Evaluation of Fatigue Crack Growth Rates in an IPE Beam Made of AISI 304 under Various Stress Ratios

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Abstract

Stainless steel is a material which is widely used in various environments, including structural, load-bearing components of buildings. Almost every engineering structure is exposed to cyclic loading, which results in fatigue damage of the material, which could, in combination with discontinuities (cracks, flaws, etc.) already existing in every material, lead to the failure of the structural part, or worse, to the failure of the whole civil structure. To understand the behavior, we prepared an experimental campaign of a stainless-steel IPE 80 beam in three-point bending under cyclic load. In total, three specimens with different stress ratios ($R = 0.1, 0.3, 0.5$) were tested and Paris’ material’s constants were evaluated and compared for the AISI 304 stainless steel material.

Keywords: IPE 80; AISI 304; stainless steel; Paris’ law; stress ratio

1. Introduction

The assessment of fatigue damage has already been studied for many decades and the results have found a direct application in the industry producing machines and parts which are cyclically loaded over their lifespans (turbines, axles, shafts, etc.). Later on, the fatigue started to be an issue in the civil engineering industry, which led to the formulation of the standardized documents for the structural design of the structural parts exposed to cyclic load. One of these documents is Eurocode 3, which uses the linear damage accumulation method for the fatigue assessment based

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on the Miner’s rule. Eurocode 3 provides the S-N curve, which is excessively used in the design of loadbearing structures exposed to the cyclic load, Eurocode (2005).

**Nomenclature**

- **a**: crack length [mm]
- **C, m**: Paris’ law material properties
- **K_I**: stress intensity factor for mode I (MPa m^{1/2})
- **R**: stress ratio (-)
- 2D, 3D: two/three-dimensional
- **P**: load (kN)
- **CMOD**: crack mouth open displacement
- **FEM**: finite-element method
- **FCGR**: fatigue crack growth rate
- **SIF**: stress intensity factor
- **LEFM**: linear elastic fracture mechanics

This normative document considers a structural component as an undamaged part, i.e., without any cracks. On the other hand, when the crack is already present in the structural component, the stress fields in it change and the Linear elastic fracture mechanics (LEFM) approach should be used. A typical LEFM approach for the assessment of the fatigue damage is using Paris’ law (Paris and Erdogan 1963) together with its constants. The Paris’ law allows for the assessment of the fatigue damage in a crack component as well as it provides information of the fatigue crack growth rate (FCGR).

In this contribution, the role of the stress ratio R on the fatigue crack propagation behavior in AISI 304 was investigated using the measurement of the crack mouth open displacement, measured on an IPE (I-Profile Européennes) 80 profile made out of the AISI 304 stainless steel. We also revisited the assessment of the Paris’ law material constant. For this purpose, a 3D numerical model was created in FEM software ANSYS Mechanical (ANSYS 2021) to obtain the geometry function necessary for the calculation of the stress intensity factor (SIF) values for mode I.

2. **Theoretical Background**

The well-acknowledged Paris’ law (Paris & Erdogan, 1963) can be express as:

\[
\frac{da}{dN} = C K_I^m,
\]

where **C** and **m** are the experimentally obtained material’s constants dependent on the asymmetry of the load cycle **R**, loading frequency **f**, time **t**, environmental conditions, material properties, and the specimen size.

\[
R = \frac{P_{\min}}{P_{\max}} \text{ or } \frac{\sigma_{\min}}{\sigma_{\max}},
\]

where **P_{\min}** is the minimum applied load, **P_{\max}** is the maximum applied load, **σ_{\min}** is the minimum applied stress and **σ_{\max}** is the maximum applied stress. The FCGR is expressed in Paris’ law as \(\frac{da}{dN}\), i.e., crack increment over a certain number of cycles, and **K_I** is the SIF for mode I, which can be calculated as:

\[
K_I = \sigma \sqrt{\pi a Y_I(\alpha)},
\]

where **σ** is the applied stress, **a** is the crack length and **Y_I** the dimensionless shape function dependent on the geometry of the studied sample versus the relative crack length **α**. The values of **Y_I** for specific test configurations can be found in numerous literatures dedicated to SIF calculation, i.e., Tada et. al. (2000), Murakami (2001).
3. Numerical Model

Since IPE 80 is a non-standardized geometry used for fatigue testing, the geometry shape function $Y_1$ has to be obtained by numerical modeling or by experimental testing. For this purpose, a 3D linear-elastic numerical model has been created in the FEM software ANSYS. The model was created as $1/4$ of the specimen given the possible plane symmetry in a load configuration of three-point bending (3PB). The input material parameters were Young’s modulus $E = 190$ GPa and Poisson’s ratio $\nu = 0.3$.

