CRACK PROPAGATION PREDICTION OF PRACTICAL FATIGUE DEFECTS USING A CRACK SHAPE FOLLOWING TECHNIQUE

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A method applicable to the prediction of both shape and rate of fatigue crack propagation for practical arbitrary shaped planar defects is briefly described. This method calculates stress intensity factors along the crack front by a three-dimensional finite element analysis, and integrates an appropriate Paris-type fatigue crack growth law to obtain local crack growth increments, from which a new crack front can be formed. Subsequently, a new finite element model is established accordingly, and the stress intensity factors along the new crack front are estimated again. Repeating this procedure enables both fatigue crack shape evolution and fatigue lives to be predicted simultaneously. Three typical practical defects are analysed to demonstrate the applicability, capability and versatility of this method.

INTRODUCTION

Practical cracks usually experience significant shape change during their propagation. The current practice for the prediction of fatigue growth lives of planar cracks usually involves the following steps: (a) Assume a crack shape that is retained during crack growth. The semi-elliptical shape is the most popular assumption for surface cracks, for instance. (b) Apply an appropriate fatigue crack growth law, such as the Paris law, at one or more key points along the crack front; the greatest depth and the surface intersection point are obvious candidates. Crack growth at the crack depth point is calculated by several guidelines, such as ASME XI and BSI PD6349, whilst crack propagation along both the depth and surface directions is usually calculated by a more accurate method, which can allow the crack aspect ratio change to be predicted. However, the crack shape constraint introduced into the calculation is likely to be unsuitable for many practical defects in complex engineering components and structures.

The present authors have recently developed an advanced numerical technique (Lin (1), Lin and Smith (2)), which enables the crack shape to be predicted directly, thus avoiding

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using the crack shape assumption. The technique employs a multiple degree-of-freedom model. The local crack advances are calculated by applying a Paris type crack growth law at a number of points rather than one or more salient positions. A three-dimensional (3D) finite element analysis is performed to estimate the stress intensity factors (SIFs) at those points. An automatic remeshing technique has also been developed to make such a sophisticated crack growth calculation possible. Three practical examples in this paper are presented after a brief description of the technique to demonstrate its applicability and capability.

THE CRACK SHAPE FOLLOWING TECHNIQUE

Calculation of Crack Growth at Multiple Points

The fatigue crack growth law proposed by Paris and Erdogan (3) has been extended to a planar defect, as shown in Fig. 1. Stress intensity factor values usually vary along a curved crack front. The direction of stress intensity factor, according to the stress field in the vicinity of crack tip, is normal to the crack front. The local crack growth increments may be calculated by the use of the fatigue crack growth law of Paris and Erdogan at different positions along the crack front, as described below:

$$da_i/dN = C(\Delta K_i)^m \quad \text{.......(1)}$$

The above equation only considers the stage of stable crack growth. But a more complex crack growth law which contains the effects of fatigue threshold, fracture toughness or loading ratio can also be used in a similar way. From Equation (1), the following equations can be derived:

$$\Delta a_i = \left(\frac{\Delta K_i}{\Delta K_{max}}\right)^m \Delta a_{max}; \quad \Delta N = \frac{\Delta a_{max}}{C(\Delta K_{max})^m} \quad \text{.......(2)}$$

where Δa_i and ΔK_i are the local crack growth increment and the SIF range at point i, respectively. Δa_{max} is the maximum crack growth increment occurring where the SIF is largest over the crack front. Equation (2), by specifying the value of Δa_{max}, can be used for the calculation of both crack growth advance and fatigue cycles, provided that the SIFs along the crack front are known. The crack shape can then be followed. It should be noted that the extension of Paris and Erdogan's relationship to a planar crack has neglected the influence of the stress and strain states along the tangential direction of a crack front, which actually vary with crack shape and are usually between plane stress at a free body surface and plane strain in the interior.

