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Leak Before Break Investigation on Sodium Piping for Prototype Fast Breeder Reactor

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ABSTRACT

Leak Before Break (LBB) is investigated for the secondary sodium pipes including bends & Tees of 500 MWe capacity Prototype Fast Breeder Reactor (PFBR). The structural material for the piping is austenitic stainless steel type SS 316LN. LBB analysis is carried out as per the French Assessment Procedure A16 [1995]. By theoretical analysis, LBB argument is justified for the pipe diameters above 250 mm. A systematic approach is adopted for validating the results. Crack propagation tests were conducted on a typical large size prototype Tee of secondary sodium piping, subjected to pressure plus in-plane bending moment. The important results obtained from the test are asymptotic crack length (Cs), crack length which can provide a guaranteed detectable leak (C_L) and critical crack length (C_G). These values are finally compared respectively with those obtained by applying A16. These experimental investigations have raised the confidence in applying A16 procedure for the LBB justification of PFBR piping in general and Tee in particular.

KEYWORDS: FBR piping, bends, Tees, LBB, austenitic stainless steel, French Assessment Procedure A16, Component testing, asymptotic crack length, detectable crack length and critical crack length, FEM.

INTRODUCTION

The structural reliability of 500 MWe capacity Prototype Fast Breeder Reactor (PFBR) components is ensured by the choice of high ductile materials, design and construction as per international codes, viz. RCC-MR and ASME. In order to respect the design code rules, detailed analyses in various domains are performed using thoroughly validated computer codes. Since very stringent inspection procedures are followed, presence of any flaw or crack like defects is not expected. Further, it is planned to incorporate in-service inspections for the important safety related components. Apart, as a defense in depth, pessimistic cracks are assumed at the critical locations for the fracture mechanics analysis, in particular, for the demonstration of Leak Before Break (LBB) argument. LBB is investigated for the primary pipe, main vessel, sodium pipes including bends & Tee and steam generator (SG) [1,2]. The structural material for the primary pipe, main vessel and secondary sodium piping is austenitic stainless steel (ASS). Modified 9 Cr-1Mo steel (G91) is used for SG.

LBB analysis is carried out as per the French Guidelines A16 (1995) [3]. The critical parameters to demonstrate LBB are asymptotic crack length (2xCs), detectable crack length ($2xC_L$) and critical crack length ($2xC_G$). $2xC_s$ is the crack length of a particular surface whose crack front touches the opposite wall surface, i.e. crack depth (a) is equal to wall thickness (h). $2xC_L$ is the crack length, which can produce detectable leak (Q_d) of sodium flowing in the pipe. Q_d is equal to the sensitivity of leak detection system (Q_s) multiplied by a factor of safety 10. $2xC_G$ is the crack length, with which the structure becomes unstable (unbounded deformation) under the design basis loads (under SSE condition). For demonstrating LBB, 2x ($Cs+C_L$) should be less than $2xC_G$ with a factor of safety (α). The value for α depends upon the procedure followed for determining C_G parameter and material. For ASS, if fracture toughness is established based on stable tearing initiation limited to 3 mm (J_3), α can be unity [4]. Fig.1 depicts the C_s, C_L and C_G, pictorially.

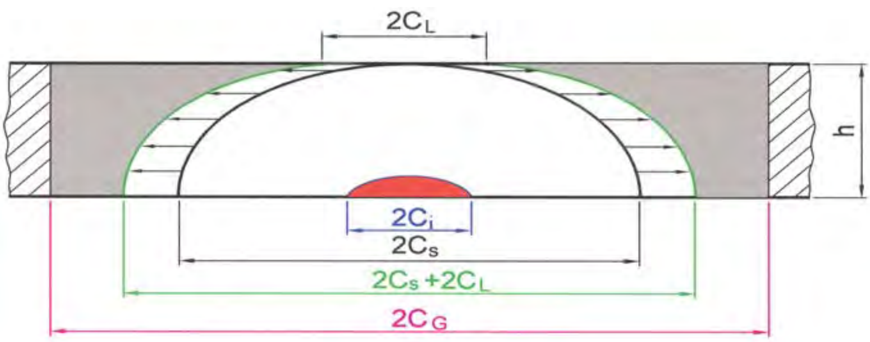


Fig.1 LBB Parameters

From the above mentioned information, it is clear that Cs, CL and CG are the critical parameters to demonstrate LBB. These parameters are determined experimentally for a complex practical geometry, i.e. a typical large size Tee for which not much information are available in the literature, and compared with those obtained by applying A16 procedure in order to have confidence on the A16 procedure.

