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Fracture assessment of straight pipes and elbows with through-wall cracks : using R-6 method

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ABSTRACT

This paper presents the results of fracture assessment of primary heat transport (PHT) piping of 500 MWe Indian Pressurised Heavy Water Reactor (PHWR), by using R-6 method. The safety margins are obtained using R-6 method. The margins are determined on crack growth initiation as well as on unstable crack growth. Sensitivity study is also performed with respect to different input parameters. The safety margins available are more than what is required by IAEA-TECDOC[6]. Therefore PHWR, PHT piping is qualified for Leak Before Break (LBB) design criteria.

1. INTRODUCTION

The Indian Pressurised Heavy Water Reactor (PHWR) is a 'Pressure Tube' type of nuclear reactor. Nuclear fuel is housed in Pressure Tube. Heavy water takes away the heat. This heavy water circuit is termed as Primary Heat Transport (PHT) system. The hot coolant coming from the coolant tube is collected in the reactor outlet header.Then it enters the steam generator where heat is transferred to light water of the secondary circuit. The primary coolant then enters a pump. From the pump the coolant goes to reactor inlet header and then back to reactor again. The main PHT pipe components including header are forged / seamless and the number of circumferential weld have been kept minimum. The fracture assessment of PHT system pipes, with postulated throughwall circumferential flaw, was done. R-6 method was used for fracture assessment. The results obtained have been applied to qualify "Leak Before Break" criteria of PHT pipes.

2.0 STRUCTURAL DETAILS & MATERIAL PROPERTIES

Although all circumferential welds are radiographed and a 100% volumetric ultrasonic examination is performed, an inaugural flaw in the weld zone may exist and can grow due to fatigue loading. Therefore, circumferential through the thickness flaw is postulated in the straight pipe at the weld location.

The piping in PHT system can be classified into three types.

1. Steam Generator Inlet Line (SGI)
2. Steam Generator Outlet Line (SGO)

3. Pump Discharge Line (PDL)
The geometrical details of these pipes is given in Table 1.

Table 1 : Geometrical Details of the Pipes .

	Line Name	Outer Dia.	Thickness	Elbow Angle	Mean Bend Radius of Elbow
1.	SGI	508 mm.	40 mm.	90^{o}	762 mm.
2.	SGO	610 mm.	50 mm.	135^{o}	910 mm.
3.	PDL	457 mm.	35 mm.	90^{o}	686 mm.

Note: Outer dia. and thickness of elbow and straight pipe is same.

The pipes are made of SA333 Gr6 type material. The material properties [1] and fracture parameters are given below in Fig.1 and Fig.2 respectively.

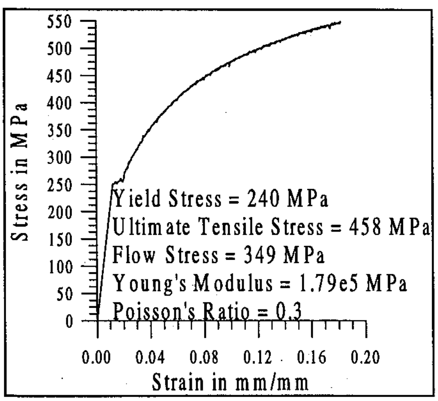

Figure 1 : Stress Strain Curve for SA333 Gr.6

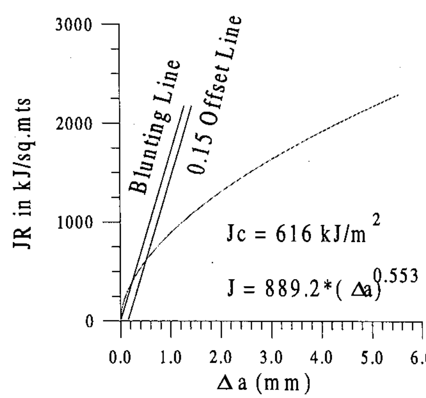

Figure 2 : J-Resistance Curve for SA333 Gr6

3.0 LOADS AND LOAD COMBINATIONS

The loads were obtained from detailed piping analysis, considering earthquake effects [2]. Table 2 to Table 6 give the magnitudes of various loads which are acting on different pipe segments.

Table 2 : Steam Generator Inlet, Straight Pipe.

