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Analysis and Prediction of Surface Crack Growth Under Fatigue Loading

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Abstract. This research uses several fatigue crack growth models to examine the cyclic evolution of fatigue cracks in a shaft. Three fatigue crack growth models are used to forecast crack growth: Walker, Paris Law, and others. Experimental data support these models. The main problem is accurately estimating the propagation of fractures in shafts under cyclic loads because the existing models frequently exhibit variations in real-world applications that could lead to failures. This study compares the experimental results with model predictions to assess the accuracy of several models and improve our understanding of fatigue crack behaviour in practical settings. The experimental approach for 4 point-bending is compared with the simulation result, including boundary conditions and material properties. Paris's and Walker's fatigue crack growth models are employed in the S-version Finite Element Model (S-FEM) to simulate the 4 point-bending models' analysis. The surface fatigue crack growth prediction is simulated and compared with the experimental results. The prediction beach marks of crack depth are slightly similar to the experimental results. Moreover, the prediction beach marks of crack length differ from the experimental results. The crack closure effect influences the difference between the experimental results. In summary, no single model is perfect in general; the selection is based on the particular circumstances and characteristics of the material. This work seeks to help engineers select the best model by improving prediction tools for maintaining mechanical components and increasing safety and performance in engineering applications.

1. Introduction

Damage initiation and progression in a structure under cyclic loading are known as fatigue crack growth propagation. These phenomena could put at risk the structural integrity and safety of components, which is a significant problem across several sectors, including biomechanics, civil engineering, automotive, and aerospace [1], [2], [3]. Cracks caused by fatigue are the most frequent kind of damage that occurs in metal and alloy structures. The fracture started progressively spreading at the elastic load limit when loading cycles increased. The crack's expansion diminishes the structure's ability to support loads, increasing the likelihood of collapse. A cracked structure often doesn't break immediately; instead, it develops until it reaches a critical limit, at which point it fails. Failure of the structure may result in loss of life and property if the fracture propagation is not identified in an exact time. Structural integrity is seriously in danger from fatigue-induced cracks in mechanical parts, particularly in shafts [4].

The fatigue crack growth (FCG) model is crucial to predicting the fatigue crack growth behaviour. FCG models provide a mathematical relationship between the number of loading cycles, load parameters, future fracture length, and existing crack length. The existence of manufacturing flaws, changing environmental circumstances, load uncertainty, and modifications to those variables that might vary the crack propagation path are some of the variables that affect the fatigue cracks' propagation path [5]. Estimating one appropriate pair of FCG model parameters in this case is complex. There will be a significant inaccuracy in the expected fatigue crack length if the FCG model parameters are set incorrectly.

The FCG model has been extensively researched in the last ten years [6]. Most current FCG models are based on the Paris-Erdogan model [7]. The Paris-Erdogan model represents the gradual phase-in crack development resulting from the start of the fracture and before the rapid rupture. The fatigue crack growth rate (FCGR) corresponds to the range of stress intensity factor (SIF) of the materials structure by using the linear data plot [6]. Several modifications of the Paris-Erdogan model have been established to take into consideration additional parameters in FCG for various applications, such as the Walker model [8], Forman model [9], Wheeler model [10], etc. The Walker model, for instance, is developed by considering the stress ratio consideration [8]. A retardation parameter is incorporated into the Wheeler model to compensate for any retardation effects [10]. A detailed review of FCG models based on physics is available in [11]. There are different models of fracture growth available [11], but there is no standard method for analysing cracked shafts [12], which results in inconsistent crack propagation management and prediction [13], [14]. Thus, the analysis of fatigue crack growth is predicted by using the Finite Element Model (FEM). Analysis of fatigue crack growth helps the materials from failure based on the causes of failure [15].