This paper deals with the details of experimental assessment of A16 procedure to estimate Cs, C_L and C_G based on tests with prototype large size Tee in the secondary sodium circuit. Tests were conducted at room temperature (RT).

EXPERIMENTAL INVESTIGATIONS ON TEE

Geometry and Loading Details

The largest Tee adopted for the secondary sodium circuit of PFBR is considered for the investigation. The nominal dimensions of the run pipe are 800 mm diameter and 18 mm wall thickness. The corresponding values for the branch pipe are 550 mm and 16 mm. The geometrical details are shown in Fig.2. The Tee is subjected to maximum steady state internal pressure of 0.7 MPa and cyclic bending moment ($15x10^4$ Nm) which can produce the permissible stress range at the critical location as per RCC-MR (1993). The test setup is shown in Fig.3. A notch of size: 25 mm width and 1.5 mm depth, is introduced by machining at the highly stressed location (identified by finite element analysis) on the outer surface of the specimen.

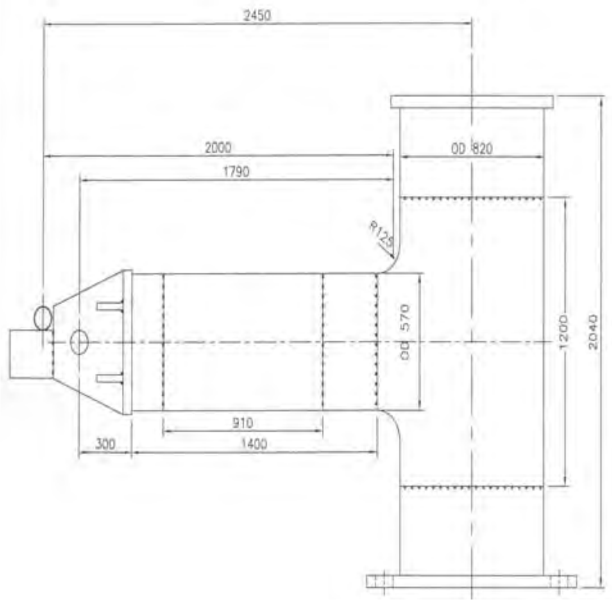


Fig.2 Dimensional details of test specimen

Fig.3 Test setup for Tee

Test Procedure

The test specimen is filled with water introducing a cover gas space in the upper portion of the straight vertical pipe attached with the Tee. By connecting the cover gas space to the constant nitrogen pressure tanks, the required internal pressure is sustained in the specimen, even under leaked condition in the course of test (Fig.4). The required bending moment is imposed on the specimen by applying cyclic vertical force at the end of the straight horizontal pipe welded to the Tee. Servo controlled hydraulic actuators with computerized control system is used for the application of cyclic loads.

For initiating surface crack at the notch, only bending moment which can introduce stress equal to ~ yield stress at the notch location is applied. For simulating crack propagation, cyclic bending moment to introduce 3Sm stress range at the location of notch is applied in association with the internal pressure of 0.7 MPa. Both pressure and cyclic bending moment (zero – peak - zero) are applied till the surface crack grows to cause a leak rate of 1000 g/h (sensitivity of leak detection sensitivity system for PFBR is 100 g/h and applied factor of safety is 10), under the minimum guaranteed sodium pressure. The crack front profiles are measured by crack depth measurement based on potential drop method (PDM) and ultrasonic. The crack lengths on the either surfaces of the through-wall crack, which has caused the leak rate of 1000 kg/h are measured and the crack length on the inner surface is identified as $2C_L$.