The dimensions of the numerical model are based on the IPE 80 profile, i.e., height $W = 80$ mm, width of the flange $B = 46$ mm and the span $S = 240$ mm $(S/W = 0.3)$. The numerical model was meshed by a SOLID186 element type with a basic length of 5 mm. In the vicinity of the notch, a fine mesh was adopted with a size of 0.1 mm. The applied load and boundary conditions were chosen to represent a 3PB test as well as to allow for the symmetry. The applied boundary conditions together with the mesh can be found in Fig. 1.

![Fig. 1. Meshed numerical model together with boundary conditions (a), and (b) detail of the vicinity of the crack.](image)

We assume that the crack will grow in the bottom flange of the IPE profile, from which a crack mouth opening displacement (CMOD) and stresses were extracted. Then a direct method for SIF calculation was used as:

$$K_I = \lim_{r \to 0} \left( \sigma \sqrt{2\pi r} \right),$$

where $r$ is the distance from the crack tip and $\sigma$ is the crack opening displacement (Westergaard, 1939).

![Fig. 2. Comparison of SIF values for various IPE 80 models and cross-section types (a), and (b) the dependency of SIF on $\Delta$CMOD for $P = 75$ kN.](image)
Using this direct extrapolation method, one can obtain the values of SIF as well as of the geometry shape function \(Y_1\). In order to verify the current 3D model, a comparison with a 2D and 3D model using a rectangular cross-section was done. Additionally, the numerical model generated the values of CMOD, which were used for the assessment of the SIF values from the experimental data. The geometry comparison is presented Fig. 2 (a), while the dependency of \(K_1\) on the CMOD value is shown in Fig. 2 (b).

The values of SIF presented in Fig. 2 (a) indicate rapid increase in the value of SIF for the IPE 80 profile when compared with the values obtained for the rectangular cross-section, especially for the greater ratios of \(a/W\). This is due to the fact that the crack is propagating through the flange plate to the web (the thickness of the flange plate is 5.2 mm). Additionally, the crack grows only in the bottom flange plate, perpendicularly to the crack front, in the direction of the loading of the IPE 80 profile, and once it reached the web, we assume brittle failure of the specimen.

4. Materials and Methods

4.1. ASIS 304

The IPE 80 beams used in fatigue experiments are coldly rolled profiles made of stainless-steel grade of AISI 304. The mechanical parameters and chemical composition of stainless steel AISI 304 for IPE 80 are mentioned in Tab. 1. The resistance to corrosion is obtained by a high content of chrome. On the other hand, the content of nickel is responsible for the microstructure and mechanical properties (Baddoo, 2008; Gardner, 2005). In comparison to structural steel, the mechanical properties of stainless steel show a different trend, especially the stress-strain diagram (Arrayago, 2015). Stainless steel does not have a determined yielding stress, so the proof test is being used.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>P [%]</th>
<th>S [%]</th>
<th>Ni [%]</th>
<th>Cr [%]</th>
<th>(\sigma_u) [MPa]</th>
<th>(\sigma_{0.2}) [MPa]</th>
<th>(\sigma_{1.0}) [MPa]</th>
<th>(\varepsilon_y) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen 1</td>
<td>0.03</td>
<td>0.4</td>
<td>1.5</td>
<td>0.03</td>
<td>0</td>
<td>8</td>
<td>18</td>
<td>0.1</td>
<td>675</td>
<td>342</td>
<td>380</td>
</tr>
<tr>
<td>Specimen 2</td>
<td>0.02</td>
<td>0.4</td>
<td>1.6</td>
<td>0.03</td>
<td>0</td>
<td>8</td>
<td>18</td>
<td>0.1</td>
<td>628</td>
<td>255</td>
<td>319</td>
</tr>
</tbody>
</table>

4.2. Experimental Testing

Experimental execution of three-point bending was processed using Vibrophore 250, a high-frequency pulsator by ZwickRoell. Dynamic loading is generated by an oscillating system in full resonance. To evaluate the fatigue parameters, crack mouth opening displacement was measured on the bottom flange of the profile, in the middle of the span, where the initial notch was created. This was obtained using a clip-on extensometer, as one can see in Fig. 3, placed on the plates, glued to the bottom flange of the beam. The extensometer measures the CMOD with a high accuracy, but is limited to the measurement of 2 mm maximum. In total, three fatigue experiments were performed, with different stress ratios \(R\) of 0.1, 0.3, and 0.5, and different forces applied, i.e., \(P_{\text{max}} = 75; 100; 120\) kN.

