Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Surface Crack Growth in Reactor Header Tee under Cyclic Pressure

D. S. Chawla, S. R. Bhate, K. K. Vaze and H. S. Kushwaha

Bhabha Atomic Research Centre, India

ABSTRACT: High stress concentration occurs at inner corner in the piping tee junction. A semi-elliptical surface crack is postulated at inner surface of piping tee corner for Leak-Before-Break design. Other type of crack shapes are also investigated before arriving at semi-elliptical shape. The surface crack growth as a result of pressure cycles, is studied. The cracks oriented in axial and circumferential direction at tee corner are considered. The results show that for the postulated crack the number of cycles required is very high for propogation through the thickness.

1 INTRODUCTION

The use of leak-before-break (LBB) concept in nuclear power plants helps to reduce the conservatism and cost without compromising safety. As a first step of this approach, the part through crack should be postulated at highly stressed region of a pressurized component and then it should be demonstrated that it will not grow through wall during the entire service life of plant. The reactor header is a part of the Primary Heat Transport (PHT) system. Its structural integrity is of great concern for the continuous operation of the reactor. The stress gradient is likely to be very high at the inner surface of the Tee corner due to internal pressure. Therefore, the surface crack is postulated at piping tee corner.

The literature review is carried out with respect to modelling of surface crack in piping tee and also the simulation of surface crack with line spring is reviewed [1-3]. The use of line spring elements for modelling of surface cracks along with shell element is now well accepted for computational economy. The line spring elements provide sufficiently accurate result. The line spring methodology is applied to piping tee in the present paper. The surface crack was simulated at the corner of the piping tee. The axial as well as circumferentially oriented surface crack was considered at piping tee corner. The semi-elliptical shape of surface crack is considered. But before arriving at semi-elliptical shape the other type of crack shapes are also analysed. The variation of crack depth with number of pressure cycles is presented.

2 GEOMETRY AND LOADING

The dimensions of reactor header piping tee, considered in the analysis, are shown in the figure 1. The material of piping tee is carbon steel SA350 Grade LF2. The material properties are given in Table 1. The varying sizes of surface cracks, oriented in axial and circumferential directions, are considered. The load considered in the analysis is internal pressure varying from zero to 1.0 Kg/mm^2.

3 MODELLING OF PIPING TEE WITH SURFACE CRACK

Due to geometrical complexity, a three dimensional finite element model is chosen. Half the geometry is modelled due to symmetricity. The symmetric plane passes through the axis of run pipe and branch pipe. Eight noded thick shell elements are used for modelling. The surface crack is simulated using line spring elements. The curvature discontinuity in the crack front at the corner of tee junction makes finite element results sensitive to mesh and element grading. Therefore, the convergence study is also carried out by reducing the element size locally near the surface crack. The converged mesh is used in the final analysis. The finite element model of the reactor header piping tee with corner surface crack is shown in figure 2. Axial crack is assumed to be running along brach and run pipe. In this case, the geometry of tee is symmetric on two sides of crack plane. Therefore three noded symmetric line spring elements are used. For circumferential orientation, the crack is simulated at intersection line of run and branch pipe. Since structural geometry is not symmetric on two sides of crack plane, unsymmetric six noded line spring elements are used for modelling the crack. Out of these six nodes, three nodes lie on one side of crack plane and remaining three nodes lie on other side of crack plane. The local increase in pipe wall thickness near corner of piping tee is modelled by supplying the increased thickness to line spring elements for axial as well as circumferential cracks.

The computer code 'ABAQUS'[4] is used for the computation of stress intensity factors (SIF). The finite element simulation of surface cracks with the line spring is validated by authors elsewhere[5]. The fracture mechanics results for piping tee are verified by comparing with numerical and experimental results published in the literature[6] as presented in Table 2.

