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Design methodology to ensure the structural integrity of the through wall cracked sodium piping system in-service

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Abstract

One of the most desirable safety features of a sodium piping system to be ensured during service condition is the structural integrity during in-service condition. Leak-Before-Break (LBB) is one of the necessary criteria to be respected towards achieving the required level of structural integrity for the pressure retaining the piping system and vessels. It is necessary to ensure the inherent safety capability of providing a clear warning before breakage. The term refers to a demonstration of the system to leak before catastrophic failure. The breakage of the system pressure boundary can cause large sodium leakage. It can lead to rapid disruption and the shutdown of the plant function.

The LBB approach requires application of fracture mechanics methodology to demonstrate that the sodium piping system will ensure detectable leakage and demonstrates that the crack will be stable under the maximum credible loading conditions. The size of this crack should be large enough so that leakage is assured of detection with a margin using the installed leak detection equipment under in-service conditions.

This paper discusses the design methodology adapted to Fast Breeder Reactor (FBR) piping system to ensure the structural integrity of a through wall cracked sodium piping system under service conditions. RCCMR A16 & CEGB R6 design methodology is adopted in this paper towards demonstrating the structural integrity of a typical secondary sodium piping system. Failure Assessment Diagram is used for computing the critical crack length. Using the fracture mechanics concepts the crack growth has been computed against fatigue loading. It is demonstrated that the typical 500 NB FBR pipe bend critical crack length is much greater than that the minimum crack length responsible for the detectable leak rate.

Keywords: Structural Integrity; Leak-Before-Break; Detectable Crack length; Failure Assessment Diagram

1. Introduction

In a pressure-containing component, such as a vessel or pip which could be detected during the manufacturing stage itself. These de several mechanisms, such as an increase in load, due to repeated appli the environmental effect such as corrosion and due to the accelerated m such as creep. The situation becomes very serious in the case of the d the material properties, it can lead to leakage/breakage in the piping (PFBR) is a 500 MWe capacity sodium-cooled fast breeder reactor, running within the plant. One of the important piping layouts of the PFE

PFBR pipes are generally thin walled, low pressure system. system. The main loading condition leads to the initiation/propagatio during the various plant startup and shutdown condition. This operat cyclic load to the pipe elbow. When a thin-walled, 90° elbow is subjec to ovalisation of the circular section into an elliptical one, introduces crack may initiate close to the crown. This crack tends to propagate likely to be imposed due to various loading conditions during the serv the elbow.

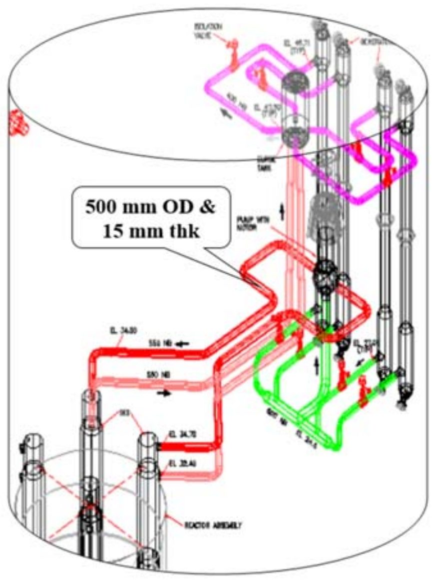
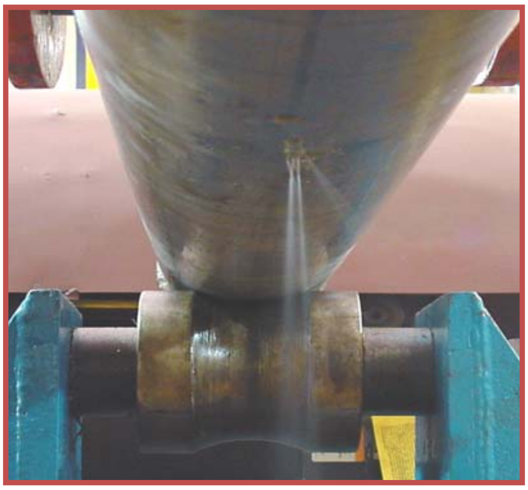