Load Case	Pressure in MPa	Axial force in kN	Bending moment in MN-mm
NOC	9.81	58.0	391.0
$NOC + SSE_{SRSS}$	9.81	158.0	640.0
$NOC + SSE_{ABS}$	9.81	202.0	730.0

Table 3 : Steam Generator Outlet, Straight Pipe.

Load Case	Pressure in MPa	Axial force in kN	Bending moment in MN-mm
NOC	9.51	241.0	564.0
NOC + SSE_{SRSS}	9.51	628.0	917.0
NOC + SSE_{ABS}	9.51	665.0	968.0

Table 4 : Pump Discharge Line, Straight Pipe.

Load Case	Pressure in MPa	Axial force in kN	Bending moment in MN-mm
NOC	11.4	54.8	242.0
NOC + SSE_{SRSS}	11.4	131.0	314.0
NOC + SSE_{ABS}	11.4	153.5	327.6

Table 5 : Steam Generator Inlet Line, Elbow

Load Case	Pressure in MPa	Bending moment in MN-mm
NOC	9.81	251.0
NOC + SSE_{SRSS}	9.81	378.0
NOC + SSE_{ABS}	9.81	423.0

Table 6 : Pump Discharge Line, Elbow

Load Case	Pressure in MPa	Bending moment in MN-mm
NOC	11.4	102.0
NOC + SSE_{SRSS}	11.4	159.0
NOC + SSE_{ABS}	11.4	168.0

Note : 1. NOC :Normal Operating Condition, SSE :Safe Shutdown Earthquake Load, SRSS : Square Root Of Sum Of Squares Combination, ABS: Absolute Load Combination
2. The NOC includes axial force and bending moment due to dead weight and thermal stresses.
3. SSE includes contribution from inertia, missing mass and anchor motion.

These loading were added using SRSS as well as ABS schemes. The analysis has been performed for both the load combinations.

4.0 ANALYSIS

The analysis is performed as per the procedure laid down in [3]. Step by step procedure is listed below.

1. Define and categorise all loads and stresses: The loads are presented in Tables 2 to 6. All the loads were considered as primary.

2. Determination of material tensile properties: The material properties were obtained [1] after testing the material at various temperatures in the range of 200° C - 350° C. Out of these the minimum valuses were obtained at 250°. Thus all the material properties used are at this temperature. The tensile material properties are presented in Section 2.

3. Select and define the Failure Assessment Diagram (FAD): R-6 offers three types of FADs for analysis (Option 1,2 and 3). Depending on the availability of data, one of these can

be used. Ref[6] also gives guidelines for selection of FAD. It recommends that the analysis should start with Option 1. If desired margins are not achieved then next Options are to be used. In the present analysis, since the full stress-strain curve was available,Option 2 was used.The desired margins[4] for demonstrating Leak-Before-Break are met and hence an Option 3 analysis was not considered.

4. Characterise the shape of the flaw: A circumferential throughwall crack is postulated. For elbows this crack has been postulated at the extrados. Fig.3 and Fig.4, give the crack configuration for the straight pipe and elbow respectively.

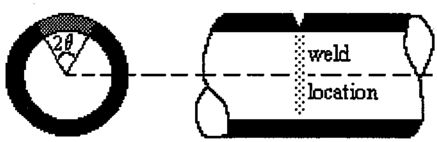

Figure 3 : The crack configuration for the straight pipe

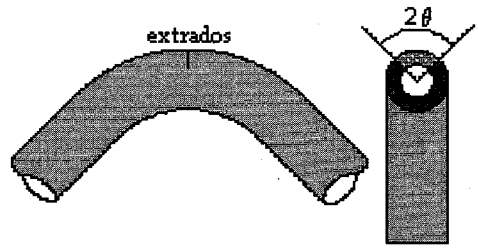

Figure 4 : The crack configuration for the elbow

5. Select the Category of analysis: In this analysis Category 1 and Category 3 have been used to determine margins with respect to crack growth initiation and unstable crack growth respectively.

6. Define the fracture toughness: The category 3 analysis uses detailed J-Resistance curve for analysis. This is shown in Section 2.

7. Define the size of the flaw: The analysis has been done to demonstrate LBB for the PHT piping. The crack size was postulated based on Ref.[4]. The crack size taken is such that leakage is detectable by the leakage monitoring instruments. This 'Leakage Size Flaw' for different piping segments are given in Table 7.

