Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division II

EVALUATION OF LEAKAGE SIZE CRACK FOR LEAK-BEFORE-BREAK ASSESSMENT CONSIDERING PIPING SYSTEM COMPLIANCE

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ABSTRACT

Leak-before-break (LBB) concept has been widely accepted as a standard practice as an alternative to the placement of pipe-whip restraints and jet-impingement shields. Evaluation of leakage size crack (LSC) and the demonstration of its stability even under extreme/accident loads are the important steps of LBB procedure. In the conventional method that is usually adopted to perform LBB analysis, the loads at the postulated crack location are evaluated from uncracked elastic piping analysis. However, this simplification tacitly assumes that the presence of crack and the local plastic deformation of the cracked section do not cause any load redistribution. Such an assumption is strictly valid only for piping systems having infinite compliance. In reality, most of the nuclear piping systems possess finite compliance. The present work is intended to address the effects of piping system compliance on the evaluation of LSC for LBB assessment of nuclear piping. Our studies have revealed that the assumption of infinite compliance leads to unconservatism in the estimation of LSC.

INTRODUCTION

Leak-before-break (LBB) has been widely accepted as a technical approach to eliminate pipe-whip restraints and jet-impingement shields in many nuclear power plants (NPPs). Concerns related to the application of this philosophical concept to nuclear reactors in United States were discussed by Wichman and Lee (1990). This alternative option is permitted by most regulatory bodies as long as it is ensured that all the 3 levels of LBB have actually been implemented in the plant. Level-1 is inherent in the design philosophy of ASME section III (2010) which is generally followed to design the primary coolant piping. In level-2 analysis, fatigue crack growth calculations are performed for a postulated surface crack that would be permitted by the acceptance criteria of ASME section XI (2010). The surface crack is usually postulated at locations at which the highest stresses coincident with poorest material properties occur for base materials, weldments and safe-ends. The objective of level-2 analysis is to demonstrate that a small flaw that might have gone undetected in the non-destructive examination would not become through thickness during the life time of the component. Finally, in level-3 LBB analysis it is necessary to demonstrate, at the design stage, that a postulated leakage size crack, in a piping system, would not become unstable even under extreme loading conditions (NUREG-1061, 1984).

The evaluation of leakage size crack (LSC) is an important concern in LBB assessment of reactor coolant piping. Thermal-hydraulic models accounting for the thermodynamic condition of fluid inside the pipe and flaw surface roughness are used to obtain the mass flux leaking through the postulated crack. The mass flux is then multiplied by the crack opening area (COA) to obtain the leak rate. Typically, LSC is defined as a throughwall circumferential or axial crack that leads to a leak rate of 0.5 Kg/s. The LSC essentially ensures that, under normal operating loads, it would lead to a coolant leak rate well in excess of that detectable by the leak detection systems which are presently employed in NPPs.

Besides the evaluation of LSC, the demonstration of its stability even under extreme/accident loads is another important step of LBB assessment. Safe-shut-down earthquake (SSE) is often considered as the design basis event for the primary coolant piping of many NPPs. Conventionally, the applied loads which are used to evaluate LSC (under normal operating condition) and to demonstrate its stability (under accident condition) are obtained from uncracked elastic piping analyses. However, this simplification tacitly assumes that the presence of crack and the local plastic deformation of the cracked section do not cause any load redistribution. Such an assumption is strictly valid only for piping systems having infinite compliance. In an actual piping system, a crack causes a significant increase in local compliance resulting in moment reduction at the cracked section (Smith, 1992).

In this study, the evaluation of LSC was carried out accounting for the finite compliance of the piping system. Our studies revealed that the conventional procedure of evaluating the loads based on uncracked elastic piping analysis leads to lower (unconservative) estimate of the LSC. In reality, the actual loads at the cracked section get reduced due to finite compliance of the piping system. We have carried out detailed 3-D elastic-plastic finite element analyses to evaluate the actual piping loads at the cracked section. It was observed that the actual LSC is larger than that estimated by the conventional procedure. The extent of unconservatism in the estimation of LSC depends on the piping system compliance and the magnitude of normal operating loads.