Finite element analysis of fatigue fracture initiation and propagation uses a variety of crack growth criteria and models. Several crucial factors about element size and the crack development threshold must be considered when defining crack initiation in a FEM meshed component. A mesh sensitivity method is essential for improved resolution of stress gradients and more precise crack initiation predictions to create a finer mesh to possible fracture initiation locations [16]. More prominent elements may not be able to capture localised concentrations of stress, which leads to cracks. The element size should ideally be smaller than or equivalent to the forecasted crack size to appropriately depict the stress distribution close to the fracture tip [17]. Often, a particular stress intensity factor (SIF) or strain energy release rate that must be surpassed for crack formation to begin serves as the baseline for crack growth. This cutoff point makes it easier to see cracks as soon as they spread. The mesh size should also be such that the energy release rate or stress intensity factor can be accurately calculated, as more extensive components may average stress levels and make it difficult to determine once the threshold has been achieved.

Engineers can estimate the remaining service life of structures, forecast the onset and progression of cracks, and create maintenance plans using finite element analysis. Engineers can guarantee the safety and durability of civil infrastructure, prevent catastrophic failures, and schedule economical maintenance and repair operations by analysing precisely what fractures are performed. By comparing well-known models such as Paris and Walker, this study seeks to create uniform parameters for fatigue crack growth models [18]. The pattern of beach marks for fatigue crack growth will be analysed in this study. The aim is to improve fatigue life forecasts for essential engineering applications.

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2. Methodology

For this study's four-point bending, or 4PB, and shaft simulations, aluminium alloy 7075-T6 [23] is used in experiments and simulations. According to Figure 1, the 140mm beam in the 4PB simulation will undergo cyclic stress at two locations, 35mm from the centre, with dimensions of 65mm in width and 25mm in height. The beam is going to be symmetrically applied with support at both ends. At these locations, a 45kN cyclic load will be used to produce a consistent bending moment for research on crack propagation. A 5mm long and 4mm deep starting crack will be inserted into the beam to model fracture growth. With an emphasis on the crack's propagation through the material, the simulation will track the crack's behaviour under the applied cyclic stress.

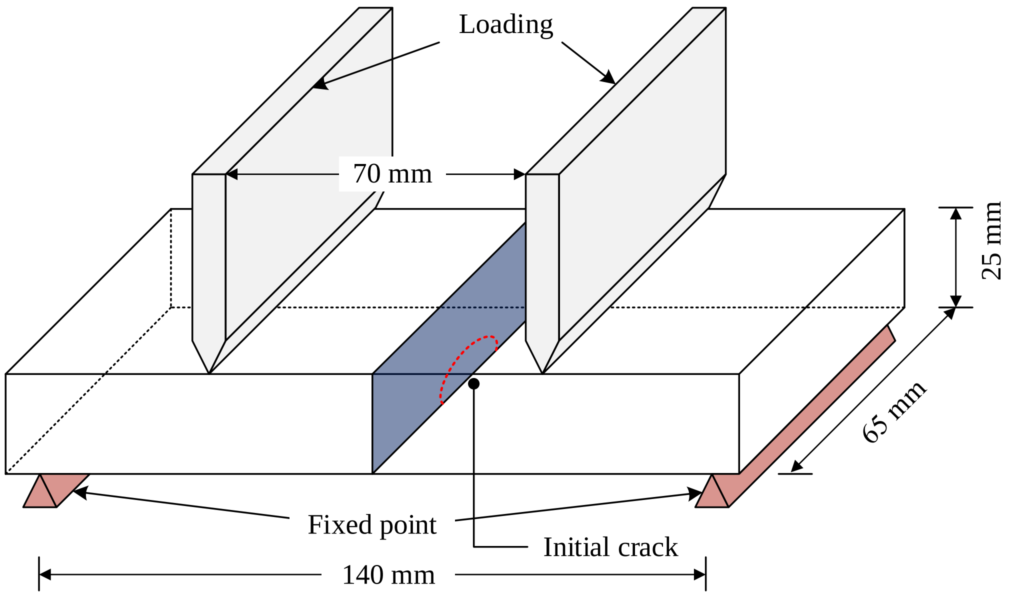

Figure 1. The four-point bending experiment setup

Regarding the shaft simulation, two points 35mm from the centre of a 130mm shaft with a 15mm radius will be subjected to a 7000N force, as illustrated in Figure 2. The crack will start the simulation at the centre of the shaft and have a length of 5mm and a depth of 4mm. This arrangement is crucial for analysing the shaft's stress distribution and deformation behaviour under certain loading conditions. Considering forces applied at these points and the fracture initiated at the centre, the simulation can accurately predict the shaft's mechanical reaction.

