FATIGUE STUDIES ON CARBON STEEL PIPING
MATERIALS AND COMPONENTS:
INDIAN PHWRS

Health, Safety & Environment Group, BARC

Introduction

The design of engineering components and structures is based on material properties, obtained from monotonic tensile tests. However in service, repeated thermal stresses are generated, due to expansion and contraction as a result of temperature gradient, which occur because of heating and cooling during start-up, shut down and thermal transient condition. This phenomenon of thermal cycling is termed as Low Cycle Fatigue (LCF). The expansion and contraction in the piping system due to thermal gradient, leads to strain cycling resulting in LCF damage, in the piping system. Therefore, it is important to consider the Low Cycle Fatigue (LCF) and cyclic stress-strain behavior of the material, in the design and integrity analysis of the structural components, subjected to plastic deformation at room and operating temperatures.

In a more general view, the localized plastic strains at notch, subjected to either cyclic stress or strain, result in strain controlled conditions near the root of the notch, due to the constraint effect of larger surrounding mass of essentially-elastically deformed material. Since plastic deformation in materials is not completely reversible, modification to the structures occurs during cyclic straining, which can give rise to changes in stress-strain response due to thermal cycling. Therefore, cyclic stress strain of the material, differs from the monotonic and needs to be evaluated.

Failure of piping components under normal operating conditions, well below the allowable stress given by codes, can often be attributed to flaws. Such failures show, that conventional stress analysis is not sufficient, to guarantee component integrity under operational conditions. Welding is one of the widely used fabrication processes in the piping system of nuclear power plants. Although utmost care is taken in following various standards to produce defect-free weld joints, some defects may be undetected during inspection at the time of welding, due to either limitation of the inspection system or human error. Fatigue is one of the mechanisms, considered active in the piping system, which may lead to crack initiation, either from the highly stressed regions or the undetected flaws or the heterogeneity in the weld material of weld joints. Therefore, it is desirable to confirm that crack initiation due to cyclic loading, will not occur during the service period of the reactor. Behavior of initiated cracks (i.e. crack growth) under cyclic loading, for accurate prediction of life of the component, is also of concern to most of the older nuclear power plants.

The current Leak Before Break (LBB) assessment procedure is described in USNRC guide [1]. LBB is
ensured by demonstrating three levels of safety assessment against sudden Double-Ended Guillotine Break (DEGB). Level 1 is inherent in the design philosophy of ASME Section III, which is normally followed in piping design. Level 2 requires postulating a surface crack mostly in the weld and shows that there is insignificant crack growth of this surface, during the entire life period of the reactor. From operating experience of PHWRs, it has been observed, that under controlled environment of primary heat transport piping system, fatigue is the only mechanism, which cannot be ruled out. Level 3 requires postulating throughwall crack at the maximum stress region, with the most unfavorable material properties and shows that this crack will withstand maximum load that may act during safe shutdown earthquake event. Level 2 assessments for LBB require evaluation of fatigue crack initiation and crack growth rate.

In the past, fatigue crack initiation was studied, using notched small specimens by evaluating local stress or strain at the notch tip, considering the stress or strain concentration, equivalent energy density method and Low Cycle Fatigue (LCF) curve [2]. Paris Law has been used for evaluation of Fatigue Crack Growth Rate (FCGR) using constants derived from Compact Tension (CT) or Three Point Bend (TPB) specimens, following the ASTM E647 [3]. The ASME Boiler and Pressure Vessel Code Section XI also gives the FCGR curve for air and water environments for carbon and low alloy ferritic steels [4], based on small specimens. The effects of stress ratio on the fatigue crack growth behaviour are widely available for standard specimens [5]. This crack growth data obtained from CT or TPB specimens, are conveniently used for prediction of crack growth in surface flawed components, assuming that surface flaw attains a semi-elliptical shape during growth, crack growth rate is independent of the states of direction and stress.

In view of this, the Reactor Safety Division initiated a component test program, to understand, demonstrate and verify the issues, related to design, safety and life extension of piping components. In this programme, pipes and elbows were procured as per specifications and requirements of the primary heat transport system piping of Indian PHWRs. Welding of the pipes was carried out as per the general requirements of ASME Section IX and the acceptance criteria of ASME Section III. Additional requirements specified by NPCIL for Indian nuclear power plants were also followed. All the tests (LCF and FCGR) on small specimens were carried out as per procedure of the ASTM standards. Actual pipe, pipe weld and elbows with surface notch were used for component tests.