EXPERIMENTAL PROGRAM

A comprehensive experimental program was pursued at Bhabha Atomic Research Centre (BARC), India and nineteen fracture tests were performed on 8″ NB (219 mm outside diameter) reactor grade pipes (SA-333 Gr-6) to demonstrate the effect of piping system compliance on crack mouth opening displacement (CMOD) and crack growth initiation load. To simulate finite compliance of piping system, pipe ends were welded to flanges (see Fig.1) and the flanges in turn were bolted to rigid pedestals.

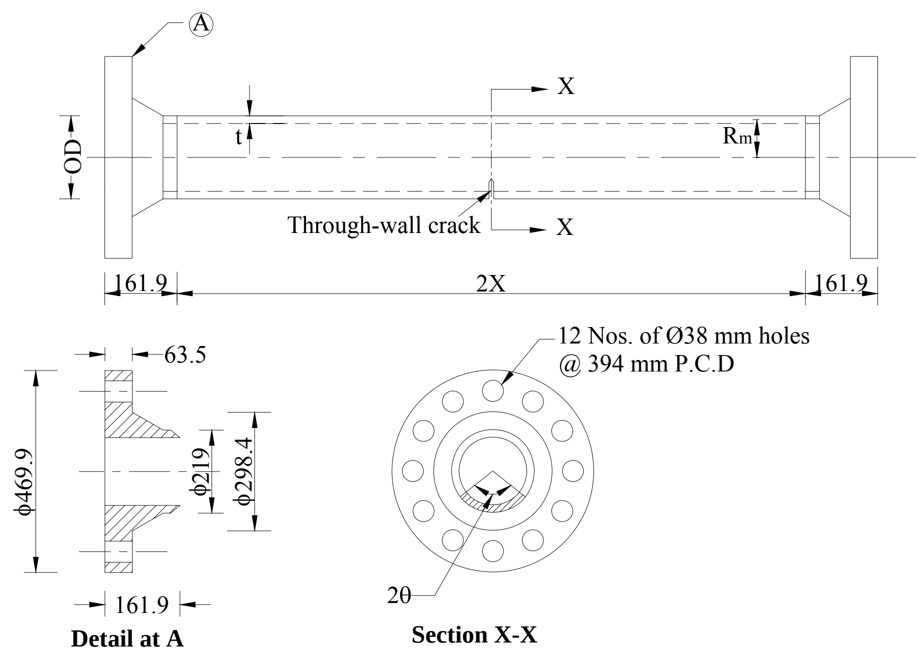


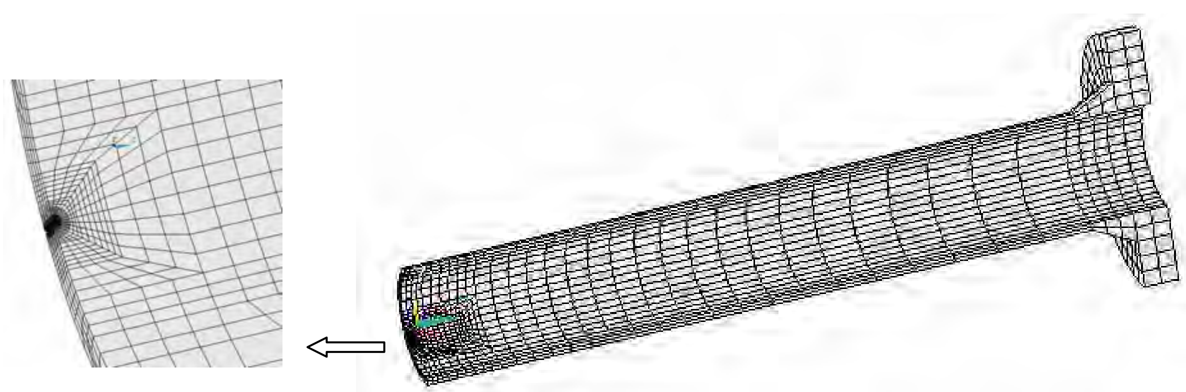
Fig.1: Details of pipe assembly with pipe having a through-wall crack at the centre. All dimensions are in mm.