Subsequently, pressure is relieved and water is drained from the specimen and then, through wall crack is further propagated by applying only cyclic bending moment till the crack length at the outer surface becomes equal to twice of $2x(C_L+C_s)$ to have a factor of safety 2 on the critical crack length. Now, bending moment is applied sequentially (due to limited stroke length of actuator) to generate load-deflection curve. By applying '2xSlop' method recommended in ASME-Appendix II-1000 [5], collapse load is determined.

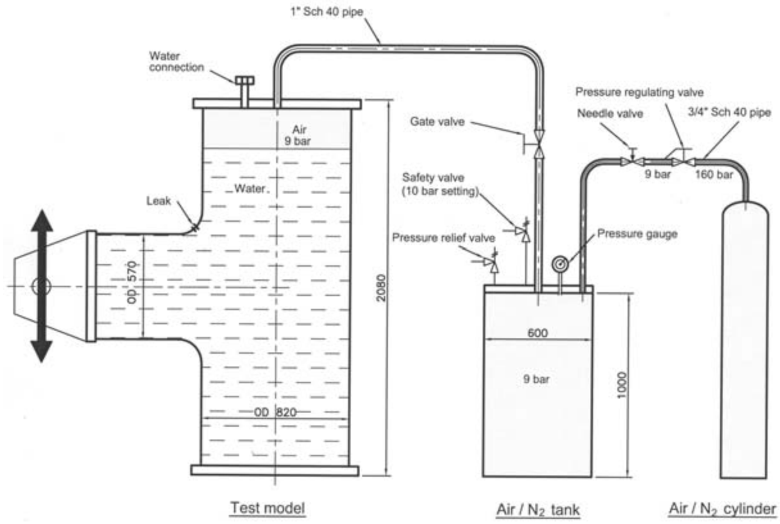


Fig.4 Pressurisation system

Results

Crack is initiated along the entire notch profile after application of about 30,000 lower range load cycles. The asymptotic crack was developed after application of further ~ 20,000 cycles. The target leak (1 kg/h under the pressure of 0.3 MPa) occurs after application of about 25,000 cycles, after crack initiation. The leak rate is also estimated for various pressures (Fig.5). The crack front profile recorded by ultrasonic system is shown in Fig.6. The $2xC_L$ as detected by this is 20 mm. The associated crack length on the outer surface is ~ 113 mm and the crack depth measurement based on PDM indicated a value of 121 mm. Fig.7 shows the developed crack on the surface just before collapse.