This article describes the results of fatigue studies on carbon steel piping materials and components of Indian PHWRs. Tests on actual pipes and elbows with part through notch were carried out, to study the behaviour of crack growth under cyclic loading for different pipe sizes, notch aspect ratios, stress ratios etc. In conjunction with component tests, experimental studies were also conducted on standard specimens to understand the effect of different variables such as size (thickness), type of specimen and components (elbow and pipe), welding, stress ratio, notch orientation on fatigue crack growth rate. The analytical predictions for crack initiation and crack growth for the tested components were compared with experimental results. In all, 80 specimens and 28 components were tested under this programme with the following objectives:

- Generation of low cycle fatigue curves and fatigue crack growth rate database for piping material.
- Demonstration of Level II, Leak Before Break design criteria showing that if there is flaw/ defect, there will be insignificant crack growth during the operating life of the plant.
To show that crack grows more rapidly in depth (thickness) direction as compared to surface (circumferential) direction. This is essential for verification of Level II, LBB.

- Applicability of FCG data generated from the specimens in the design and analysis of the component.
- To understand the effect of various parameters such as base and weld, orientation of notch, product form, thickness, stress ratio etc. on FCGR.
- To verify the existing analytical procedure for the prediction of fatigue life of the flawed components.

We require our own component integrity test programme considering the fact, that fatigue behaviour of the piping system is dependent on the material, fabrication process, geometry and degradation mechanisms encountered in the piping system. The studies carried out on actual materials and components will help in reducing the factor of safety. Reduction in safety factor will lead to lowering of cost of construction of the plants. Remaining life of the component can be accurately predicted.

**Experimental Programme**

**Materials**

Studies were carried out on seamless pipes of SA333 Gr.6 and elbows of SA420 WPL6 material used in Indian PHWRs. The pipes and elbows were in the normalized and tempered condition conforming to specifications of ASME Section II [6] and Section III.

Welding of pipes was carried out as per guidelines given in section XI of the ASME code. Additional requirements specified by NPCIL were also followed. The Gas Tungsten Arc Welding (GTAW) process was followed, for root pass and the second pass and Shielded Metal Arc Welding (SMAW) for the remaining passes. ER-70S-2 welding rod was used, for GTAW and E-7018-1 electrode for SMAW. After completion of welding, post weld heat treatment was carried out, to relieve stresses introduced during welding.

The measured chemical composition and tensile properties of the pipe and pipe weld material are detailed in a paper by the author [7]. Fatigue tests were conducted on specimens and components (pipes and elbows). A brief summary of tests conducted under this programme is discussed below.

**Component and Specimen Testing**

Fatigue crack growth analysis in flawed components requires FCG data, which is usually evaluated using CT or TPB specimens and expressed as Paris law. FCGR in component and specimens may differ because of difference in the stress ahead of their crack tip. Range of DK obtained from the specimen tests are lower as compared to that of components for a given stress range. Therefore, extrapolation or suitability of Paris law constants for higher ranges of DK is also one of the issues to be resolved. In view of this, we plan to carry out studies on components and specimens.

**Specimen Testing**

Specimen testing was conducted, to determine the basic cyclic stress strain curve, Low Cycle Fatigue (LCF) and Fatigue Crack Growth Rate (FCGR) properties. In addition to this, transferability (specimen data to component) and extrapolation (for higher crack growth and ΔK) of crack growth data are the issues, which need to be resolved.

- Low Cycle Fatigue: Tests were conducted on standard uniaxial specimens under strain-controlled condition in which strain range (Δε) was varied from 0.4 to 3.0 %. In all, 40 specimens were tested. The outcome of these tests was cyclic stress strain and low cycle fatigue curve. These properties were used, for assessment of crack initiation life of the notched component.
Fatigue Crack Growth Rate: Tests were conducted on CT and TPB specimens. The location of machine with respect to pipe is shown in Fig. 1a. The outcome of these tests was the material constants of Paris law. About 50 specimens were tested, to understand the effect of different parameters on FCGR:

a) Specimen type: CT and TPB, these specimens were selected to understand the effect of constraint on the FCGR because the state of stress ahead of crack tip is different. Both the specimens are acceptable as per ASTM standard.

b) Stress ratio: \((R = \text{Minimum load} / \text{Maximum load})\): 0.1, 0.3 and 0.5. Varying stress ratio was considered, to understand the effect of crack closure.

c) Base and Weld: Specimens were machined from pipe base and pipe weld.

d) Thickness of specimen: Specimens were machined from different sizes of pipe, that is 10 mm, 15 mm and 20 mm from 219 mm, 324 mm and 406 mm outer diameter respectively.

e) Product form: Specimens were machined from seamless pipe and pipe bend (elbow)

f) Notch orientation: Specimens were machined in two orientations namely LC and CL. The notch is in longitudinal direction with respect to the pipe in CL orientation, whereas it is in circumferential direction in LC orientation.

