EXPERIMENTAL AND ANALYTICAL STUDIES ON TRANSFERABILITY OF FRACTURE TOUGHNESS FOR PIPING COMPONENTS

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ABSTRACT

Ductile tearing resistance of a material is conventionally characterized by a J-resistance (J–R) curve, which is obtained from laboratory fracture specimens. The original idea was that a unique fracture resistance curve would suffice to characterize the material. However, testing of different types of specimens and under different loading conditions revealed considerable differences in the J–R curves, especially in the slopes. This raises the fundamental question of transferring fracture parameters from specimens to components. To resolve this problem two parameter fracture mechanics model is proposed, where one parameter is J-integral and second parameter is crack tip constraint. Crack tip constraint or stress triaxiality is quantified with different parameters available in literature like T, q, Q, A2, etc. Due to simplification, the J-q theories are applied extensively to the constraint analysis of stationary cracks. As a part of project on “Advanced Component Integrity Test Program”, extensive experimental investigations have been carried out on straight pipes at the CSIR-SERC, Chennai to study their fracture behaviour. Two nos. of 8 inch pipes with through wall crack have been tested under combined loading of four point bending and internal pressure. To maintain the internal pressure with through-wall crack, an indigenous sealing arrangement has been developed by CSIR-SERC. The internal pressure was maintained constant throughout the fracture testing. Different parameters like load, load line displacement, surface crack-growth, CMOD, etc are monitored during test. Subsequent to the tests, three dimensional finite elements analysis (FEA) have been performed with material and geometric non-linearity. The stress triaxiality has been computed using q parameter in the remaining ligament for specimen as well as pipes. The transferability of the J-R curve has been studied qualitatively, in the light of stress triaxiality parameters q for two straight pipes under internal pressure.

INTRODUCTION

It is now well known that transferability of J-R curve from specimen to component is mainly governed by stress triaxiality/constraint ahead of crack tip. There are several parameters to quantify the stress triaxiality ahead of crack tip, such as the T-stress [1], Q parameter [2], the multi axiality quotient (q) [3], A2 parameter [4], etc. In this paper, multi axiality quotient (q) is used as a measure of triaxiality. The multi-axiality quotient, q is defined as:

\[ q = \frac{1}{\sqrt{3}} \frac{\sigma_e}{\sigma_m} \]  

(1)

Where,  

\[ \sigma_m = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3} \]  

(2)

\[ \sigma_e = \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2} \sqrt{2} \]  

(3)

Here \( \sigma_m \) and \( \sigma_e \) are respectively mean stress and von-Mises stress. While \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are principal stresses. Small value of \( q \) represents a high degree of stress triaxiality according to this definition. This quotient can be determined by finite element analysis of the specimen and the pipes. By comparing the \( q \) value of the specimen and component it can be assessed whether the component will show similar fracture behaviour to the specimen or not.

FRACTURE EXPERIMENTS ON TPB SPECIMEN AND STRAIGHT PIPES.

TPB Testing
TPB specimens were machined from the 8-inch diameter pipe and tested to obtain the fracture resistance curves. It is well known that TPB specimens are the easiest fracture specimens for laboratory testing and using unloading compliance method, even for shallow cracks [5]. The single specimen technique is employed for the determination of $J-R$ curves of the pre-cracked specimens as per ASTM E-1820. All the specimens are fatigue pre-cracked and subsequently side grooved to 20% of the thickness, prior to conducting the fracture test. The $a/w$ ratio is varied from 0.2 to 0.453 in the specimens. However no significant effect of $a/w$ on the specimen $J-R$ curve has been observed. This may be due to high toughness of the material. Consequently, one representative sample T08_5B has been chosen for FEA. The relevant dimensions of TPB specimen are given in Table 1. During testing of TPB different experimental data like load, load line displacement, Crack Mouth Opening Displacement (CMOD) and crack growth are recorded.

