FRACTURE BEHAVIOUR OF CARBON STEEL STRAIGHT PIPE WITH THROUGH-WALL CRACK UNDER CYCLIC LOADING

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Abstract

Carbon steel straight pipes form part of the primary heat transport system of nuclear power plants. They may be subjected to dynamic-cyclic loads during earthquake event. This dynamic-cyclic loading significantly affects the fracture resistance and the load carrying capacity of cracked components. Further, for the application of leak-before-break concepts, experimental investigations are essential. Therefore, the aim of the present study is to investigate the effect of cyclic loading on fracture resistance of through-wall cracked straight pipes.

The paper presents details of the cyclic fracture test on a straight pipe and the results thereof. The behaviour of the pipe was compared with the fracture behaviour under monotonic loading. The study has shown that the load capacity of the pipe is reduced under cyclic loading and the failure is by cyclic tearing followed by sudden collapse.

Keywords: Fracture experiment, pipe, crack, cyclic, J-integral.

Introduction

Piping components used in the primary heat transport system of nuclear power plants should have in-built safety against fracture due to improbable accidental loads. The crack growth behaviour and failure load can be predicted using fracture mechanics principles leading to safe design and material selection. Fracture tests on full-scale components are important since it is difficult to accurately model the geometry and crack growth analytically. J-R curve depends not only on the material but also on the crack tip triaxiality. The transferability of CT specimen J-R curve to component level is important for predicting the fracture behaviour of piping components. A major research project on investigations on cyclic tearing and crack growth in straight pipes is currently in progress at the Fatigue Testing Laboratory (FTL), Structural Engineering Research Centre (SERC), Chennai. As a part of this project, fracture tests were conducted on straight carbon steel (SA 333 Gr.6) pipes of 219 mm OD with through-wall circumferential notch. This paper deals with experimental studies on cyclic fracture of straight pipe with through-wall notch. An attempt is made to study cyclic fracture behaviour vis-a-vis monotonic fracture behaviour.

Test Specimen Details

Test specimens consist of straight pipes made of SA 333 Gr.6 carbon steel material with through wall circumferential crack at the middle of its length. Fig.1 shows the geometry of the pipe specimens. The pipe specimens are initially pre-cracked by fatigue loading under four point bending using computer controlled servo-hydraulic actuator of ±500kN capacity. The cyclic load for fatigue pre-cracking has upper bound equal to approximately 20% of the maximum expected load (Pmax) on the pipe and the lower bound is about 2% of Pmax. The frequency of fatigue loading was kept at 2Hz. Fatigue pre-cracking was carried out to obtain sharp cracks of about 2 mm length on both sides of the notch. The crack growth was detected using the dye penetrant technique.

Experimental Study

The fracture tests were conducted on the fatigue pre-cracked pipe specimens under four-point bending using computer controlled servo-hydraulic actuator of ±500kN capacity. Pipe fracture tests were performed under the conditions as shown in Fig.2, subjected to monotonic
loading and quasi-static cyclic loading. The tests were conducted till the failure of the pipe. The failure implies either the crack grows in an unstable manner or the component collapses so that it cannot be loaded further to any significant extent.

**Monotonic Loading Test**

Static monotonic load was applied under displacement control, the rate of displacement being 0.055 mm/sec. Since the actuator has a maximum displacement of 100 mm, the test was programmed to stop after reaching the maximum displacement using the limit switch of the controller. The test was again continued after adjusting the displacement of the actuator using manual control and by providing packing plates at the loading points. In the case of monotonic fracture, the pipe was subjected to bending in a continuous manner till collapse.

**Quasi-Static Cyclic Loading Test**

After fatigue pre-cracking, the pipe was subjected to fracture under quasi-static cyclic load in the load control mode. Fig.3 shows the experimental set up. The frequency of loading was fixed at 0.083 Hz. The load was applied with triangular waveform such that the load range remained constant throughout the experiment. The load range for the test was ±0.75 times the theoretical collapse load. The test was conducted at room temperature and till the failure of the pipe. For cyclic fracture, load reversal was applied, which needed special fixtures to hold the pipe in place during reversal of load, as shown in Fig.3.