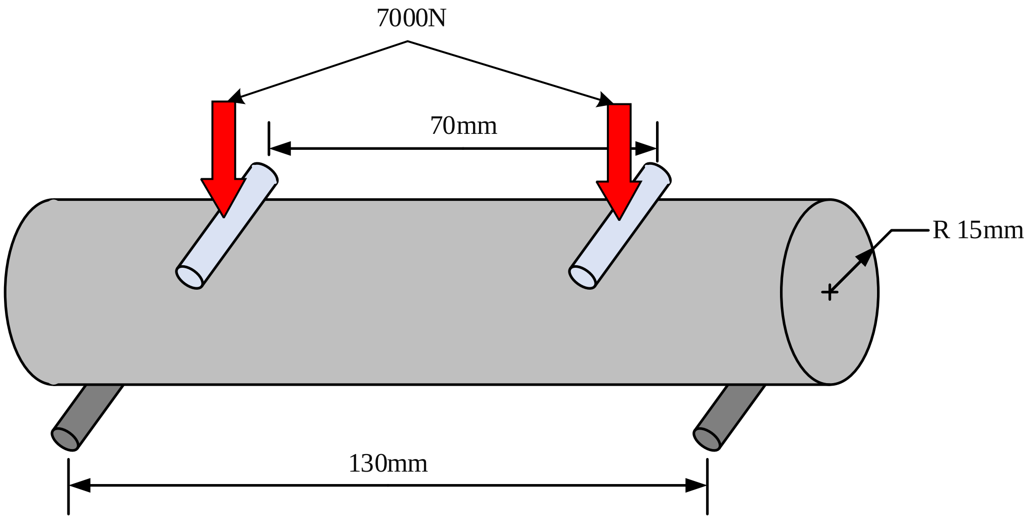

Figure 2. The shaft simulation setup

The S-version Finite Element Method [19] is employed in the simulation technique. The fatigue analysis consists of a fatigue crack growth model.

2.1 Fatigue Crack Growth Models

The Paris and Walker models involve two fatigue crack growth models. Given the fatigue force applied to the specimen, the fracture propagation can be represented using the Paris law equation [7], which is

$$\frac{da}{dN} = C_p(\Delta K)^n \tag{1}$$

In the log-log plot of da/dN versus ΔK, the slope is represented by n, and the intercept is C_p. The area II of the fatigue rate curve is defined by the straight line in equation (1) on the log-log plot of da/dN versus ΔK.

In contrast, the Walker model's equation [8] incorporates the effects of different stress ratios and is a more generalised version of crack growth models. You may express the Walker Equation as follows:

$$\frac{da}{dN} = C_W\left[\frac{\Delta K}{(1-R)^{1-\gamma_w}}\right]^{m_w} \tag{2}$$

Which is the same as Paris, where C_p=C_w and n= m_w.

3. Results and discussion

The Paris model is used to compare the fracture propagation under fatigue stress in Figure 3. Crack depth generally correlates with experimental findings. Yet, a deviation in the direction of the crack length is identified. The crack length of prediction of surface crack growth indicates that it propagates with a significant difference for four beach marks based on Figure 3. Otherwise, the crack depth propagates slightly similar to the experimental beach marks. The pattern of beach marks is likely the same as the experimental ones.