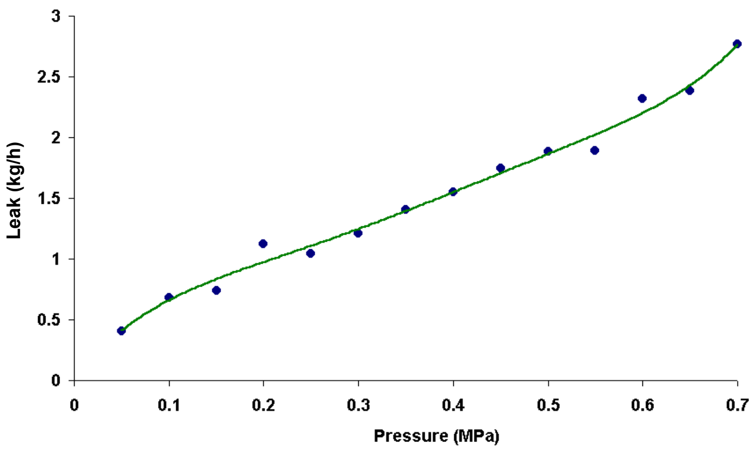


Fig.5 Leak rate Vs pressure

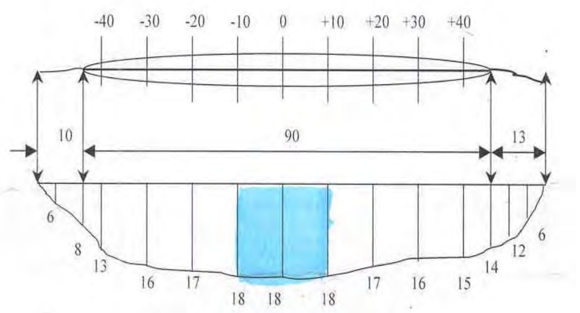


Fig.6 Crack profile for C_L

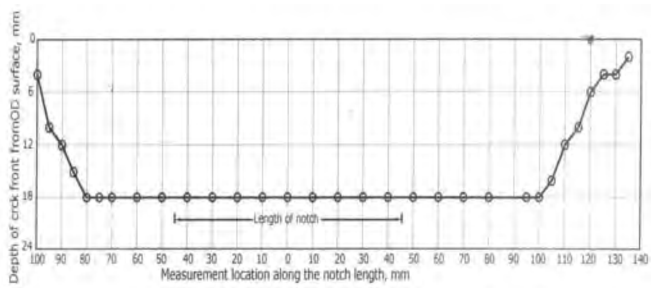


Fig.7 Crack profile at collapse state

The visual inspection of cracked surface after completing the collapse test indicated a few striations as shown in Fig.8. Asymptotic crack is measured from striations from which $2xC_s$ is found to be 115 mm and corresponding 2Cs/h is equal to 6.4. The derived $2x(C_L+ Cs)$ is (20 + 115), i.e.135 mm which is closer to the value of 121 detected by PDM compared to the crack length of 113 mm detected by ultrasonic.

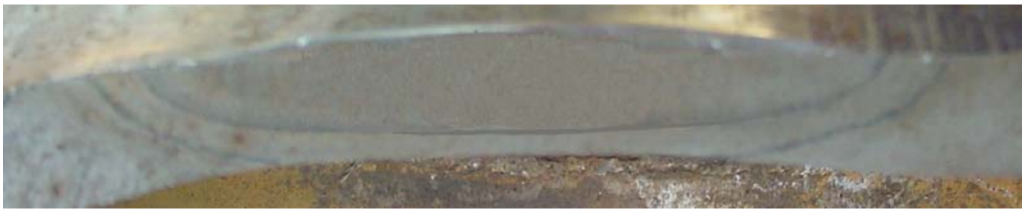


Fig.8 Striations appeared on the cracked surface

Collapse load is derived from load-deflection curve shown in Fig.9. The collapse load at the loading point and corresponding bending moment at the end of pullout are 280 kN and 560 kNm respectively. The deformation behaviour of specimen under collapsed condition as shown in Fig.10 indicates that the collapse is due to local buckling of the pullout portion of the nozzle which is subjected to compressive stress, rather than crack instability due to tearing or net section yielding. The crack remained stable at the time of collapse. It is worth mentioning that, since the bending moment is limited to a value of 388 kNm in the design to limit the stress intensity at the critical location less than the allowable value for level D loading as per RCC-MR, there is additional safety margin of 560/388 (=1.44) on collapse