---

**Component Testing**

Fatigue crack growth studies were conducted on pipes and elbows with pre-machined notch. In all, 28 tests were conducted to cover the effect of the following variables:

a) Component type and size: Component type is pipe and elbow. Three pipe sizes tested were of outer diameters, 219 mm, 324 mm and
406 mm, which are designated in this paper as 200NB, 300NB and 400NB, respectively. The corresponding thickness are 15 mm, 22 mm and 26 mm. Elbow size tested was 90° short radius of 219 mm outer diameter and 15.1 mm nominal wall thickness.

b) Stress ratio (R = Minimum load / Maximum load): 0.1 and 0.5.

c) Pipe and pipe weld: Tests were conducted on seamless pipes with initial notch in pipe base and girth welded pipe with notch at weld location.

d) Notch size or notch aspect ratio: Notch length (2C), Notch depth (a/t) range covered was 0.13 to 0.4 and aspect ratio (2C/a) varying from 11 to 57. This was considered to better understand the evolution of flaw shape under cyclic loading.

Notch shape and the nomenclature are shown in Fig. 1(b).

e) Notch location: In elbow tests, the notch was machined at crown and intrados.

Schematic and actual test set up for pipes are shown in Figs. 2(a) & 2(b), for elbow in Figs. 2(c) & 2(d). The support system for pipe test consists of two pedestals with two rollers, which provides four-point bending. This type of loading ensures, that the mid section of the specimen, where the notch is located, is subjected to pure bending.

Tests were carried out at room temperature and air environment under load control mode using sinusoidal

---

**Fig. 1(b): Pipe cross section of notch plane with circumferential, rectangular, external surface crack**
waveform loading with constant amplitude. The cyclic loading frequency was kept in the range of 0.5 to 1.0 Hz.

**Low Cycle Fatigue (LCF)**

Cyclic stress-strain and LCF properties were evaluated according to the procedure given in ASTM E606 standard [8]. The specimen (diameter 4.5 mm) was machined from the 400 mm outer diameter pipes and is shown in Fig. 2(e). Tests were conducted under fully reversible condition for different strain ranges at room and operating (288°C) temperatures and air environment. The LCF curves for room and operating temperature

![Fig. 2(a) : Schematic set up for pipe test](image)

![Fig. 2(b) : Actual set up for pipe test](image)
are given in Fig. 3. The cyclic stress strain curve can be represented by equation (1) and LCF curve by equation (2).

\[
\frac{\Delta \varepsilon}{2} = \frac{100}{E} \times (\Delta \sigma/2) + (\Delta \sigma/2k)^{\nu}
\]  

(1)

\[
\Delta \varepsilon/2 = \sigma_i \varepsilon_i /E (2N)^{b} + \varepsilon_f (2N)^{c}
\]

(2)

Where, \(\Delta \varepsilon/2\) is total strain amplitude (%), \(\Delta \sigma/2\) is total stress amplitude (%), \(2N\) is number of reversals (one cycle consists of two reversals), \(N\) is number of cycles to failure, \(\sigma_i\) is Fatigue strength coefficient, \(\varepsilon_f\) is fatigue ductility coefficient, \(b\) is fatigue strength exponent, \(c\) is fatigue ductility exponent, \(E\) is Young’s Modulus in MPa.

Values of constants in above equations as evaluated from tests are given in Table 1.