Table 1: Details of TPB specimen

<table>
<thead>
<tr>
<th>Test</th>
<th>Width of Specimen, $w$ (mm)</th>
<th>Crack depth/Width ($a/W$)</th>
<th>Thickness, $t$ (after side grooving) (mm)</th>
<th>Support span (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPB</td>
<td>25.0</td>
<td>0.513</td>
<td>7.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Pipe Testing:
As a part of advanced component integrity test program, two 8-inch diameter pipes having different sizes of throughwall flaws, has been tested under constant internal pressure of 10 MPa and quasi-statically increasing four point bending load as shown in Fig. 1. Table 2 shows the details of the geometries of the pipe. Different experimental results like load, load line displacement, CMOD and crack propagation are recorded during experiment. The crack growth is monitored by taking pictures at regular intervals and processed for instantaneous crack size by image processing technique.

Sealing Arrangement for Through-wall Cracked Pipes:
Various adhesives and packing materials were tried to withstand internal pressure and bending by throughwall cracked pipe. The sealing arrangement with teflon pad and aluminium sheet as backing material at notch location and silicon rubber sheets with two component fevitite super strength epoxy adhesive withstood the pressure and bending. The sealing arrangement consists of a teflon pad and over that an aluminum sheet placed at inner side of the notch portion (with out any adhesive). Fig. 1(e) shows the sealing arrangement in straight pipes with circumferential through-wall notch. The two sheets act as a backing material. Then two layers of silicon rubber sheets were fixed to the pipe with fevitite epoxy adhesive. Initially, the pipe was pressurized upto 10 MPa and subsequently static monotonic load applied.

FINITE ELEMENT ANALYSIS FOR TPB SPECIMEN AND PIPE
The 3D elastic-plastic analysis has been carried out on the through wall cracked straight pipes and the TPB specimen. Due to symmetry in both the geometry and loading conditions only 1/4 of the pipes and 1/4 of TPB specimen are modeled. A fine mesh has been provided near the crack front to capture the steep stress-strain accurately. The side groove is also modeled in case of the TPB specimen. Fig. 2 and Fig. 3 show the finite element-

**Table 2: Dimensions of tested pipes:**

<table>
<thead>
<tr>
<th>Test</th>
<th>Outer Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Outer span (mm)</th>
<th>Inner span (mm)</th>
<th>Crack angle (2θ˚)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRSPTWC8-1</td>
<td>219</td>
<td>18.2</td>
<td>3374</td>
<td>990</td>
<td>90.52</td>
</tr>
<tr>
<td>PRSPTWC8-2</td>
<td>219</td>
<td>18.5</td>
<td>3480</td>
<td>990</td>
<td>152.8</td>
</tr>
</tbody>
</table>

mesh for TPB and the pipes, respectively. Large strain, large displacement relations based on geometry changes are assumed in the analysis. The isoparametric 20-noded brick elements are adopted in the models. Reduced order of integration (2x2x2) is used to eliminate artificial locking under incompressibility condition imposed by plastic deformation. The finite element models are analysed under displacement controlled loading to simulate the experiments.

![Fig. 2. (a) Finite element mesh used for TPB specimen, (b) Detailed mesh near crack front](image)

![Fig. 3. (a) Finite element mesh used for straight pipes having through wall crack, (b) Detailed mesh in region A, (c) Detailed mesh in region B.](image)

**Material Parameters:**
The tensile specimens have been machined from the piping material (SA333Gr6 Carbon Steel). The true stress-strain curves derived from the uni-axial test is shown in Fig. 4. Table 3 summarizes the material properties [6]. The uni-axial true stress-strain curve is modeled in multi linear fashion as indicated in Fig. 4. The data is given up to the ultimate tensile stress level (20% of strain). Ramberg Osgood equation is fit up to ultimate stress and for further points the curve is extrapolated.

**Table 3: Mechanical properties of piping material (SA333Gr6 steel):**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength, $\sigma_y$</td>
<td>288MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Strength, $\sigma_u$</td>
<td>420MPa</td>
</tr>
<tr>
<td>Young’s modulus of elasticity, $E$</td>
<td>203GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Fig. 4. True stress-strain curve obtained from tensile specimen machined from the pipe

RESULTS AND DISCUSSION

Three Point Bend Bar

The comparison of Finite Element Analysis (FEA) and experimental Load-deflection characteristics of the TPB specimen is shown in Fig. 5. The numerical and experimental results are showing good agreement. The good matching between experimental and numerical results ensures the validation of the numerical model as well as experimental results. The effect of crack propagation is not evident in the experimental results as the amount of crack growth is very small.