**Instrumentation**

During the fracture experiments, the pipe was instrumented to measure various parameters. The total applied load was measured directly using a strain gauge based load cell. The load-line displacement was measured by an in-built LVDT of the actuator. Crack mouth-opening displacement was measured at the center of the crack using clip gauges and crack length was measured using image processing technique with four digital cameras. Crack initiation and crack extension were measured by two techniques namely, the camera imaging and the ACPD technique. Crack section rotation was recorded using LVDTs fixed at various locations along the pipe. The entire test was automated using computer-controlled loading and data acquisition.
Experimental Determination of J-R Curve

For fracture assessment of piping components, the material resistance for crack growth is represented by J-R curve, which is usually obtained from tests on CT or TPB specimens. However, the J-R curve obtained from specimens will have only small crack extension due to size of the specimen and it is extrapolated to obtain crack extension for component, which will have larger crack extension. The effect of geometry and stress triaxiality cannot be represented properly in this method. Due to complex geometry and crack shape, numerical evaluation of J-R curve is difficult. The component J-R curve can be obtained using load, load-line displacement and crack growth data from the fracture test on the component. The η-factor method is a method used to estimate the J-R curve for a pipe material from experimental data (Miura, 1993 and Rudland, 1996).

J-R Curve for Monotonic Loading

The energy absorbed during the test, i.e. the area under the moment-rotation or load-displacement curve, is proportional to the fracture resistance through a geometric term, i.e., the η-factor. In this method, J is separated into an elastic and plastic component.

\[ J = J_{EL} + J_{PL} \]  

\[ J_{EL} = \frac{K^2}{E} = \frac{R_m^2 \pi c^2 F (c/b, R_m/t)}{E I^2} \]  

where \( b = \pi R_m, c \) is half crack length, \( F \) is the elastic stress intensity factor geometry function, \( I \) is second moment of area, and \( M \) is bending moment.

\[ J_{PL} = 2 \int_0^{\Delta_{PL}} \beta (\phi) Pd\Delta_{PL} + \frac{2}{R_m} \int_{c_0}^{c} \gamma (\phi) J_{PL} \, dc \]  

\[ \beta (\phi) = - \frac{h'(\phi)}{R_m \sin \theta (\phi)} \]  

\[ \gamma (\phi) = \frac{h''(\phi)}{h'(\phi)} \]  

\[ h (\phi) = \cos \frac{\phi}{4} - \frac{1}{2} \sin \frac{\phi}{2} \]  

where subscripts \( EL \) and \( PL \) denote the elastic and plastic component respectively, \( K \) is stress intensity factor, \( E \) is Young's modulus, and \( c_0 \) is initial half crack length. The second term on the right side of Eq. (3) represents a contribution to J due to crack growth, which is equal to zero until crack initiation. The plastic component of the displacement, \( \Delta_{PL} \), in Eq. (3) is obtained by subtracting the elastic components from the total load-line displacement, \( \Delta \).

Cyclic Maximum J-integral, \( J_{max} \)

The \( J_{max} \) for a circumferentially through-wall cracked pipe subjected to cyclic load is defined below according to the η-factor approach as in the case of the monotonic J-integral.

\[ J_{max, i} = J_{max, EL, i} + J_{max, PL, i} \]  

\[ J_{max, EL, i} = \frac{K^2}{E} = \frac{R_m^2 \pi c_i F (c_i/b, R_m/t)}{E I^2} \]  

\[ J_{max, PL, i} = 2 \int_0^{\Delta_{PL,i}} \beta (\phi) Pd\Delta_{PL} + \frac{2}{R_m} \int_{c_0}^{c} \gamma (\phi) J_{max, PL} \, dc \]  

where \( i \) denotes the maximum load point in the \( i^{th} \) cycle.

With \( i = i \) and \( i = i-1 \) each substituted into the Eq. (7), the difference between both of the equations can be rearranged as follows:

\[ J_{max, PL, i} = J_{max, PL, i-1} + 2 \int_{\Delta_{PL,i}}^{\Delta_{PL,i-1}} \beta (\phi) Pd\Delta_{PL} \frac{2}{R_m} \int_{c_0}^{c} \gamma (\phi) J_{max, PL} \, dc \]  

Since, in the above equation, the variation of half crack length \( c \) with a change of \( \Delta_{PL} \) is generally unknown, this equation cannot be solved explicitly. It is assumed that the crack extension from point \( i = i-1 \) to point \( i = i \) is relatively small, and that the total crack angle can be represented by a constant value of \( \theta = \theta_1 \). The second and third terms on the right side of Eq. (8) can be approximately expressed as follows:

\[ 2 \int_{\Delta_{PL,i}}^{\Delta_{PL,i-1}} \beta (\phi) Pd\Delta_{PL} = 2 \beta (\phi_1) \Delta_{PL,i} Pd\Delta_{PL} = 2 \beta (\phi_1) \Delta_{PL,i} \int_{\Delta_{PL,i-1}}^{\Delta_{PL,i}} \Delta_{PL} \, dc \]
Thus, the plastic component of $J_{\text{max}}$ can be obtained.