Fig. 1. Typical piping layout of PFBR

If LBB conditions cannot be met, catastrophic failure for the piping system may result. The breakage of the piping pressure boundary can cause massive leakage of the coolant, which is sodium for the PFBR. This can lead to rapid disruption and the shutdown of the plant function, but also severe damage to components. Whereas a leak failure normally does not prevent continued plant operation and can usually be detected before significant damage has occurred [1]. It is important to be able to predict whether a given surface defect would cause a leak before a break. The leak and break consequence are presented in Fig.2.



a) Leakage

b) Breakage

Fig. 2. Different mechanism of piping failure under crack propagation

2. Leak-Before-Break Design Approach

The design of components and piping such that, leakage proceeding failure and giving adequate time for remedial action can help to preclude failure. This criterion is a further barrier within the safety related considerations to preclude rupture. After postulating a pessimistic initial surface crack at the critical location. It is demonstrated that such a surface crack does not grow to the extend to cause a leak of fluid, that is to say, that the ligament ahead of the crack tip is not failed. This is mainly due to low level of primary stresses in FBR components. For demonstrating LBB justification, 3 parameters are required. They are $2C_S$, $2C_L$ & $2C_G$. $2C_S$ represents the asymptotic crack length, $2C_L$ represents the through wall crack length that causes a leak which can be detected definitely within the sensitivity limit of the leak detection system and $2C_{G,}$ represents the critical crack length which produces global instability of the component under application of maximum possible loads. It is to be shown that $2C_G > 2\ C_S + 2C_L$ with a comfortable margin to demonstrate LBB justification. The significance of $2C_S$, $2C_L$ & $2C_G$ are represented in Fig.3. RCC MR A16 [2] is used for the computation of the above parameters.

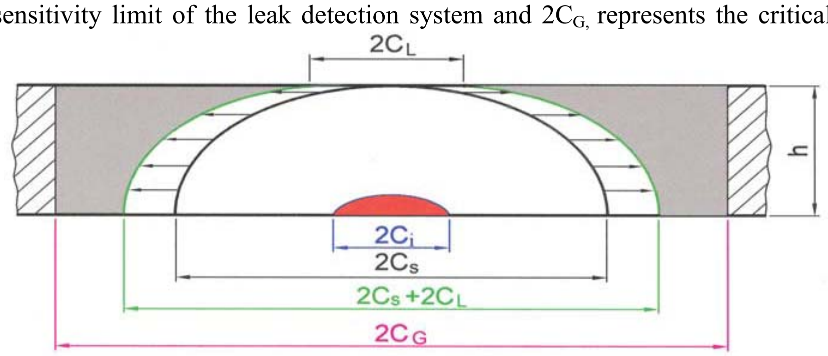


Fig. 3. Crack LBB parameters

3. Leak Before Break Assessment

One of the typical pipe bend has been simulated using the numerical methods towards computing the critical stresses required for calculating the membrane and bending stresses during the cyclic conditions. The dimension of the pipe bend considered for the analysis is 550 NB diameter and 8 mm thickness. Both internal pressure and cyclic bending loads considered for the analysis. The internal pressure of 0.6 MPa has been applied towards the analysis. The in plane bending cyclic load is applied such that, the critical location experiencing the maximum allowable design stress limit during in service. Elastic stresses were computed and the finite element model highlighting the critical location is presented in Fig. 4.