Material undergoes cyclic strain hardening which is more pronounced at operating temperature. The attainment of maximum stress is also faster at 288°C as compared to room temperature. The cyclic hardening rate for this type of steel can be attributed to interaction between dislocations and solute atoms. Solute atoms in the material cause obstruction to the movement of dislocations and to maintain the strain rate with continued cycling, dislocations are generated continuously. The generation of more dislocation results in increase of dislocation density, which leads to increase in stress. LCF properties have been observed to be superior at room temperature than at 288°C for low strain ranges, whereas properties are almost identical at higher strain ranges. This is consistent with the fact that serrations were observed, in hysteresis loop, for strain amplitude above ± 0.5% and
Table 1: The values of fatigue curve constants and cyclic stress strain curve constants

<table>
<thead>
<tr>
<th>Strain ratio</th>
<th>Temperature (^{\circ}\text{C})</th>
<th>(\sigma_f)</th>
<th>(\varepsilon_f)</th>
<th>b</th>
<th>c</th>
<th>n</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28</td>
<td>91207</td>
<td>47.97</td>
<td>-0.1283</td>
<td>-0.5551</td>
<td>349.9</td>
<td>0.1766</td>
</tr>
<tr>
<td>-1</td>
<td>28</td>
<td>58606</td>
<td>24.06</td>
<td>-0.0757</td>
<td>-0.4814</td>
<td>354.27</td>
<td>0.1523</td>
</tr>
<tr>
<td>0</td>
<td>288</td>
<td>50727</td>
<td>21.15</td>
<td>-0.0454</td>
<td>-1.004</td>
<td>360.46</td>
<td>0.04865</td>
</tr>
<tr>
<td>-1</td>
<td>288</td>
<td>966240</td>
<td>127</td>
<td>-0.0049</td>
<td>-0.7150</td>
<td>358.27</td>
<td>-0.00575</td>
</tr>
</tbody>
</table>

Curve was also compared with ASME Section II of Boiler and Pressure Vessel code design fatigue curve. In order to do so, a factor 2 on stress and 20 on number of cycles was used, on experimental data points, because ASME design fatigue curve takes into account these factors. The comparison is shown in Fig. 4. It is observed that material fatigue curve compares well with that given by ASME Section II of Boiler and Pressure Vessel code for C-Mn steel.

**Fatigue Crack Growth Rate: Specimen Tests Results**

The FCGR tests on specimens were conducted to determine the crack growth rate constants. FCGR is modeled using the Paris Law given as: \(\frac{da}{dN} = C (\Delta K)^m\), where \(\Delta K = \Delta \sigma \sqrt{a} F_g\). C and m are FCGR constants, \(\Delta \sigma\) is applied stress, \(\Delta a\) is crack depth, \(F_g\) is geometry factor (depends on the pipe and notch size). As mentioned earlier, several tests were conducted to understand the effect of different parameters such as stress ratio, source of specimens, thickness of specimen etc. The experimentally observed effects of these parameters are discussed in the following paragraphs.

**Effect of Stress Ratio and Type of Specimen**

The fatigue crack growth rate curves were generated for stress ratios as per the ASTM standard E647 [3] using TPB and CT specimens machined from the same pipe material. The effect of R is shown in Figs. 5 and 6. The comparison temperature 288\(^{\circ}\text{C}\) showing that, the material is susceptible to Dynamic Strain Aging (DSA). Samuel K.G. et al [9] have made a similar observation. LCF
of da / dN obtained using CT and TPB is shown in Fig. 6. These specimens were machined from 400 mm outer diameter pipe. Figures indicate that, for a given ∆K, da / dN increases with increase in stress ratio. This effect is relatively more significant at lower R-values. This variation is mainly because of the crack closure effect, which gets reduced as stress ratio increases. It is also observed that da / dN versus ∆K behaviour is nearly the same in CT and TPB specimen tests.

Specimens machined from pipes and elbows also exhibit the same FCGR behaviour, as shown in Fig. 8. This indicates that manufacturing process of the piping components, does not affect FCGR curve significantly, for this grade of steel.

Fig. 5: Comparison of FCGR curves at different stress ratios, obtained using CT specimens

Fig. 6: Comparison of da/dN for CT and TPB specimens

Effect of Thickness and Product Form

TPB specimens were machined from all sizes of pipe of diameter such as 219 mm, 324 mm and 406 mm. The specimens from different pipe sizes differed with respect to thickness. The aim of this study was to see the effect of thickness of specimen on FCGR. The results are shown in Fig. 7. It was found that there is no significant difference in the FCGR property.