Fig. 3. Experimental configuration (set up) (a), and (b) bottom flange after experiment.
5. Experimental Results

For each specimen, ΔCMOD was captured every 100 load cycles. The measured experimental data is shown in Fig. 4 (a), where ΔCMOD is plotted in relation to the cycle number for the given force for $R = 0.1; 0.3; 0.5$, respectively. The highest number of loading cycles was obtained for the specimen with the smallest stress ratio of 0.1 ($P_{\text{max}} = 75$ kN). For the specimens with the stress ratio of 0.3 ($P_{\text{max}} = 100$ kN), a smaller number of cycles were measured with the same final deformation. The smallest number of cycles were measured for the $R = 0.5$ ($P_{\text{max}} = 120$ kN).

$$\text{ΔCMOD} \text{ [mm]} \quad N \text{ [cycles]} \times 10^5$$ (a)

$$d_a/d_N \text{ [mm/cycles]} \quad \Delta K \text{ [MPam}^{1/2}]$$ (b)

Fig. 4. ΔCMOD data obtained from the experimental test (a), and (b) an example of postprocessed data IPE 80, $R = 0.1 \ P_{\text{max}} = 75$ kN.

Fig. 5 Fitting of linear part of the FCGR-SIF relation for the evaluation of Paris’ law for different stress ratios $R \ (0.1; 0.3; 0.5)$.

The values of ΔCMOD obtained from experiments were postprocessed using their relation to the value of SIF and to the crack length for each 100 load cycles. Thus, all the variables used to determine FCGR and its relation to SIF were easily calculated. Fig. 4 (b) shows an example of the postprocessed data on a logarithmic scale. It is visible that for this specimen, the fatigue crack initiated after reaching a certain value of SIF which can be considered as the threshold value.
The linear part of the data presented in Fig. 4 (b), was fitted using a power function. In Fig. 5, experimental data with fitted functions is plotted. From this fitting, Paris’ law material constants $C$ and $m$ were evaluated. A comparison for all the studied cases is given in Table 2. The constant $m$ does not show a significant variance, but its value grows with the stress ratio $R$ used in the experiment. In contrast, the constant $C$ decreases in relation to the growth of the stress ratio.

<table>
<thead>
<tr>
<th>Load ratio $R$ [-]</th>
<th>$m$ [-]</th>
<th>$C$ [mm/no of cycles MPa$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.231</td>
<td>$1.038 \times 10^9$</td>
</tr>
<tr>
<td>0.3</td>
<td>2.426</td>
<td>$1.330 \times 10^9$</td>
</tr>
<tr>
<td>0.5</td>
<td>2.524</td>
<td>$2.635 \times 10^{10}$</td>
</tr>
</tbody>
</table>

The values of the interval of $m$ for metallic materials are usually from 2 up to 8. In a recent study by Seitl et al. (2022) the influence of a thickness to Paris’ law constants for the same grade of stainless steel was investigated. In comparison, the values in this study for $m$ were in the range between 4.9 and 5.4, and for $C$ it varied between 0.9-4.9×10$^{-11}$.

**Conclusion**

In this contribution, we analyzed the influence of the stress ratio $R$ on the FCGR in an IPE 80 beam made of AISI 304 stainless steel. In total, three specimens were tested under three-point bending with various stress ratios $R$ (0.1, 0.3 and 0.5). To evaluate the experimentally obtained data, a numerical model in the ANSYS Mechanical APDL software was created. The linear part of the experimental data (SIF vs. FCGR) was evaluated using Paris’ equation. The obtained results of the material parameter $m$ show higher values of the crack growth rate with a higher stress ratio applied. The dispersion of the values does not show a significant trend. These results could be interpreted as a faster growth of a fatigue crack with a greater stress ratio. On the other hand, the values of Paris’ law constant $C$ show inverse proportionality to the size of the load ratio. The results of this study could also be used in a probabilistic analysis of fatigue damage assessment, see e.g. Krejša et al. (2016).

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