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Prediction of shape change of corner crack by fatigue crack growth circles

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ABSTRACT

As a fatigue crack grows, its shape changes. Conventional method for predicting the shape change typically requires the computation of several hundred increments to get accurate results. In this paper, a new finite element simulation technique that uses fatigue crack growth circles is developed. Since the circles are perpendicular to the new crack front as well as to the current crack front, they can represent the real path of the fatigue crack well and yield more accurate results. The new technique is validated by applying it to the case of a quarter-elliptical corner crack in a plate with an open hole subjected to tension loading. The effect of the Paris–Erdogan exponent is also investigated.

1. Introduction

Shape development is one of the most important issues related to corner cracks that are subjected to fatigue loading. Crack growth is usually calculated based on the Paris–Erdogan law:

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

where da/dN is the crack growth rate, ΔK is the stress intensity factor range, and C and n are material constants. In the problem of fatigue shape analysis, the shape assumption method was commonly used, the corner crack configuration was usually assumed to be quarter-elliptical shape [1]. Snow [2] carried out a test program for a plate specimen with an open hole under the tension loading, Grandt and Macha [3] digitized the crack front profiles of quarter-elliptical fatigue cracks from the test program of Snow. Schijve [4] fitted the test profiles reported by Grandt and Macha.

Efforts have been made to predict the shape evolution of semi-elliptical surface cracks accurately. Usually multi-points along the crack front were used to predict the new crack front and crack growth was assumed to be perpendicular to the current crack front [5–8]. However, few authors studied the prediction of the shape evolution of a quarter-elliptical corner crack. Lin and Smith [9] simulated the fatigue crack shape by a step-by-step finite element technique for corner cracks emanating from fastener holes in plates under cyclic tension loading. They calculated the local growth crack increments at points to define a new crack front by employing the Paris–Erdogan law. The crack growth paths were perpendicular to the current crack front. The new crack front is fitted by a cubic spline curve. In their simulation, about more than 100 crack front increments were needed.

In the crack shape prediction, a crack is usually assumed to advance perpendicularly to the current crack front that it starts from, but not to the new crack front that it approaches [9]. The objective of this study is to propose a shape prediction method that uses fatigue crack growth circles. In this method, the crack is modeled to grow perpendicularly to both the current crack front and the new crack front. This method will make it possible to use quite fewer crack front increments. This study presented the problems of a quarter-elliptical corner crack in a plate with an open hole subjected to tension loading. The fatigue shape was simulated for three different hole radius and several different initial aspect ratios. For a given crack growth in one surface, the corresponding growth in the other surface direction can be predicted by iteration. The crack fronts are assumed to be quarter-elliptical in shape. The stress intensity factors for pre-assigned cracks are stored as a database from the finite element solution. During the iteration process, the stress intensity factors of the points on the assumed crack front are obtained by interpolating the stress intensity factor database. The validity of the present method will be shown by comparing its results with experimental results previously reported by other authors.

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As revealed by many experimental observations and by the simulation of crack evolution, a stable crack front configuration is always reached. It is well known that a surface fatigue crack will grow toward a so-called preferred propagation path, whatever the shape of the initial flaw is [6,10–12]. This study will also check this phenomenon in the corner cracks. The influence of the Paris–Erdogan law exponent n will also be discussed.

2. Numerical models

2.1. Specimen details

Corner crack can be found in a plate with an open hole. In the experimental test and numerical simulation two typical models were used by some authors [3,4,9]. As shown in Fig. 1, the simulation of fatigue propagation in two finite thickness plates with an open hole is conducted. Grandt and Macha [3] and Schijve [4] studied the plates with single corner crack in experimental tests, Fig. 1a shows a specimen with an asymmetric single corner crack at the edge of the hole. Lin and Smith [9] studied the plates with double corner cracks in their numerical simulation, Fig. 1b shows a specimen with symmetric double corner cracks at the edge of the hole. This study will compare the fatigue crack propagation results for the single crack and double corner cracks.

σ represents the applied monotonic tension load. The geometries of the specimens are listed in Table 1. For r/t = 0.5, 1, 3, Table 2 lists six initial elliptic crack sizes with different aspect ratios a_0/c_0. The material of the plate was PMMA [4], with E = 3100 MPa and ν = 0.35.