Fig. 7: Comparison of FCGR curves for specimens of different thickness machined from various sizes of pipes

Fig. 8: Comparison of FCGR curves for TPB specimens machined from pipe and elbow
**Effect of Notch Orientation with Respect to Pipe Extrusion Axis**

CT specimens machined from the 400 mm outer diameter pipe were tested in two orientations, namely LC and CL. In CL orientation, the notch is in longitudinal direction with respect to the pipe, whereas in LC orientation it is in circumferential direction. The test results in Fig. 9 show, that there is no significant difference in FCGR behaviour with respect to orientation of the notch and with respect to pipe axis.

**Fig. 9: Comparison of FCGR curves for specimens notch in different orientations with respect to pipe axis**

**Effect of Base and Welds**

TPB specimens were prepared from different sizes of pipes and pipe welds and tests were carried out. The test results for CT specimens from pipe (base) and pipe weld of 406 outer diameters are compared and shown in Fig. 10. FCGR curves obtained for TPB specimens from pipe welds of outer diameters 219, 324 and 406 mm are also compared and shown in Fig. 11. Comparison of FCGR curves for base and weld obtained using TPB specimens are shown in Fig. 12. Figs. 10 and 12 indicate that there is no significant difference between base and welds of different sizes of pipes.

**Fig. 10: Comparison of FCGR curves for specimens machined from pipe and pipe weld**

**Fig. 11: Comparison of FCGR curves for TPB specimens from different sizes of pipe welds**

**Fig. 12: Comparison of FCGR curves of base and weld using TPB specimen**
Summary of the specimen testing

The above results show, that for the present grade of material, the FCGR is not significantly affected by specimen type (CT and TPB), specimen thickness, product form (specimen from elbow and pipe), base and weld metal and notch orientation. The effects of stress ratio are mildly significant at lower R-values.

Component Test Results

The basic aim of carrying out the fatigue tests on components (that is, pipe and elbow), was to compare the fatigue crack growth rate determined using specimens (CT or TPB) and that of pipe which is under more realistic stress field. A brief detail of the fatigue tests on pipes and elbows was described in the preceding section. Milling machining process was used, to machine the blunt notch having a tip radius of approximately 0.1 mm. This value was assumed based on milling cutter tip radius and hence, it is approximate.

The initial cycles of loading produce sharpening of machined blunt notch. Once the crack tip is sharpened, then each loading cycle produces incremental crack growth. The initiation of crack was detected using instrument based on Alternating Potential Current Difference (ACPD) technique. The instrument used, had a detection threshold of 0.1 mm. This in turn implies that, crack initiation can only be detected after a crack growth of 0.1 mm. In few cases crack initiation could only be detected after a crack growth of 0.5 mm. The experimental findings and related number of cycles to crack initiation, fatigue crack growth and their analytical modeling are discussed in the following sections.

Analytical Estimation for crack initiation

In order to predict the number of cycles to crack initiation, a model was used, in which the elastic-plastic strain range is estimated, based on K-fields (where K is linear elastic crack driving force parameter) combined with Neuber’s Rule. The crack tip triaxiality was accounted for, by using a correction term based on A-16, appendix of RCC-MR code [12]. These calculations are based on cyclic stress strain curve of this material. Briefly the model can be described as follows:

It is assumed, that the state of stress is plane 2D type. For the notch having a tip radius $\rho$ and the remote stress range $\Delta\sigma^0$, the approximate value of maximum pseudo elastic stress range $\Delta\sigma^{pe}$, at distance $d$ (known as characteristic distance), from the notch tip can be evaluated by the Creager formula (Creager et al, 1967) [10].

$$\Delta\sigma^{pe} = [\Delta K / \sqrt{2\pi r}] \times (1.0 + \rho/2r)$$  \hspace{0.5cm} (3)

where, $r = d + \rho/2$ ($\rho = 100 \mu m$ based on cutter radius, $d = 70 \mu m$).

$$\Delta K \text{ (stress intensity factor range)} = \Delta\sigma^0 \sqrt{\pi a} \times F_g;$$

For Pipe

$$\Delta K = (\Delta\sigma_m M_m + \Delta\sigma_b M_b) \sqrt{\pi a} \times F_g;$$ For Elbow

$\Delta\sigma_m$ is Membrane stress range, $M_m$ is Correction factor for membrane stress $\Delta\sigma_b$ is Bending stress, $M_b$ is Correction factor for bending stress, $a = \text{depth of the notch, } F_g = \text{Geometry factor (A16, 1995) (depends on the type of notch, shape of the component and type of load).}$

