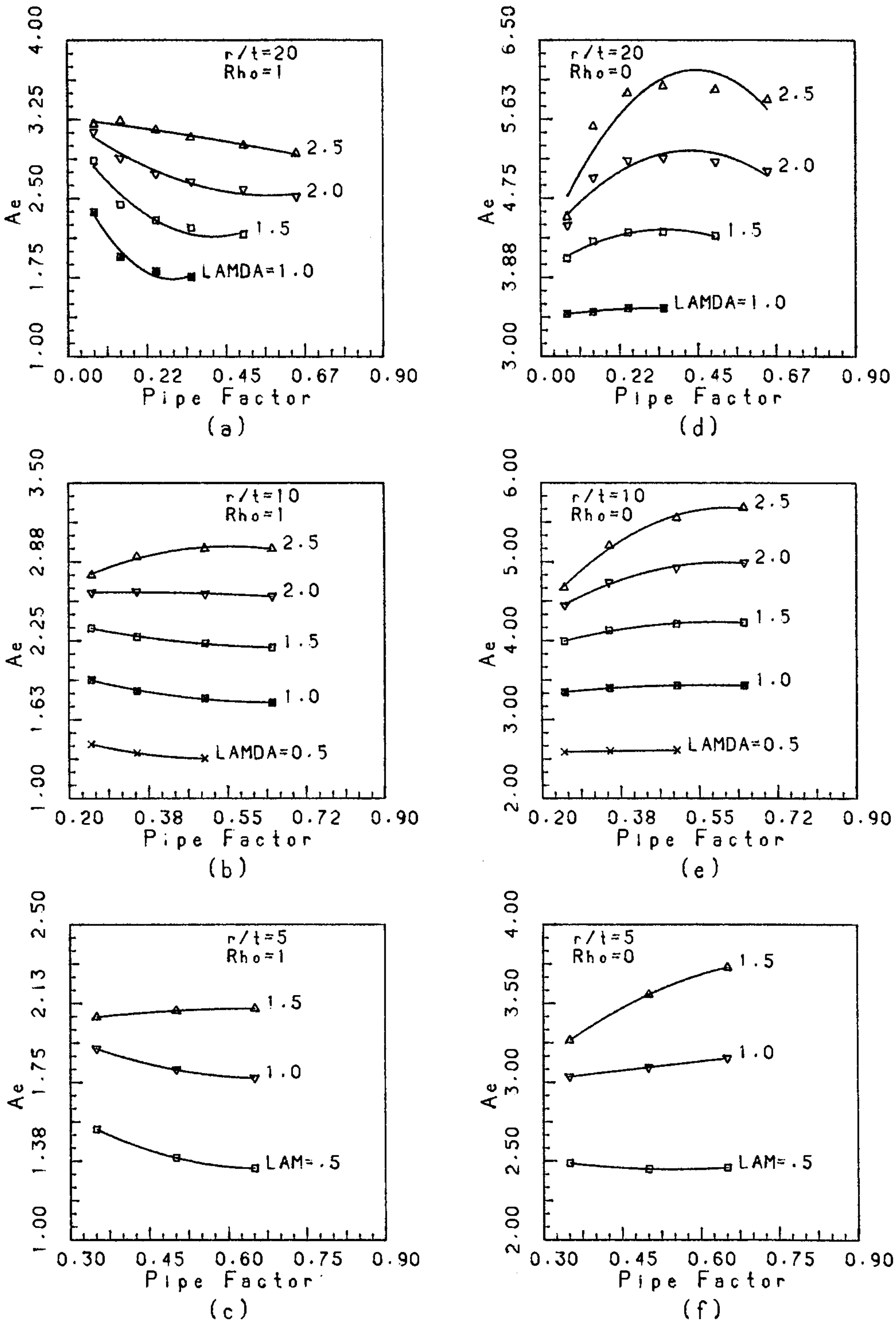

Fig.5 VARIATION OF Ae FOR LONGITUDINALLY CRACKED ELBOW UNDER INTERNAL PRESSURE & MOMENT