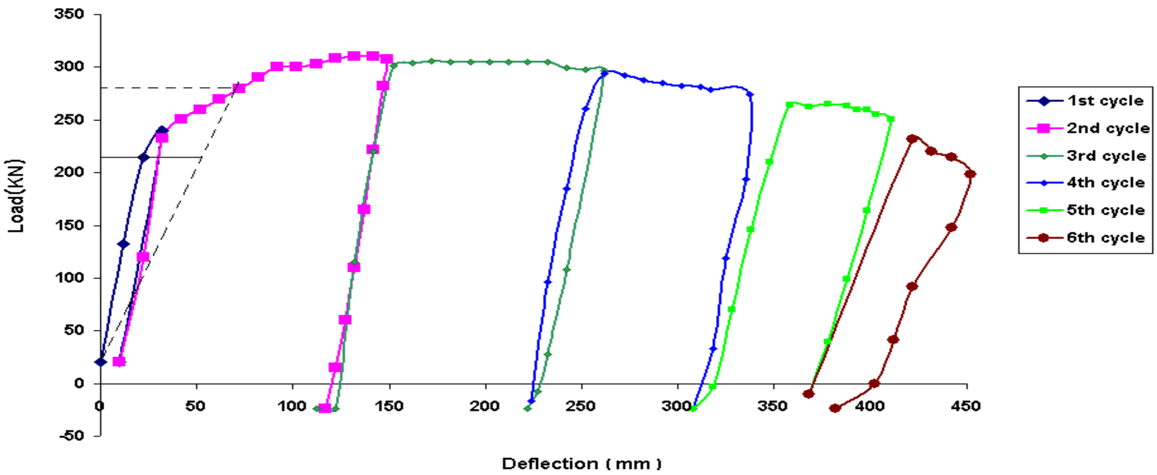


Fig.9 Load Vs deflection during collapse

Fig.10 Collapsed state of specimen

ASSESSMENT OF A16 PROCEDURE

The ratio between the membrane and bending stress components in the vicinity of crack location under steady internal pressure and cyclic end force, is required for the determination of C_s using the master curve given in A16. Longitudinal tensile at the same location is required for calculating crack mouth opening displacement, from which C_L is calculated. These elastic stresses were determined by the analysis of with CASTEM 2000, employing four noded thin shell elements. The analysis geometry includes basic Tee along with straight pipes and end connections. Considering the symmetricity, only ½ model is employed. Notch is not included in the finite element model. The overall deformation of the model is depicted in Fig.11. Since, the longitudinal stress distribution at crack location (perpendicular to the crack length) is important component, the distribution of same is shown in Fig.12. With the computed stresses, A16 procedure is followed to derive Cs, C_L and C_G values which are elaborated below.

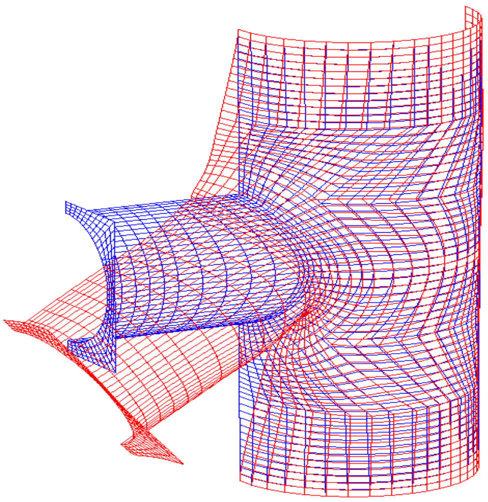


Fig.11 Deformed shape of FE model

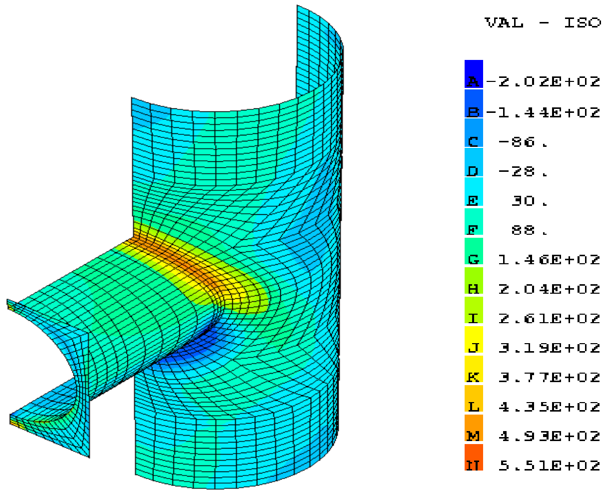


Fig.12 Longitudinal stress distribution

Asymptotic Crack Length (2xCs)

From the stress resultant components (N_{11} and M_{11}) extracted at the notch location, membrane and bending stress ranges viz. $\Delta\sigma_m$ and $\Delta\sigma_b$ are computed as 102 MPa and 73 MPa respectively for the application of 10 t vertical downward force applied at the end (Fig.2). Corresponding to the parameter ($1/(1+ \Delta\sigma_b/\Delta\sigma_m)$ equal to 0.58, Cs/h as read from the Master Curve of A16 is 2.5, which gives the value of 2xC_s as 90 mm for the thickness of 18 mm at the junction. This compares well with the measured value of 115 mm. From the comparison it is also clear that A16 provides a lower C_s value which does not yield conservative results for LBB assessment.