After evaluation of $\Delta\sigma^{pe}$, the corresponding pseudo plastic strain range has been evaluated by equation (4), which approximately takes into account the state of tri-axial stress on the pseudo plastic strain range

$$\Delta e^{pe} = (\Delta\sigma^{pe}/E) \times [2(1 + \mu)/3]$$  \hspace{0.5cm} (4)

where $\mu$ is the Poisson’s ratio $= 0.3$
Once the elastic plastic strain range is known then the number of cycles to crack initiation is determined from the LCF curve. This procedure is similar to that recommended by French A-16, Appendix of RCC-MR code. Predicted number of cycles required for crack initiation are given in Table 6 for the pipes and elbows for which crack initiation could be detected at 0.1 mm of crack growth.

The comparison of experimental and analytical crack initiation results, given in Table 2, show that agreement is reasonable for many cases for this appropriate model. Differences in the experimental and analytical results may be due to various assumptions made in the model of fatigue crack initiation. Initiation of the crack is strongly dependent on the material condition, state of stress ahead of the crack tip and characteristic distance (d) ahead of notch tip. In reality, characteristic distance varies with grain size and inclusion content of the material and hence it is difficult to determine an exact value. The state of stress is assumed to be plane 2D and the triaxiality effect is accounted for approximately in the present model.

**Fatigue Crack Growth in Component: Test Results**

The fatigue crack growth tests on pipes and elbows were conducted, to determine the crack growth rate constants and demonstrate the Level II requirement of LBB assessment. As mentioned earlier, several tests were conducted to understand the effect of different variables such as stress ratio, notch orientation, pipe size, pipe and pipe weld. The experimentally observed effects of these variables are discussed in the following sections.

**Comparison of FCGR between pipes and specimen (CT or TPB)**

FCGR curves were determined for pipes, from the crack length versus number of cycles record,

---

**Table 2: Comparison of experimental and analytical results for crack initiation**

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Component</th>
<th>Stress ratio</th>
<th>Experimental (for crack to grow by 0.1 mm)</th>
<th>Analytical</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBSC8-1</td>
<td>Pipe</td>
<td>0.1</td>
<td>53,000</td>
<td>89,646</td>
</tr>
<tr>
<td>PBSC8-2</td>
<td>Pipe</td>
<td>0.5</td>
<td>320,000</td>
<td>344,275</td>
</tr>
<tr>
<td>PBSC8-3</td>
<td>Pipe</td>
<td>0.5</td>
<td>235,000</td>
<td>250,329</td>
</tr>
<tr>
<td>PBSC8-4</td>
<td>Pipe</td>
<td>0.1</td>
<td>8,000</td>
<td>6,000</td>
</tr>
<tr>
<td>PBSC8-5</td>
<td>Pipe</td>
<td>0.5</td>
<td>45,000</td>
<td>35,835</td>
</tr>
<tr>
<td>PBSC8-6</td>
<td>Pipe</td>
<td>0.1</td>
<td>3,000</td>
<td>4,098</td>
</tr>
<tr>
<td>PBSC12-1</td>
<td>Pipe</td>
<td>0.1</td>
<td>2500</td>
<td>1550</td>
</tr>
<tr>
<td>PBSC16-1</td>
<td>Pipe</td>
<td>0.1</td>
<td>500</td>
<td>278</td>
</tr>
<tr>
<td>PBSC16-4</td>
<td>Pipe</td>
<td>0.1</td>
<td>400</td>
<td>270</td>
</tr>
<tr>
<td>EWC8-2</td>
<td>Elbow</td>
<td>0.1</td>
<td>249000</td>
<td>240180</td>
</tr>
<tr>
<td>ESCC8-3</td>
<td>Elbow</td>
<td>0.1</td>
<td>2000</td>
<td>2556</td>
</tr>
<tr>
<td>ESC18-4</td>
<td>Elbow</td>
<td>0.1</td>
<td>8000</td>
<td>13629</td>
</tr>
</tbody>
</table>
obtained during the tests. Stress intensity factor range was evaluated based on the stress range, instantaneous crack length and the geometry factor [13]. FCGR curves determined for 219 mm, 324 mm and 406 mm outer diameter pipes are shown in Figs. 13 to 16. The comparison of crack growth rate curves of pipes with TPB specimens and the ASME curve [4] are shown in Figs. 13, 15 and 16. The comparison of the crack growth curve indicates that for all ΔK, the crack growth rate given by ASME is higher. It can be inferred that use of the crack growth rate given in ASME will give a conservative prediction.