Table 7 : Leakage Size Cracks (LSC) for different pipes

Piping Components	Crack angle in degrees (2θ)
Steam Generator Inlet, Straight Pipe	34.6
Steam Generator Inlet, Elbow	52.5
Steam Generator Outlet, Straight Pipe	32.4
Pump Discharge Line, Straight Pipe	34.0
Pump Discharge Line, Elbow	50.0

8. Calculate Lr': The Lr' parameter denotes nearness to plastic collapse. Ref.[5] is used for calculating the limit loads for straight pipes and elbows.

9. Calculate Kr': The Kr' parameter denotes nearness to brittle fracture. The stress intensity factor (SIF)values for straight pipes were obtained from Ref.[5]. For elbows with circumferential cracks at extrados, Finite Element Studies were performed and it was seen that for crack sizes greater than 50^o, the SIF value matches closely with that of straight pipe with similar crack configuration. Therefore the same reference [5] was used for elbows also.

10. Plot all points on the FAD: The FAD and sensitivity curves are shown for SGI elbow only. The figures are drawn for SRSS load combination. Similar methodology was followed for other cases also. Fig. 5 shows the assessed point as 'X' for the SGI elbow.

11. Assess the significance of results: a)Reserve Factors: The reserve factors for any components may be expressed with respect to any parameter:

Reserve on load, F^L = limiting load / applied load
Reserve on flaw, F^a = limiting defect size / defect size of interest
Reserve on fracture toughness, F^K = K_C of the material / K_C to produce limiting condition
Reserve on yield stress, F^σ = σ_y of the material / σ_y to produce limiting condition

The limiting condition with respect of load, defect size, K_C, σ_y is reached when assessed point lies in the unsafe zone.

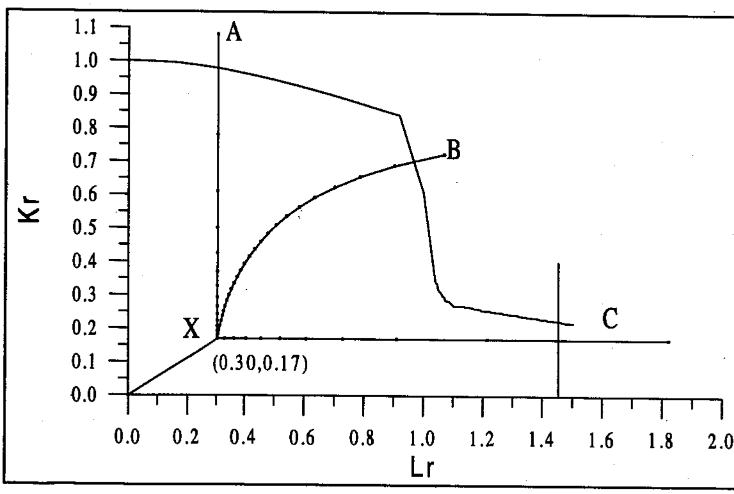

Figure 5 : The assessed point and the sensitivity locus : SGI, elbow

All the reserve factors are displayed in Table 8 and Table 9. The same table is used for qualifying the components for LBB. The minimum required margins are as per Ref.[4]. Thus for SRSS loading combination a margin of 2 on crack size and a margin of 1.414 on load is required. For ABS load combination a margin of 1 on crack size and a margin of 1 on load is necessary. It is seen that all the components which were analyzed, qualify for these margins and hence it meets the LBB criterion.

Table 8 : Reserve Factors for Straight Pipe Portion

	F^L		F^a		F^K	F^σ
category	1	3	1	3	1	1
SGI_{SRSS}	2.61	3.31	3.31	3.47	5.12	2.67
SGI_{ABS}	2.28	2.90	3.20	3.24	4.61	2.40
SGO_{SRSS}	3.25	4.03	3.92	3.95	5.53	2.86
SGO_{ABS}	3.08	3.82	3.83	3.86	5.35	2.86
PDL_{SRSS}	3.69	4.78	3.82	3.97	6.15	2.86
PDL_{ABS}	3.54	4.58	3.75	3.91	6.15	2.86

note : Category 1 represents initiation of crack growth and Category 3 represents unstable crack growth.