Detectable Crack length (2xC_L)

C_L was derived for 1 kg/h leak rate under 0.3 MPa internal water pressure, based on the correlations given in A16-43. The critical parameter in this computation is crack mouth opening displacement (δ) which is derived from the expression for the infinite plate: $\delta_{plate} = 4x\sigma xc/E$ where σ is the effective membrane stress, c is half of the through crack length and E is the Youngs modulus, including the curvature effects. Further, a rectangular slit type crack over the thickness of 18 mm is assumed. The computed 2xC_L is 114 mm, against the measured value of 20 mm. This indicates that A16 prediction is very conservative, i.e. A16 predicts higher value for 2x(C_s + C_L). The conservatism is partly due to assumption of rectangular slit for the crack which has much higher crack length on the outer surface.

Critical Crack Length (2xC_G)

For the known bending moment which caused collapse in experiments (M_L = 560 kNm) and further using the flow stress value for ASS at RT (R_L = 387 MPa), mean pipe radius (Rm = 280 mm) and thickness (h = 17 mm), β (= C_L/rm) is calculated and in turn C_L is calculated using the expression of global bending moment to cause plastic collapse of pipe with a through wall circumferential crack given in A16-8311.3. The computed value is equal to 750 mm, as against 240 mm observed experimentally. In the experiment, since the failure mechanism is buckling of pullout portion opposite to the

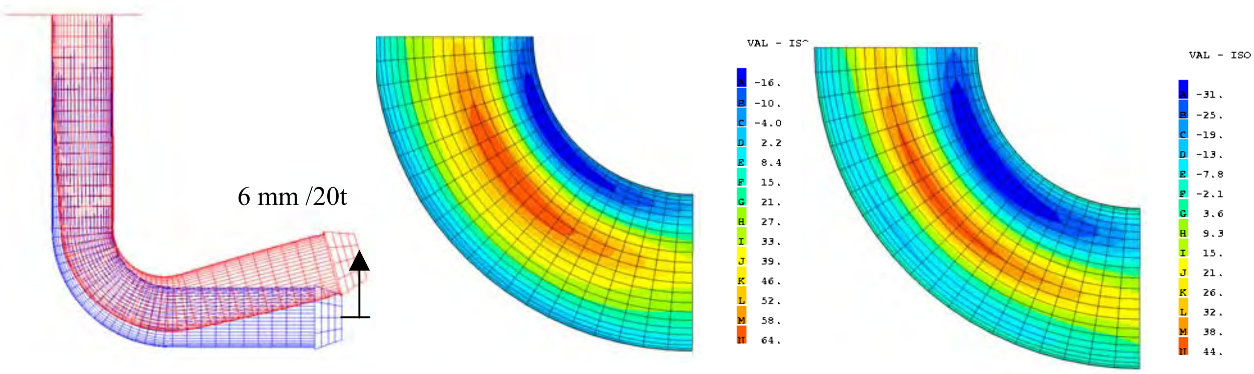
Fig.13 Stable crack opened after collapse test

cracked portion, the collapse occurred at lower load than the value predicted by A16. It is worth mentioning that the crack remained stable even after buckling (Fig.13) and hence, guillotine rupture of such geometry is not possible.