From the component test results it can be concluded, that the FCGR curve for the pipes and TPB specimens, are not significantly different. Experimental FCGR curve for pipes lies on the lower side of ASME Section XI curve. This observation is consistent with the specimen test results, too. Prediction of fatigue life based on Paris constants given in ASME, will be conservative.

**Effect of stress ratio on FCGR in pipes**

In the previous section, effect of stress ratio on FCGR has been brought out based on the results of the tests on CT or TPB specimen. Investigations on the stress ratio effect on FCGR have
been also carried out for pipes and is shown in Fig. 14. This figure indicates that FCGR is mildly affected by stress ratio in Paris region, which is consistent with the observation of specimen test results.

**Aspect ratio evaluation with crack growth in pipe**

During the pipe test, crack length (circumferential direction) and crack depth (thickness direction) were measured at different loading cycles. Based on this data, variation of crack aspect ratio (2C/a) with crack growth in thickness direction is shown in Fig. 17 for 300 NB and 400 NB pipes. It is observed that aspect ratio decreases and becomes constant in the range of 4 to 5 at the time of through wall. Variation in 2C/a versus a/t behaviour, as shown in Fig. 17, clearly highlights, that crack grows more rapidly in the depth direction than in surface direction. Such behavior is very important from the point of view of Level 2 LBB requirements.

Crack depths were measured along the crack length using ACPD instrument for all the cases. Typical crack shapes as measured using ACPD and on the fracture surface are shown in Figs. 18 and 19 respectively.

**Analytical Estimation for FCGR in component**

In order to predict the number of cycles required for a crack to grow through thickness after crack initiation, analytical calculations were carried out based on the Paris law. In this analysis FCGR constants obtained from the TPB specimen were used. The details of the analysis can be seen in the paper by Singh et al [11].

Experimental and analytical results (shown in Figs. 21-22 for pipes and Fig. 23 for elbow) for crack growth in the thickness direction have been observed to be in good agreement for the pipes till a/t = 0.8. Fig. 3 shows the crack growth for the crown notched elbow where closing bending moment is applied. The closing bending moment introduces stress gradient across the thickness (maximum at outer surface and minimum at the inner surface). This stress pattern leads to
Fig. 20: Maximum crack depth vs number of cycles for different initial crack depths ($a_i$) and $R=0.1$

Fig. 21: Maximum crack depth vs number of cycles for different initial crack depth ($a_i$) and $R=0.5$

Fig. 22: Comparison of experimental and analytical crack growth for pipes of different outer diameters

Fig. 23: Comparison of experimental and analytical crack growth for crown crack elbow

decreasing stress intensity factor range from outer to the inner surface. Hence, the crack growth pattern decreases with crack growth in thickness direction. The overall comparison of analytical and experimental observation proves, that the fatigue crack growth model, as discussed in the present paper, yields satisfactory results.

Conclusions

The study describes the fatigue behaviour of carbon steel material and piping components used in Indian PHWRs. It also compares the fatigue behaviour of pipe welds with base material. The results of the study can be summarized as follows:

1. Low cycle fatigue properties are higher (better) at room temperature as compared to 288°C for low strain range, whereas at higher strain range, properties are almost identical. Fatigue strength (life) curve of SA333 Gr.6 compares well with that given by ASME Section II of Boiler and Pressure Vessel code for C-Mn steel.

2. FCGR does not depend on notch orientation, pipe size, manufacturing process. FCGR in case of base and weld are also the same. There is a mild dependence on stress ratio at lower values of $R$. 
3. FCGR Paris law constants obtained for the pipe and standard specimen, prepared from the tested pipe, are approximately the same for all the pipes. Slope of Paris curve, that is, m, is marginally higher for TPB as compared to that of pipe.

4. Number of cycles to crack initiation can be predicted relatively well by a model based on evaluation of local stress based on fracture mechanics approach.

5. The use of the fatigue crack growth curve given in ASME Section XI will predict conservative results.

6. Experimental results also confirm that significant margin is available against Level 2 LBB requirements. The number of cycles required to produce through wall penetration is considerably higher than that anticipated in Indian PHWRs.

7. The crack growth in depth (thickness) direction is significantly more rapid than in length (circularferential) direction. This is desirable for application of LBB.

References