4 SURFACE CRACK SHAPE STUDY

The semi-elliptical crack shpae is extensively studied and used by researchers and is also recommended by ASME Boiler and Pressure Vessel code. In practice cracks may be found during in-service inspection having arbitrary shapes due to fatigue loading. In order to assess whether other crack shapes can become more critical, a study involving three different crack shapes, is carried out. Crack depth to thickness ratio is taken as 0.25 in this study. The various crack shapes considered are semi-elliptical, circular and flat/straight (hacksaw cut). These crack shapes are shown in figure 3. The finite element model is modified to incorporate different crack shapes. The stress intensity factors are computed along the crack front for internal pressure of 1.0 Kg/mm^2. The stress intensity factors obtained for different crack profiles are compared in figure 4. It can be seen that maximum SIF for each of the crack profiles occurs at centre. There is small difference in magnitude of maximum SIF for different crack profiles. The semi-elliptical crack profile gives slightly higher SIF as compared to other crack profiles and hence it is conservative. This result suggests the use of semi-elliptical crack profile.

5 COMPUTATION OF SIF FOR SURFACE CRACKS

The SIF is computed for surface cracks having different crack depths using computer code 'ABAQUS'[4]. The SIF is evaluated for semi-elliptical surface cracks oriented in axial and circumferential direction placed at inner surface of tee corner. The crack length to depth ratio is considered as 6 for all the cracks as per ASME Section XI [7]. The variation of maixmum SIF with crack depth is shown in figure 5 for axial and circumferential cracks. For axial as well as circumferential cracks the maximum SIF is generated at centre of crack. For axial surface cracks the SIF is higher as compared to circumferential cracks.

6 CRACK GROWTH WITH PRESSURE CYCLES

The fatigue crack growth rate as defined in ASME Section XI [7] is ussed for the evaluation. The equations used are,

$$da/dN = (1.02E\text{-}6).\ \Delta K^{5.95}, \quad \text{for} \quad \Delta K < 19\text{Ksi}\sqrt{\text{in}} \tag{1}$$

$$da/dN = (1.01E\text{-}1).\ \Delta K^{1.95}, \quad \text{for} \quad \Delta K > 19\text{Ksi}\sqrt{\text{in}} \tag{2}$$

Where, da/dN is fatigue crack growth rate in inch/cycle and K is stress intensity factor range in Ksi$\sqrt{\text{in}}$

The number of pressure cycles required for crack extension up to 75 percent of thickness is evaluated. Since the left out ligament will not be sufficient to take up any load once the crack has grown to 75% of thickness, it can be considered as through wall crack. The initial crack depth is considered as 12.5 percent of thickness. The variation of required number of pressure cycles with increase in crack depth is shown in figure 6 for axial crack. Figure 7 shows the variation of crack depth with number of pressure cycles for circumferential crack. It can be seen that for axial cracks 17299 cycles will be required for initial crack depth of 9.375mm (12.5% of thickness) to extend up to 56.25mm (75% of thickness). While for circumferential crack very large number of cycles (20817620) are required for similar amount of crack growth.

7 CONCLUSION

Fracture mechanics study is carried out for surface crack at tee corner in pressurized piping using shell and line spring elements. The crack shape study show that the semi-elliptical crack profile gives slightly conservative results.

It is noted from the fatigue crack growth study that the axial surface crack will grow much faster than the circumferential surface crack due to pressure cycling. Approximately 17000 cycles will be required for axial surface crack having initial crack depth of 9.375mm (12.5% of thickness) to become through wall. These cycles are very large compared to expected load cycles.

REFERENCES

1. Brocks,W. & Kunecke,G., "Elasto-plastic fracture mechanics analysis of a pressure vessel with an axial outer surface flaw," Nuclear Engg Design, Vol.119, 1990, pp.307-315.

2. Schuler,X., et al, "Fracture mechanics evaluation of cracked components with consideration of multiaxiality of stress state," Nuclear Engg Design, Vol.151, 1994, pp.291-305.

3. Parks, D.M. and White, C.S., "Elastic-plastic line spring finite elements for surface cracked plates and shells," JPVT, Vol.104, 1982, pp.287-292.

4. ABAQUS version 5.3, Hibbit, Karlson and Sorenson Associates.

5. Chawla, D.S., et al, "The shape influence on the behaviour of surface cracks," Proc. of the 13th International conference on Structural Mechanics in Reactor Technology, Vol.2, pp.461-466, Porte alegreBrazil, August 1995.

6. EPRI-NP-2024, Static stress intensity factors and dynamic crack propogation in pipes.

7. ASME Boiler and pressure vessel code, Section XI, Division 1, Rules for Inservice Inspection of Nuclear power plant components, 1986.