EXPERIMENTAL INVESTIGATION ON BEND

In order to assess the A16 in a similar way for the bend geometry, tests were carried out on full-scale bends fabricated for technology development purposes (Fig.14). The dimensions bend are: outer diameter of pipe is 550 mm, nominal wall thickness is 16 mm, bend radius is 840 mm and lengths of strain portion is 2 m. Preliminary static tests to understand the effects of end conditions (length of straight portions) and manufacturing imperfections (ovality and wall thickness variations) were completed. Flexibility coefficients and stress indices estimated based on design code (RCC-MR/ASME) procedures are found to be conservative compared to test data by about 10 % for the case when the flanges are close to the bend. With longer straight portions (> 2 m for 800 mm pipe bends), the codal values are conservative by < 5 %. The deformations and strains measured on the specimen which has got a thickness variation of ~12 % (max) and ovality of ~2.7 % (max), were compared with the finite element analysis of bend without introducing imperfections (Fig.15). From the comparison of hoop and longitudinal stresses along the circumference at the critical section, shown in Fig.16, it is concluded that effects of manufacturing imperfections do not influence much the stress indices under pure bending moment. However, under pressure loading, stress indices vary significantly due to manufacturing imperfections. For the LBB tests, a notch of 25 mm width and 1.5 mm depth is introduced by machining. Fatigue tests to initiate crack along the notch front is in progress.

Fig.14 LBB test setuo for pipe bend



Deformation

Hoop stress

Longitudinal stress

Fig. 15 Finite element analysis results

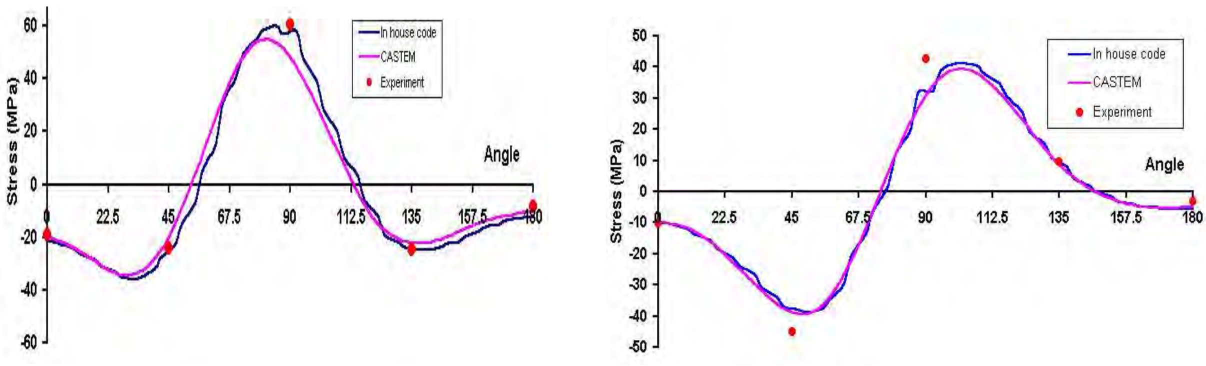


Fig.16 Stress distribution at the critical section of bend

CONCLUSION

The A16 LBB analysis procedure which has been applied for the LBB justification of ASS pipings for PFBR, is assessed critically based on experimental data generated by conducting tests on a typical large size prototype Tee. Even though the A16 prediction of asymptotic crack length (90 mm) is closer to the measured value (115 mm), it does not yield conservative results. The detectable crack length as well as critical crack length predicted by A16 (114 mm and 750 mm respectively) are very conservative compared to the corresponding measured values (20 mm and 240 mm). Thus, the experimentally measured $2x(C_s + C_L)$ is equal to 135 mm and 2xCG is equal to 240 mm, a factor of safety on critical crack length available is 1.8 which is more than the allowable value of unity. As per A16, $2x(C_s+C_L)$ is equal to 204 mm and $2xC_G$ is equal to 750 mm. This has a factor of safety 3.7 which is again more than unity. Hence, in a global sense, LBB is justified by both experimentally and using A16 procedure. For the FBR pipe Tees and bends which are large size thin walled structures, buckling is the possible failure mode, rather than crack instability. Hence, the critical crack length is lower than that associated with crack instability. However, the collapse load even with crack is larger than the value permitted by code by a factor of 1.44 and apart, the crack remains in stable configuration. In view of these, a double ended guillotine rupture is not possible in sodium piping of PFBR, if diameter is more than 250 mm. Further, the investigations have raised the confidence in applying A16 procedure for the LBB justification of PFBR piping in general and Tee in particular. LBB Tests on bend and smaller diameter pipes are in progress.

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