Table 9 : Reserve Factors for Elbow Portion

	F^L		F^a		F^K	F^σ
category	1	3	1	3	1	1
SGI_{SRSS}	3.32	3.91	3.43	3.43	5.78	4.8
SGI_{ABS}	2.97	3.43	3.35	3.37	5.29	4.24
PDL_{SRSS}	5.39	6.72	3.82	3.82	8.17	7.96
PDL_{ABS}	5.13	6.43	3.81	3.81	7.77	7.56

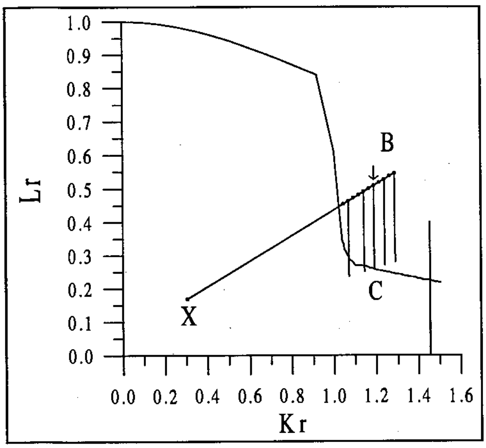

Figure 6 : Critical load for unstable crack propagation

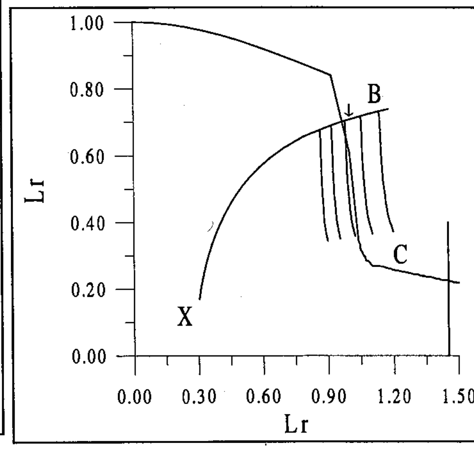

Figure 7 : Critical crack size for unstable crack propagation

It is seen from the Table 9 that the margins on crack size do not change when advantage of J-resistance curve is used in the study. This underlines the fact that the material has excellent fracture properties and net-section collapse is the dominant failure mechanism.

b). Sensitivity analysis: The sensitivity studies are done to assess the affect of various input variables on the results. The effect of variations of LSC, K_C, and σ_y (varied one at a time) on Reserve Load Factor, are evaluated. In Fig. 5, 'X' is the assessed point. If the initial crack size is increased the locus of assessed points will move along X-B. The point B lies outside the safe zone. The crack size for which X-B intersects the Failure Assessment Line (FAL), is the limiting crack size. For each of the points on the segment X-B, reserve load factor (F^L) is obtained. This is plotted against the crack size, as shown in Fig. 8 which gives the idea of the effect of initial crack size on the margin. Study is also done with K_c and σ_y (Fig. 9 - 10). In these two cases the values were decreased till the assessed point lies it the unsafe zone (A and C in Fig. 5).

The sensitivity studies in Category 3 are done as follows. Consider Fig.7. The first assessed point is X. The crack is increased until FAL is crossed (Region B). Now for this crack length J-Resistance curve was used to check the arrest of the crack (a point in the region B moves to C). This is done successively until a crack length is obtained for which the arrest takes place (denote by '↓' in the Fig.7). For each crack extension and subsequent growth F^L is obtained. Same procedure was applied to bending moment as shown in Fig. 6. This is then plotted against the crack growth to study the variation. (Fig. 11 - 12). In Fig.11 load increases from 1.3 MN-m to 1.6 MN-m in steps of 0.03 MN-m.(A to B). The critical position is indicated by the '←' arrow. This occurs at a load of 1.48 MN-m. Thus this is the critical load for unstable crack growth. In Fig. 12 the initial crack length is increased from 175° to 185° in step of 1° (A to B) .The critical position is indicated by the'←' arrow. This occurs for an initial crack size of 180°. Thus this is the critical crack size for unstable crack growth.