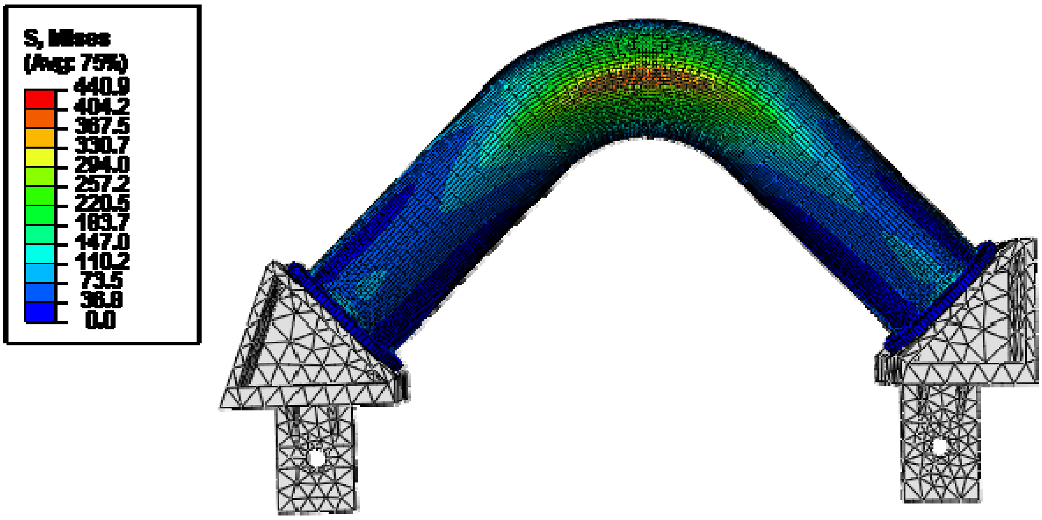


Fig. 4. Von-Mises stress distribution of the combined application of internal pressure and cyclic load

3.1. Computation of Asymptotic Crack Length ($2C_S$) as per RCCMR A16[2]

Based on the membrane stress and the bending stresses obtained during the finite element analysis, the obtained value of $2C_S$ value is computed with the help of the master curve from the RCC MR A16 3442 [2]. Accordingly obtained $2C_S$ value is 50 mm.

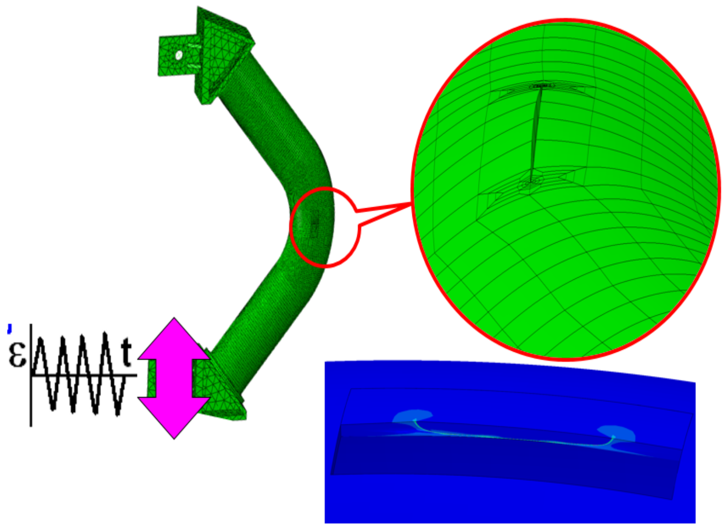


Fig. 5. Numerical predictions of the asymptotic crack length for the typical pipe bend

3.2. Asymptotic Crack Length ($2C_S$) assessment using numerical method

The typical FBR pipe bend has been analysed using the ZENCRACK* software towards predicting the crack propagation behaviour. Accordingly obtained $2C_S$ value is 70 mm. This value is higher than the RCC MR A16 prediction. The discrepancy between the numerical & A16 prediction will be confirmed with the experimental investigation in due course of time. The images of the ZENCRACK numerical prediction is presented in Fig.5. Towards reaching the crack size of 70 mm it takes around one lakh and sixty cycle as shown in Fig.6. Typical pipe bend considered for the crack propagation studies was SS 316 LN. The K_{IC} assumed for the calculation of the above material was 300 MPa√m [3]