\[
\frac{2}{R_{m}} \int_{c_{i-1}}^{c_{i}} \gamma(\phi) J_{\text{max, PL}} \, dc
\]

\[
= \frac{\Delta c}{R_{m}} \gamma(\phi) J_{\text{max, PL, i-1}} + J_{\text{max, PL, i}}
\]

By substituting $\Delta c = c_{i} - c_{i-1}$ into Eq.(8)

\[
J_{\text{max, PL, i}} = \frac{1 + \frac{\Delta c}{R_{m}} \gamma(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i} + \frac{2 \beta(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i}
\]

\[
J_{\text{max, PL, i-1}} = \frac{1 + \frac{\Delta c}{R_{m}} \gamma(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i-1} + \frac{2 \beta(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i-1}
\]

\[
J_{\text{max, PL}} = \frac{1 + \frac{\Delta c}{R_{m}} \gamma(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i} + \frac{2 \beta(\phi)}{1 - \frac{\Delta c}{R_{m}} \gamma(\phi)} U_{i}
\]

Table-1 : Results of fracture tests

<table>
<thead>
<tr>
<th>Fracture test</th>
<th>Outer dia. (mm)</th>
<th>Wall thickness (mm)</th>
<th>Span (mm)</th>
<th>Crack angle (°)</th>
<th>M_{\text{max}} (kNm)</th>
<th>Crack extension (mm)</th>
<th>COD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monotonic</td>
<td>219</td>
<td>15.15</td>
<td>4000</td>
<td>60</td>
<td>65.6</td>
<td>155.2</td>
<td>282.4</td>
</tr>
<tr>
<td></td>
<td>219</td>
<td>15.60</td>
<td>2500</td>
<td>60</td>
<td>67.48</td>
<td>116.3</td>
<td>299.1</td>
</tr>
</tbody>
</table>

Results and Discussion

Results of fracture tests are given in Table-1. Fig.4 through 6 show results of the quasi-static cyclic loading test. Figs.4 and 5 show the load vs. displacement and load vs. COD relation, respectively. These relations form a hysteresis loop in each cycle. Area of hysteresis loop also increases with accumulation of cycles. Load vs. crack extension relation is shown in Fig.6.

Figures 7 through 9 show results of the monotonic loading test. Figs.7 and 8 show the load vs. displacement and load vs. COD relation, respectively. The maximum load is given where the displacement equals 73.88 mm and COD equals 10.80 mm. Load vs. crack extension relation is shown in Fig.9. The experimentally obtained J-R curve

\[
\frac{2}{R_{m}} \int_{c_{i-1}}^{c_{i}} \gamma(\phi) J_{\text{max, PL}} \, dc
\]

\[
= \frac{\Delta c}{R_{m}} \gamma(\phi) J_{\text{max, PL, i-1}} + J_{\text{max, PL, i}}
\]

Fig. 4 Load vs. displacement relation for quasi-static cyclic loading test

Fig. 5 Load vs. COD relation for quasi-static cyclic loading
under quasi-static cyclic loading and monotonic loading is shown in Fig.10. Close up view of the crack after quasi-static cyclic fracture test is shown in Fig.11 for typical through wall-cracked pipe.

It is observed from the studies that the fracture is sudden in the case of cyclic loading with no indication of ductile behaviour. In the case of monotonic loading the load attains a maximum value and reduces but the pipe deflection continues in a ductile fashion. From the J-R curves for the two cases, it can be seen that the crack resistance is considerably reduced for the cyclic load case. This assumes significance as the piping systems are expected to experience dynamic-cyclic loads during earthquake event.
Conclusions

The fracture experiments have been carried out on through wall circumferentially cracked straight pipes having outer diameter of 219 mm under four point bending load. The following conclusions have been drawn from the above work:

1. The through-wall cracks in the carbon steel pipe experiments grew out of the circumferential crack plane.

2. The J-R curves from the pipe experiments were calculated using η-factor method using the load, displacement and crack growth data for each experiment.

3. It was also found that the J-R curve for the cyclic experiment is significantly below the J-R curve for the monotonic experiment.

4. In the cyclic fracture test the pipe withstood 70 cycles of loading corresponding to 75% of maximum bending obtained for monotonic fracture test and in the 71st cycle, the crack started growing in unstable manner, leading to sudden failure.

5. Response of pipe experiments under quasi-static cyclic load test provides a realistic assessment of the likely pipe behaviour during earthquake event.

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References