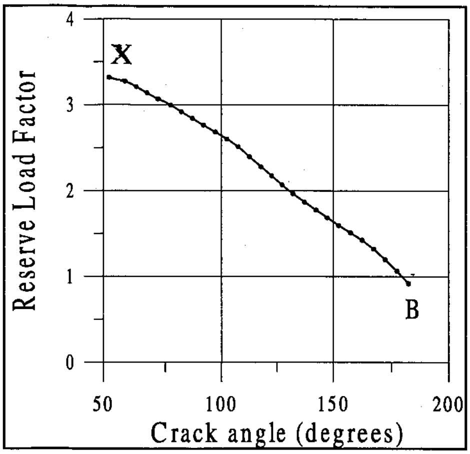

Figure 8 : Sensitivity analysis w.r.t. crack size, SGI elbow

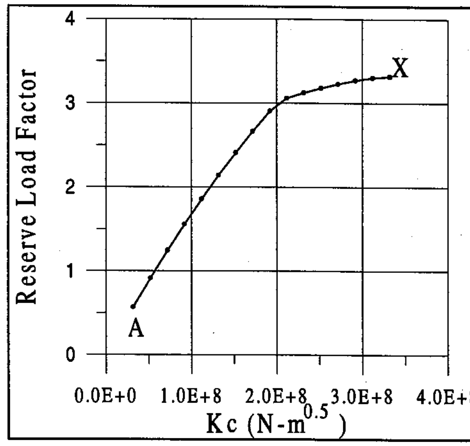

Figure 9 : Sensitivity analysis w.r.t. fracture toughness, SGI elbow

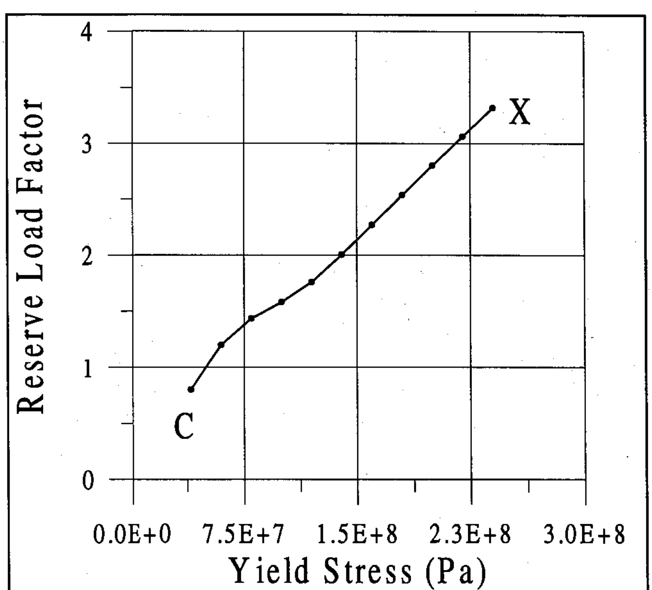

Figure 10 : Sensitivity analysis w.r.t. yield stress, SGI elbow

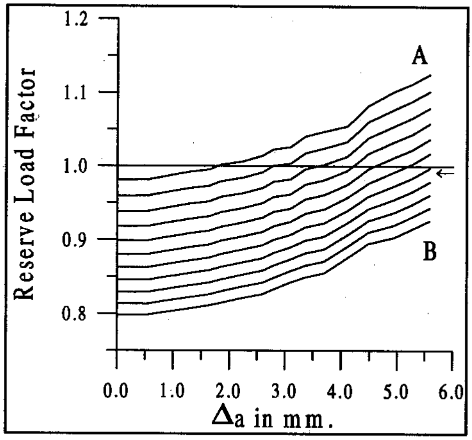

Figure 11 : Limiting load, category 3

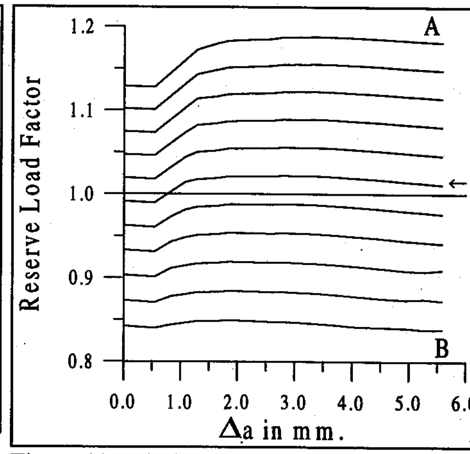

Figure 12 : Limiting crack size, Category 3

4. CONCLUSIONS

It is concluded that significant margin is available on the critical load, critical crack size. Sensitivity studies show that the fairly good amount of margin is available on material properties. Based on this study, it is possible to qualify the piping for LBB subjected to material properties used and analysis made in .....

5. REFERENCES

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