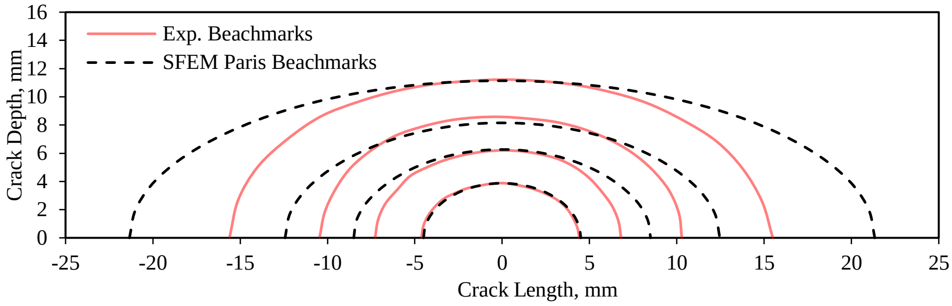

Figure 3. The comparison of fatigue crack growth experiment and simulation using the Paris model for 4PB

The comparison of crack propagation under fatigue loading with the Walker model is displayed in Figure 4. Similar to the Paris model, experimental results are consistent with crack depth; however, a variation is identified in the direction of crack length. Using the Paris model, the surface crack growth beach marks indicate more experimental beach marks than the Walker model. The prediction differs from the experimental, influenced by the crack closure phenomenon [20].

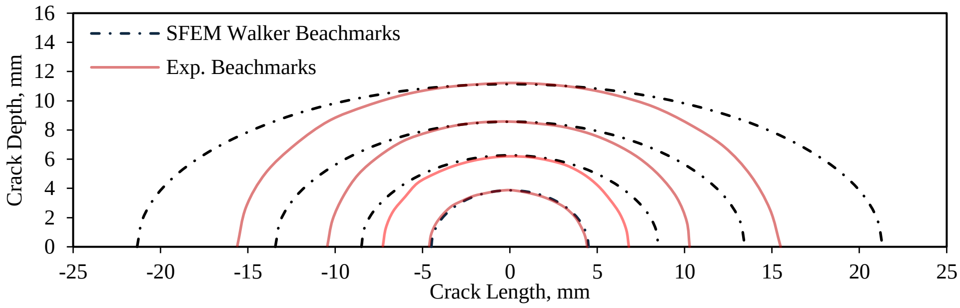

Figure 4. The comparison of fatigue crack growth experiment and simulation using the Walker model for 4PB.

The fracture propagation under fatigue loading for the cracked shaft using the Paris model is compared in Figure 5. Since the work is ongoing, comparing the experiments still needs to be done. Furthermore, the surface crack growth indicates gradual, consistent propagation for the cracked shaft.

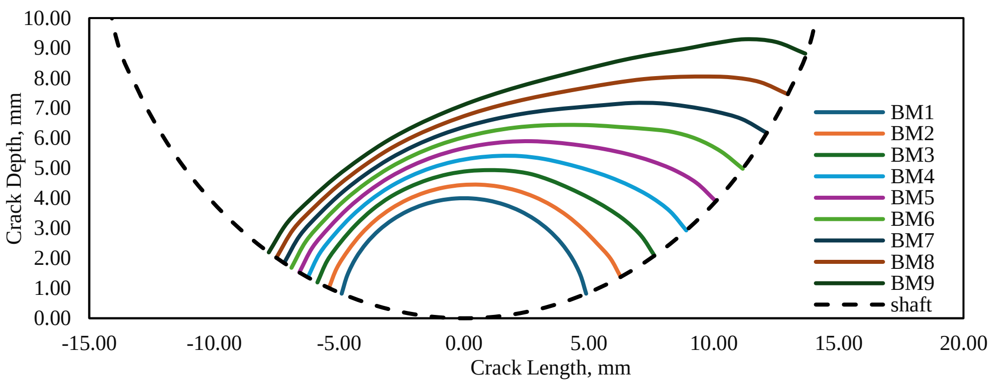

Figure 5. The fatigue crack growth simulation using the Paris model for a cracked shaft.

4. Conclusion

According to the study goal of these investigations, which was to use S-FEM modelling to mimic fracture propagation, it was successful. The simulation's output demonstrated the S-FEM's efficacy in simulating experimental circumstances and results by enabling precise predictions of fatigue crack formation. In summary, there is no one perfect model; instead, the selection is contingent upon the particular circumstances and characteristics of the material.

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