Table 1 Properties of reactor header piping tee material.

Material	: SA350 Grade LF2
Young's modulus	: 179 GPa
Yield stress (0.2% offset)	: 200 MPa
Ultimate stress	: 520 MPa
Stress-strain curve data	
[Engg stress, MPa (Engg strain, %)]	: 300 (1.85), 400 (4.07), 450 (6.11), 500 (10.2), 520 (18.5)

Table 2 Comparison of computed result for circular crack with published experimental/numerical results at piping tee junction.

Present study Normalized K	Experimental [Ref 6] Normalized K	Numerical [Ref.6] Normalized K
4.28	3.47 (4) 3.01 (4)	2.82

Note: 1. K=SIF; P=Pressure; d=diameter; t=thickness; a=crack depth

2. Normalized $K = K / [(Pd/2t)\sqrt{(\pi a)}]$

3. Above result is for circular axial inner surface crack at shell nozzle junction corner.

4. Two different experimental values were available in literature and both are quoted here for comparison.

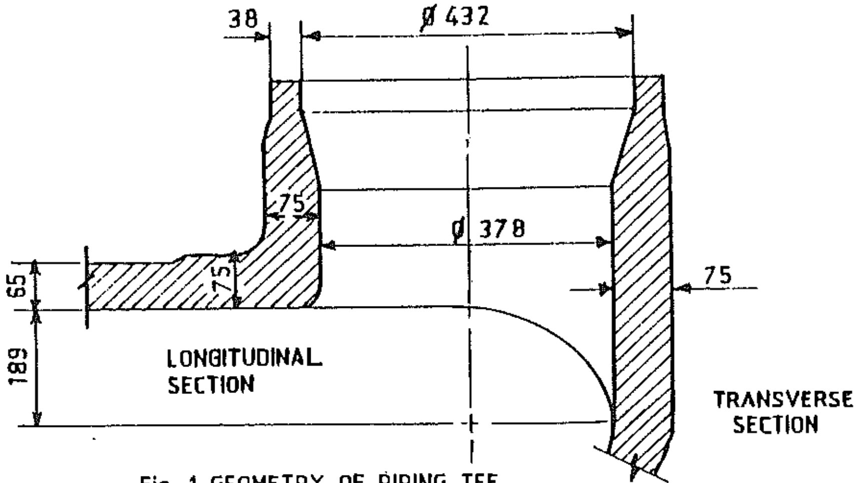

Fig. 1 GEOMETRY OF PIPING TEE

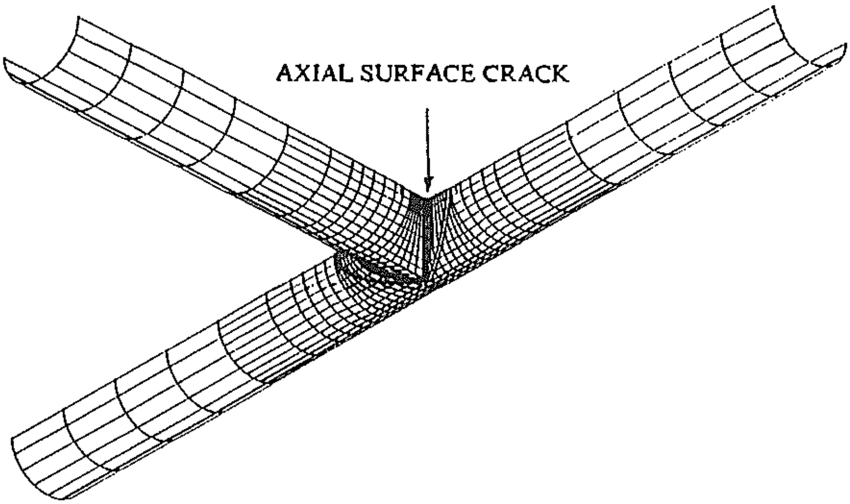

FIG. 2 FINITE ELEMENT MODEL OF PIPING TEE

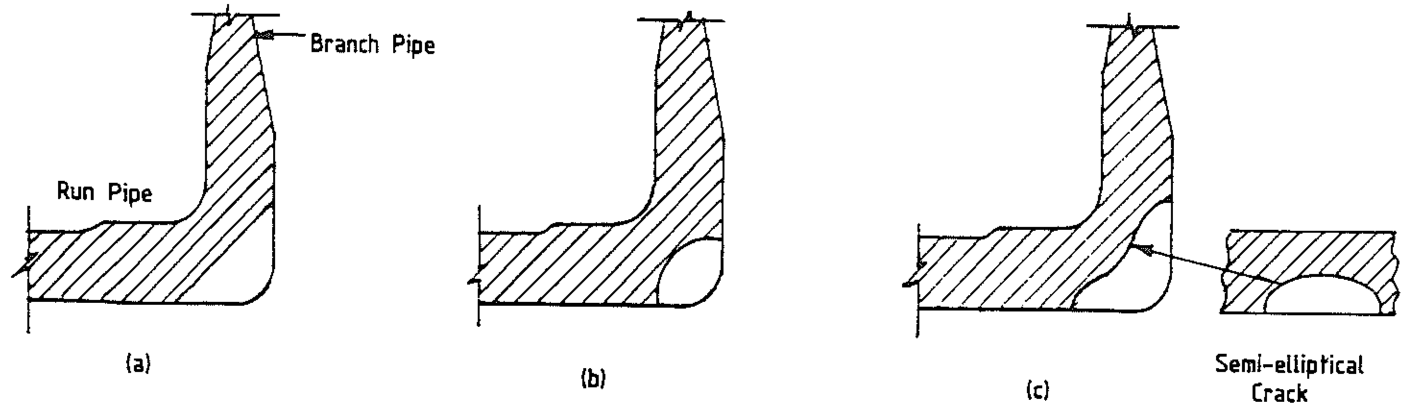

Fig. 3 Different crack shapes considered for study
(a) Flat/Straight (hacksaw cut) crack
(b) Circular crack
(c) Semi-elliptical crack profile mapped

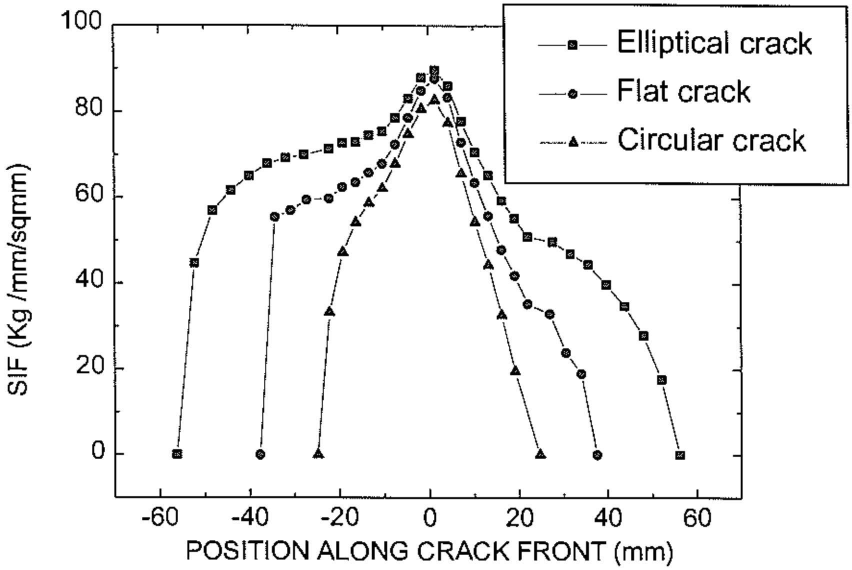

Fig. 4 COMPARISON OF SIF FOR VARIOUS SHAPES OF INNER AXIAL SURFACE CRACK AT TEE CORNER (Crack depth=9.375mm).