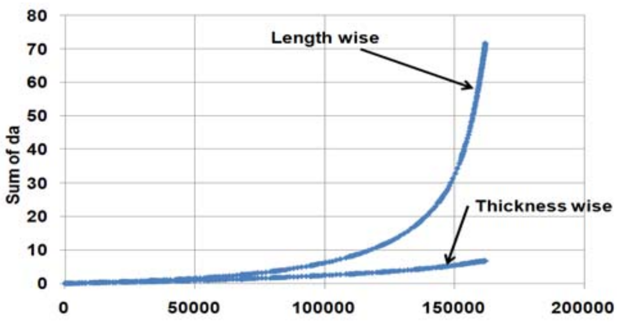


Fig. 6. Pipe bend crack propagation prediction by ZENCRACK

3.3. Computation of Detectable Crack Length ($2C_L$)

The detectable crack length ($2C_L$) is computed iteratively as per the procedure given in RCC MR A16 3430 [1]. C_L is derived for a leak rate of 1 Kg/h (Q_d) under an applied internal pressure of 0.6 MPa. As per ASME Sec XI, a leak rate of the order 100 g/h has to be detected within a time of 20 h. This introduces a requirement of a leak detection system having a sensitivity of 100 g/h (Q_s). However the design code guaranteed a factor of safety 10 against the calculation of C_L. The critical parameter required for the computation of the C_L was elastically computed crack mouth opening distance, effective membrane stress and the leak rate. Accordingly obtained $2C_L$ value is 90 mm.

3.4. Computation of Critical Crack Length ($2C_G$)

The Critical Crack Length of $2C_G$ has been obtained based on the consideration of linear elastic fracture and fully plastic collapse. It can be assessed by using the Failure Assessment Diagram (FAD) provided in CEGB R6 [4]. In FAD, the linear elastic fracture is considered by the factor K_r and the plastic collapse is considered by the factor L_r. K_r is defined as the ratio between the stress intensity factor (K_I) and the fracture toughness (K_{IC}) of the material. L_r is defined as the ratio between the reference stress (σ_{ref}) and the collapse stress ($\sigma_{Collapse}$) of the material. FAD assesses the integrity of the pipe bend by considering the degradation from both fracture and plastic collapse point of view. The crack size has been iteratively varied to arrive the value of $2C_S$. The assessment of the structural integrity of the pipe bend with the advancement of the crack size is presented in Fig. 6. Accordingly obtained $2C_S$ value is 700 mm.

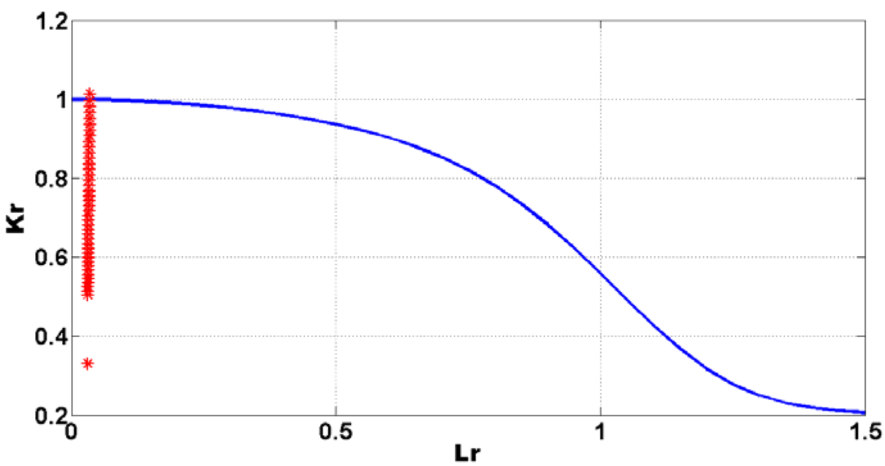


Fig. 6. Assessment of the structural integrity of the pipe bend against the advancement of the crack size on Failure Assessment Diagram

4. Conclusion

LBB justification is an important design requirement towards ensuring the integrity of the pressure boundary against the catastrophic failure under the worst loading scenario can occur during the service condition. Apart from providing the confidence in the structural integrity, LBB provides additional saving of money by omission of the additional safety measures required to protect the system against the double-ended guillotine break. Asymptotic crack length obtained of based on the RCC MR A16 procedure is 50 mm against the numerically predicted value of 70 mm using the ZENCRACK software. The detectable crack length obtained as per A16 method against the leak rate of 1 Kg/h was 90 mm. Thus the 2 total crack opening which is required for the detectable leak rate is ($2C_S$+$2C_L$) = 140 mm. Critical crack length ($2C_G$) obtained as per the R6 method was 700 mm. Since the $2C_G$ was much higher than that of the ($2C_S$+$2C_L$), hence the present pipe bend met the required the LBB criteria with a factor of safety on crack size is 5.0.

5. Future Works

Full scale experimental simulation is planned towards confirming the RCC MR A16 prediction and the numerical prediction by ZENCRACK software.

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