Fig. 5. Comparison between experimental and analytical results for TPB specimen. (a) Load v/s Load Line Displacement data. (b) Load vs. CMOD data

The stress triaxiality is a maximum at the mid thickness of the specimen. Hence the results of multi-axiality quotient (q) across the ligament are shown at the mid thickness in Fig. 6.
Fig. 6. Variation of q across ligament at the mid thickness of the TPB specimen at various load levels for a stationary crack.

However the stress triaxiality reduces on applying more load, as a result of stress redistribution associated with the local plastic deformation. It is observed that highest degree of stress triaxiality occurs around 1 mm ahead of crack tip. For a given load, if one move further from crack tip the stress triaxiality reduces, that results in to stable crack growth in this regime. It is also observed that the variation of q is found to be the function of loading which is a sign of stress redistribution with the associated plastic flow (q is independent of loading if the material is elastic, or the yielding

**Straight Pipe containing Throughwall Circumferential Flaws**

![Graph showing Load vs. CMOD for PRSPTWC8-1](image)

(a)

![Graph showing Load vs. Load Line Displacement for PRSPTWC8-1](image)

(b)

Fig. 7. Comparison between experimental and FEA results for PRSPTWC8-1. (a) Load vs. load line displacement data. (b) Load vs. CMOD data

The comparison of finite element analysis and experimental Load-deflection characteristics for 8-in Straight Pipes (PRSPTWC8-1 and PRSPTWC8-2) are shown in Fig. 7 and Fig. 8. The numerical and experimental
results are showing good agreement. The good matching between experimental and numerical results ensures the validation of the numerical model as well as experimental results. The FEA computed load is matching reasonably well up to certain point. After that the stiffness decreases for experimental results than computed results. This is because of crack growth during fracture testing, which is not accounted in the FEA.

![Graph](image1.png)

**Fig. 8.** Comparison between experimental and FEA results for PRSPTWC8-2. (a) Load vs. load line displacement data. (b) Load vs. CMOD data

![Graph](image2.png)

**Fig. 9.** Variation of q across ligament at the mid thickness at various load levels for tested pipes. (a) PRSPTWC8-1 and (b) PRSPTWC8-2

The multi-axiality quotient \( (q) \) represents a characteristic quantity for the degree of stress triaxiality. The stress triaxiality is a maximum at the mid thickness of the specimen. Hence the results of multi-axiality quotient \( (q) \) across the ligament are shown at the mid thickness in Fig. 9. It is observed that highest degree of stress triaxiality occurs around 1.5 mm ahead of crack tip.

**Comparison of stress triaxiality among TPB specimen and pipes:**
Fig. 10 Variation of q across ligament at the mid thickness for TPB specimen, PRSPTWC8-1 and PRSPTWC8-2.

Fig. 10 shows the variation of stress triaxiality (q) across remaining ligament for Three Point Bend Bar (TPBB), PRSPTWC8-1 and PRSPTWC8-2. The results are comparable and matching well up to 4.5 mm ahead of crack tip in the remaining ligament. It can be concluded that the stress triaxiality is level is almost same for specimen and pressurized pipe with throughwall crack. Hence, similar J-R curves are expected from TPB specimen and pipes.

CONCLUSIONS:

- Two 8-inch straight pipes with different sizes of through wall cracks are tested under combined loading of internal pressure of 10MPa and four point bending. Different experimental results like load vs. load line displacement, load vs. CMOD, etc are recorded.
- Finite element analyses of the tested pipes are performed. Different experimental results like load vs. load line displacement and load vs. CMOD are matching reasonably well.
- Finite element analysis of TPB specimen is performed and experimental results like load vs. load line displacement and load vs. CMOD are found to be in good agreement.
- Stress triaxiality parameter, multiaxiality quotient (q) have been computed for pipes and TPB specimen in the remaining ligament.
- Crack tip constraint level is compared among TPB specimen and 8 inch pipes and they are found in reasonably good agreement. From this conclusion, it can be implied that the J-R curves for these cases should be almost same. Hence J-R curve from TPB specimen can be transferred to pipes under pressure with through wall crack. However further studies is recommended for calculation of J-R curve and crack initiation load.

REFERENCES: