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Experimental and Modelling Approaches to the Determination of Fatigue Crack Growth from a Structural Steel T-Butt Weld Toe

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Experimental and Modelling Approaches to the Determination of Fatigue Crack Growth from a Structural Steel T-Butt Weld Toe

Abstract

T-butt welded joints are found in many structural steel applications including buildings, bridges and offshore structures and are susceptible to fatigue crack initiation and propagation, which often leads ultimately to fast fracture failure. An example of this was the I-35W bridge in Minneapolis, which collapsed in 2007 resulting in 13 fatalities, as shown in Figure 1 [1]. The experimental work for this project was conducted using A350 grade black mild steel plate. An ultrasonic peening treatment was applied to one T-butt specimen to introduce compressive residual stress at the weld toe, in order to reduce the effective fatigue crack propagation rate. The results generated from 3-D FEA modelling plus a FORTRAN program (implementing parametric stress intensity factor and crack propagation equations) will be compared with experimental fatigue test results.

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PROJECT AIMS

- T-butt welded joints are found in many structural steel applications including buildings, bridges and offshore structures and are susceptible to fatigue crack initiation and propagation, which often leads ultimately to fast fracture failure.
- An example of this was the I-35W bridge in Minneapolis, which collapsed in 2007 resulting in 13 fatalities, as shown in Figure 1 [1].
- The experimental work for this project was conducted using A350 grade black mild steel plate.
- An ultrasonic peening treatment was applied to one T-butt specimen to introduce compressive residual stress at the weld toe, in order to reduce the effective fatigue crack propagation rate.
- The results generated from 3-D FEA modeling plus a FORTRAN program (implementing parametric stress intensity factor and crack propagation equations) will be compared with experimental fatigue test results.

Table 1: Geometric and material properties of T-butt weld.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table thickness (T)</td>
<td>30mm</td>
</tr>
<tr>
<td>Weld thickness (t)</td>
<td>10mm</td>
</tr>
<tr>
<td>Weld angle (α)</td>
<td>45°</td>
</tr>
<tr>
<td>Root radius (r)</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Weld width (b)</td>
<td>2mm</td>
</tr>
<tr>
<td>Weld height (h)</td>
<td>40mm</td>
</tr>
<tr>
<td>C</td>
<td>0.6</td>
</tr>
<tr>
<td>Fatigue crack growth threshold (da/dN)</td>
<td>3.2 MPa/√l</td>
</tr>
<tr>
<td>Initial crack length</td>
<td>213 GPa</td>
</tr>
<tr>
<td>Initial crack length</td>
<td>350 MPa</td>
</tr>
</tbody>
</table>

APPROACHES

1. Finite Element Analysis (FEA) Computational Approach:

- A three-dimensional fatigue life cycle model of a T-butt welded specimen under tension (membrane) loading was implemented using ANSYS (Workbench version 17.2).
- The boundary conditions were applied in accordance with the experimental testing, as illustrated in Figure 4.a.
- The crack mesh structure was set to tetrahedron in order to achieve local refinement with a smooth change (Figure 4.b).
- The number of stress cycles was calculated using the Paris Law propagation equation together with the FEA stress intensity factor (SIF) range for various crack lengths (from 2mm to 7mm).

2. FORTRAN Program Analytical Approach:

- A fatigue crack propagation life program has been written in FORTRAN based on the tensile BDKH parametric equation along with the Paris Law propagation equation.
- The geometric input parameters used to predict the number of stress cycles are enumerated in Table 1.
- The FORTRAN program has been thoroughly tested for convergence. The best result was achieved with a number of 100,000 crack increments.
- The number of stress cycles taken was predicted using crack lengths from 2mm to 7mm with a 1mm increment.

3. Experimental Test Experimental Approach:

- A T-butt welded specimen was fabricated from A350 grade mild structural steel material.
- A schematic diagram of the T-butt welded specimen is given in Figure 2.
- A semi-elliptical notch 2mm deep by 40mm wide was wire cut at one side of the specimen as shown in Figure 3.
- Fatigue testing was conducted using an INSTRON Digital 8804 servo-hydraulic testing machine.
- This experiment was conducted to determine whether the simulation model and BDKH parametric equation were able to provide accurate prediction of the number of stress cycles.

RESULTS

<table>
<thead>
<tr>
<th>Crack Length</th>
<th>FEA Simulation</th>
<th>FORTRAN Program</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4.08</td>
<td>4.61</td>
<td>13.00</td>
</tr>
<tr>
<td>4</td>
<td>7.36</td>
<td>7.18</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>9.38</td>
<td>9.14</td>
<td>2.38</td>
</tr>
<tr>
<td>7</td>
<td>16.84</td>
<td>17.02</td>
<td>0.63</td>
</tr>
</tbody>
</table>

2. Paris Law

Paris and Erdogan (1963) proposed a simple crack propagation equation by assuming fatigue crack propagation rate (da/dN) was dependent on SIF range (ΔK).

\[ \frac{da}{dN} = C (\Delta K)^m \]

where \( C \) is the fatigue crack growth constant, \( n \) is the fatigue crack growth exponent [4].

CONCLUSIONS

In this study the SIF was investigated using both FEA simulation and a FORTRAN program. Both models were in close agreement when predicting the SIF range and fatigue propagation life of a T-butt welded specimen with a semi-elliptical flaw. Material characterisation (tensile testing, Charpy testing) was performed in order to check that the material used in this experiment was consistent with the mill certificate and conformed to standards.

FUTURE WORK

- A full fatigue test on a notched T-butt under tension (membrane) loading is underway.
- Further material characterisation (notched tensile fatigue threshold testing) is currently being planned. The specimens have already been machined.

REFERENCES