Two pipe fracture tests were conducted under simply-supported end conditions (simulating a piping system with infinite compliance) and the remaining seventeen fracture tests were conducted under fixed-end conditions simulating piping system with finite compliance. All studies were performed on straight pipes having through-wall circumferential cracks. In the test specimens, the through-wall circumferential notch was machined by means of a cutter. To produce sharp cracks fatigue pre-cracking of the notch was undertaken. The fatigue pre-cracking load was applied at a frequency between 0.3 Hz and 2.0 Hz. The maximum cyclic load was 10% to 20% of the theoretical plastic collapse load and the load ratio (defined as the ratio of the minimum to the maximum load during the load cycle) was varied from 0.1 to 0.2. Image Processing Technique was used to measure the fatigue pre-cracking length during the tests. All the pipe specimens were fatigue pre-cracked till the crack growth in the direction of the notch (circumferential) reached approximately 2 mm at both the notch tips.

The various data acquired during the fracture tests include Load, Load-Line Displacement (LLD), Crack Mouth Opening Displacement (CMOD), rotation at the ends (flanges), pipe deflection at four salient locations and strains. Applied load was measured using a strain gauge based load cell connected to the servo-hydraulic actuator. LLD was measured by an in-built LVDT (linear variable differential transducer) of the actuator. CMOD was obtained from the clip gauge mounted at the crack mouth. During the tests, rotations were noted manually at the pipe ends by means of two inclinometers. Finally the deflections of the pipe were measured at four selected locations by LVDTs. The crack growth at outer surface of the pipe was monitored using Image Processing Technique (IPT). All the fracture tests were conducted at Fatigue and Fracture Studies Laboratory, Structural Engineering research Centre, Chennai, India and further details of this experimental program were provided by Khan et al. (2011).

FINITE ELEMENT ANALYSIS

Detailed finite element studies were performed for some representative cases to numerically simulate the pipe fracture experiments. The geometry was discretised using 3-D 20 noded continuum elements with reduced integration. For cases where the crack was lying at the centre of pipe only a quarter model was analysed due to symmetry. A typical FE mesh employed in the present investigation is shown in Fig.2. Since rotations at the flange were negligible through out the test, fixity boundary condition was applied at the face of flange.



(a) (b)

Fig.2: (a) Zoomed view of crack region and (b) one-quarter finite element model of pipe-flange assembly.

Using round tensile specimens, machined from 8″ NB (219 mm outside diameter) and 16″ NB (406 mm outside diameter) straight pipes, tensile properties of SA-333 Gr-6 were generated by

Chattopadhyay et al. (2000). Stress-strain data of this material obtained from tensile specimens, machined from 8″ NB pipe, is shown in Fig.3

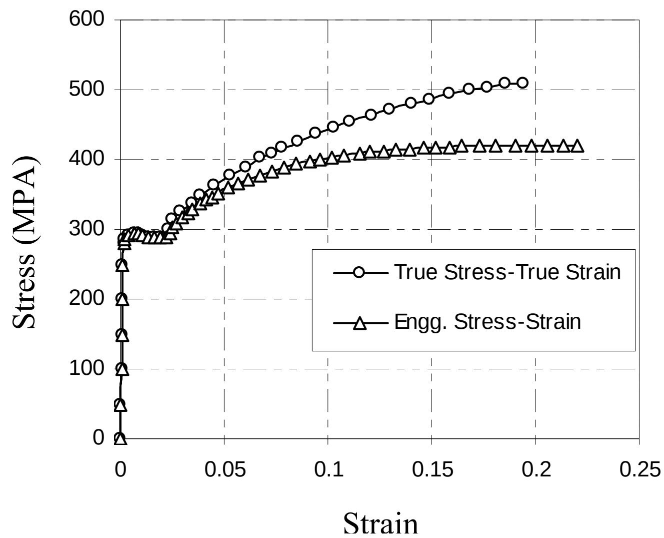


Fig.3: Stress-strain data of SA-333 Gr-6 material (Chattopadhyay et al., 2000).