2.2. Finite element models of specimens

The finite element analysis software Abaqus™ was used to simulate the specimens. As shown in Fig. 2a and b, the 1/2 model of the single crack plate and the 1/4 model of the double cracks plate were modeled. Symmetry constraints were applied. The models were created using quadratic hexahedral elements (3D stress elements). According to the different crack sizes, about 16,000–30,000 elements were used for each 1/2 plate model, and about 28,000–34,000 elements were used for each 1/4 plate model. To improve the accuracy of the contour integral calculation [13], the 1/4-node displacement method [14,15] was used; the midside node parameter was 0.25 to move the midside nodes to the 1/4 points [16] (Fig. 2d). The mesh size around the crack front line was 0.25 mm.

Table 1
Geometries of the specimens.

Dimension	W	H	t	r (r/t = 0.5)	r (r/t = 1)	r (r/t = 3)
Single crack [4] (mm)	201.93	177.80	17.73	8.865	17.73	53.19
Double crack [9] (mm)	1436.07	567.33	17.73	8.865	17.73	53.19

Table 2
Initial crack sizes of different aspect ratios.

a_0/c_0	1	1.2	1.4	1.6	1.8	2
a_0 (mm)	3.546	3.546	3.546	3.546	3.546	3.546
c_0 (mm)	3.546	2.955	2.533	2.216	1.970	1.773

3. Numerical procedure

3.1. Determination of the selected points

In Fig. 3a, the quarter-elliptical shape crack is already given. Then a tangent line tangent with the slope of −cot α to the quarter-ellipse is drawn. Once the point of tangency is located, the

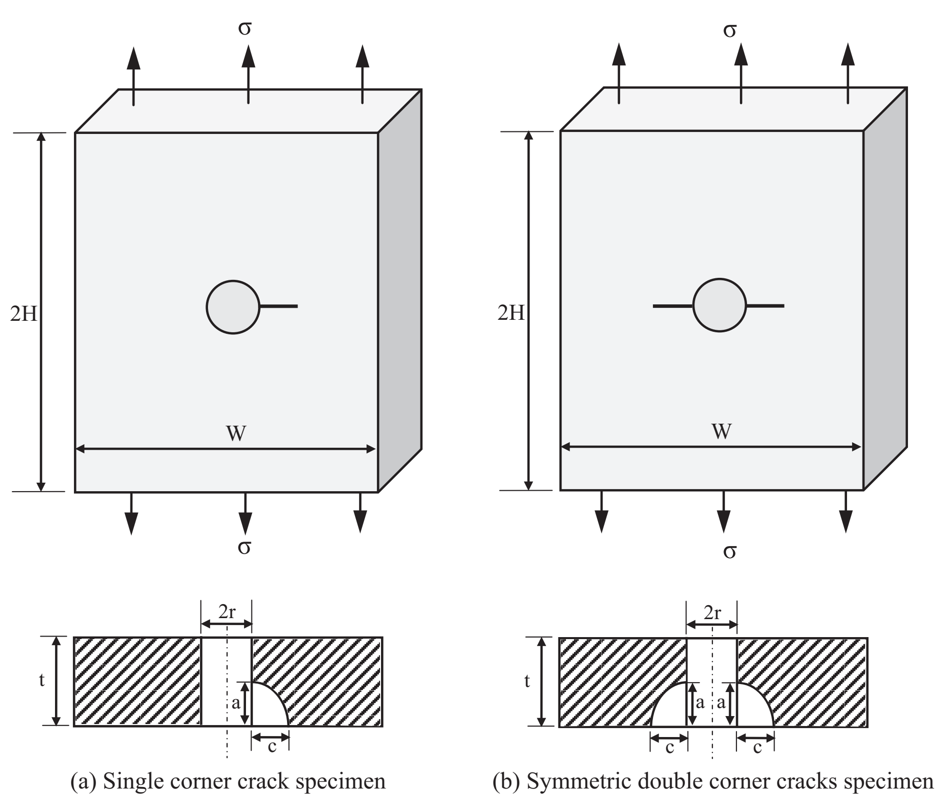

Fig. 1. Specimen geometry and loading.