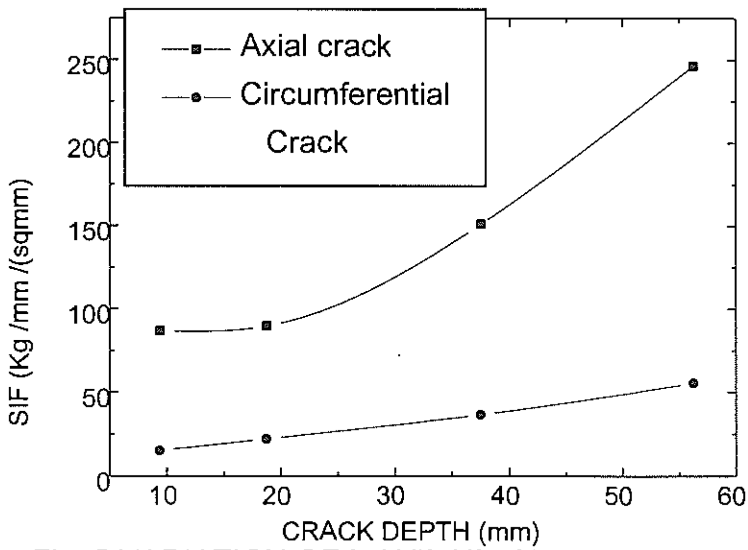

Fig. 5 VARIATION OF MAXIMUM SIF WITH CRACK DEPTH FOR INNER SURFACE CRACKS AT TEE CORNER.

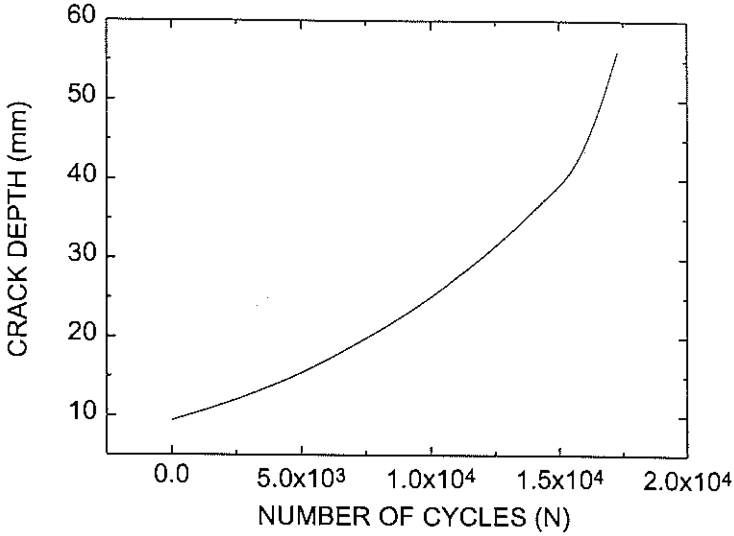

Fig. 6 VARIATION OF CRACK DEPTH WITH PRESSURE CYCLES FOR AXIAL INNER SURFACE CRACK AT PIPING TEE CORNER.

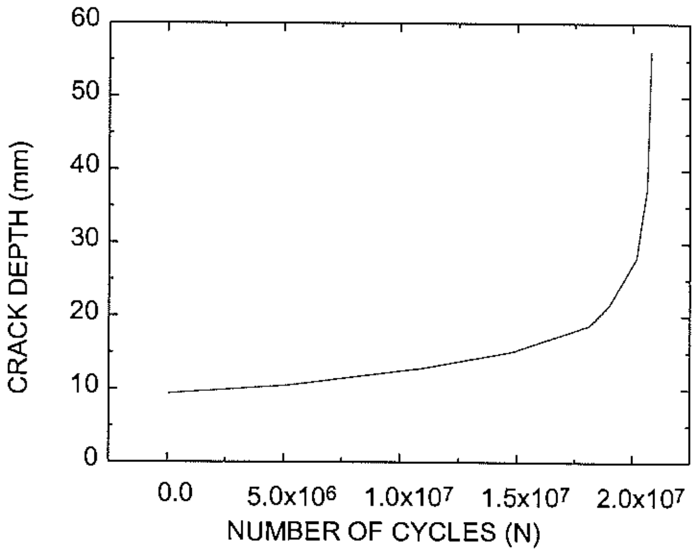

Fig. 7 VARIATION OF CRACK DEPTH WITH PRESSURE CYCLES FOR CIRCUMFERENTIAL INNER SURFACE CRACK AT PIPING TEE CORNER.