Both load-line displacement and crack mouth opening displacement were obtained from FE analysis. Numerical (FE) results were then compared with experimental data. The suitability of these numerical results to predict CMOD in light of the experimental data is discussed in the next section.

RESULTS

In this section, we present the comparison of results obtained from FE analysis with experimental data. In Fig.4, load-CMOD response of two straight pipes tested under simply supported condition, representing the case of a piping system having infinite compliance, were compared with FE results.

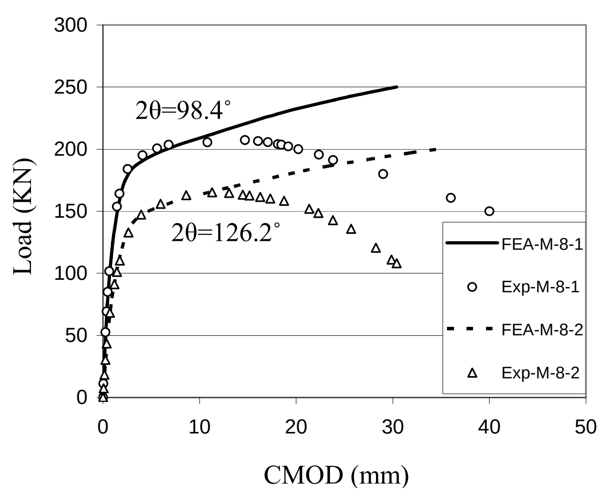


Fig.4: Comparison of load-CMOD response obtained from FE analysis with experimental data.

Good agreement was observed between the experimental data and FE results till maximum load. Since all the present computations were performed for stationary (initial) crack size, FE results deviate from experimental data beyond maximum load due to significant crack growth.

As discussed earlier, piping system (in general) possess finite compliance. Results of pipe fracture experiments clearly revealed that significant load re-distribution occurs in piping systems having finite compliance. To quantify the actual moment at the cracked section, detailed 3-D elastic-plastic finite element (FE) analyses of some of these fracture tests were performed. Fig.5 shows a typical comparison of the bending moment obtained from uncracked linear elastic analysis (conventional approach) with the actual moment obtained from detailed elastic-plastic FE simulation. It is apparent that the conventional approach leads to much higher estimates of the bending moment at the cracked section.

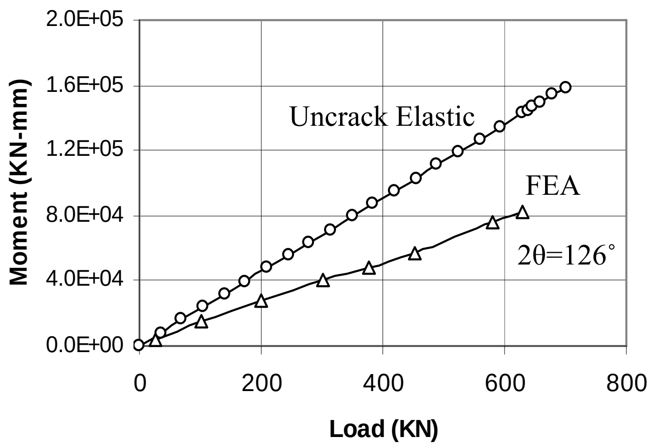


Fig.5: Comparison of bending moment obtained from uncracked elastic analysis (conventional approach) with the actual moment obtained from detailed elastic-plastic FE analysis.

We now compare the load-CMOD response for a straight pipe fixed at both ends representing the case of piping system with finite compliance (see Fig.6). Three sets of calculations were performed. In the first case, a detailed elastic-plastic FE analysis of the entire piping system was performed. The results of FE analysis were in close agreement with experimental data till the initiation of crack growth. Beyond this stage the FE model showed a slightly stiff response due to the neglect of crack growth in numerical computations. Calculations were also carried out as per the conventional approach where the moment at the cracked section was evaluated using uncracked linear elastic analysis. The moments so obtained were then applied on a stand-alone pipe containing a throughwall circumferential crack. As can be seen from Fig.6, this approach leads to much higher estimate of CMOD (for a given applied load) and, thus, would lead to smaller LSC. For a given applied load, if the actual bending moment at the cracked section can be evaluated (accounting for the load redistribution effects arising due to finite piping compliance) then a reasonably good estimate of load-CMOD response can be obtained even from the analysis of stand alone component. Simplified schemes to obtain the actual load at cracked section in a piping system have been suggested in literature (Smith, 1992, Khan et al., 2005). In the present study, the actual bending moment as obtained from detailed FE analysis was used. The load-CMOD response obtained from the simplified approach was in good agreement with results obtained from detailed elastic plastic FE analysis of entire piping system. The difference in results obtained from the two schemes was visible only at higher values of CMOD. The inaccuracy in the results obtained from simplified scheme arises mainly due to the neglect of axial forces that developed at the cracked section when the pipe ends are rigidly fixed.

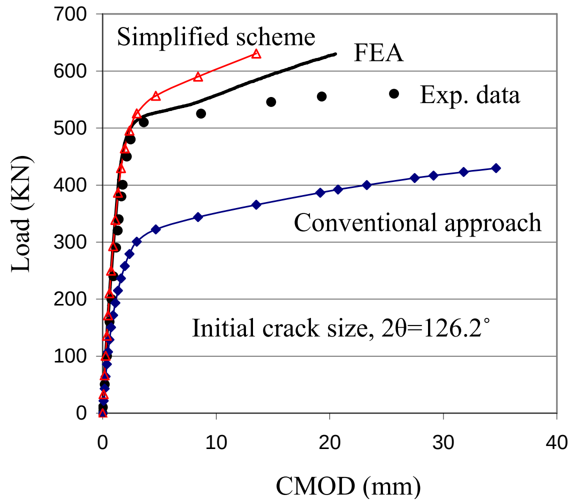


Fig.6: Comparison of load-CMOD response, of a piping system having finite compliance, obtained from FE analysis with experimental data.

DISCUSSION AND CONCLUSIONS

The evaluation of leakage size crack (LSC) for leak-before-break (LBB) assessment of reactor coolant piping requires calculation of mass flux (leaking through the postulated throughwall crack) and crack opening area (COA). Conventionally, COA which is dictated by the crack mouth opening displacement (CMOD) is obtained by performing fracture mechanics analysis of the stand-alone piping component. The applied loadings (under normal operating condition) used in such an analysis are, generally, evaluated from uncracked elastic piping analysis. This simplified fracture assessment procedure is justified provided the compliance of the remaining uncracked piping system is infinite. In general, a real piping system will tend more towards a finite compliance situation. To address these issues, detailed computational (FE) and experimental studies were carried out so that the influence of piping system compliance on the evaluation of leakage size crack can be quantified. Both numerical and experimental studies have clearly revealed that in piping systems, with finite compliance, there is appreciable load redistribution. Thus, the conventional practice of evaluating CMOD without accounting for the finite compliance of the piping system may lead to unconservative (lower) estimate of LSC. However, a detailed elastic-plastic FE analysis of the entire piping system would be time consuming. For a given applied load, if the actual bending moment at the cracked section can be evaluated (accounting for the load redistribution effects arising due to finite piping compliance) then a reasonably good estimate of load-CMOD response can be obtained even from the analysis of stand alone component. Simplified schemes to obtain the actual load at the cracked section in a piping system have been suggested in literature. In the present study, however, the actual bending moment as obtained from detailed FE analysis was used. The load-CMOD response obtained from analysis of stand-alone component (subjected to actual bending moment) was in good agreement with results obtained from detailed elastic plastic FE analysis of entire piping system. This is an interesting finding that allows the incorporation of piping system compliance effect on the evaluation of LSC in a simplistic manner. Further studies are in-progress to provide some general guidelines related to the effects of system compliance on LBB assessment of nuclear piping.

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