Calculation of Stress Intensity Factors

The calculation of stress intensity factors is performed using the 1/4-point displacement method proposed by Henshell and Shaw (4) and Barsoum (5). The out-of-plane displacements adjacent to the crack-tip are obtained by a three-dimensional linear elastic finite element analysis. A special crack-tip element block, as shown in Fig. 2, is used to simulate the theoretical inverse square-root singularity of stresses and strains in the vicinity of crack tip. The element block employed in this study consists of twelve 20-node prism elements with relocated mid-side nodes in the first element ring at their 1/4-points, as shown in Fig. 2. This method has been verified to be of good accuracy for a wide of planar crack configurations (1, 2, 6).

Creation of Finite Element Models

In order to facilitate automatic re-generation of finite element models during crack propagation, a unique mesh generation technique has been developed. The structure is usually divided into two blocks. One block (the cracked block) represents the small volume of material surrounding the crack and is meshed finely, and the other block (the uncracked block) defines the bulk of structure and is usually meshed coarsely. A two-dimensioanal (2D) 8-node isoparametric element mesh is first generated to represent the crack plane within the cracked block. The cracked mesh, comprising 20-node isoparametric elements, is then formed by expanding this 2D mesh into three dimensions (1, 2). The cracked block mesh is finally merged with the pre-meshed uncracked block to form a complete mesh for the cracked structure. Between the contact planes of those two blocks, a so-called "multi-point constraint" method is used to reduce the effect of the mesh mismatch across the contact plane. The cracked block mesh is automatically re-created after the crack extends, and is re-connected to the uncracked block mesh which is maintained unchanged. However, the uncracked block may be omitted if the cracked structure has a particularly simple configuration.

PRACTICAL EXAMPLES

Corner Crack at the Root of a Fastener Hole

Figure 3 shows the modelling results of crack shape evolution for a pair of symmetric corner defects emanating from a fastener hole subjected to a remote cyclic tension load. The initial shape of the defects is irregular. The cracks develop rapidly to a smooth shape, which seems close to a quarter ellipse. A detailed investigation into the crack shape change for such corner cracks has been carried out in an early work of the present authors (Lin and Smith (7)). The crack aspect ratio change predicted by the present method has been shown to be in close agreement with experimental results.

Surface Crack at the Root of a Notched Round Bar

It has been widely observed in engineering practice that final failure of round bars is often due to the initiation of cracks at the free surface and the propagation through the bar cross section. Crack shape development for a surface crack at the root of a semi-circularly notched bar can now be predicted by the present technique. The result is shown in Fig. 4, which agrees with experimental observations on crack shape change, i.e. a crack in a mildly notched round bar develops with its shape evolving from "almond" to near straight (Fuchs and Stephens (8)).

Interaction and Coalescence of Adjacent Cracks in a Cylinder

It has also become possible to use the present technique for the prediction of interaction and coalescence of multiple defects. Figure 5 is an example for two external surface cracks in a pressure vessel. The process of crack growth from two initially separate cracks to a smooth surface crack with approximately semi-elliptical shape can be modelled. The predicted shape evolution trend is generally in good agreement with experimental results reported in the literature (Lin and Smith (9)).

CONCLUSIONS

This work demonstrates that the method presented in this paper is capable of predicting the fatigue propagation of complex crack configurations, which is seldom possible for methods which assume and retain during the analysis particular crack front configurations. With the aid of an automatic mesh re-generation technique, it has become straightforward to model fatigue crack propagation for practical cracked components and structures. This paper has introduced examples which illustrate the utility of the technique.

SYMBOLS USED

C = Coefficient in the Paris type fatigue crack growth law

m = Power-index in the Paris type fatigue crack growth law

Δa_i = Local crack growth increment

Δa_{max} = Maximum crack growth increment over crack front

ΔK_i = Local stress intensity factor range

ΔK_{max} = Maximum stress intensity factor range over crack front

ΔN = Increment of fatigue cycles

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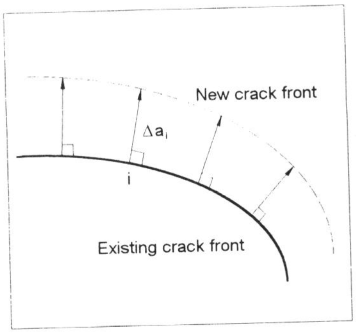

Figure 1 Crack growth prediction

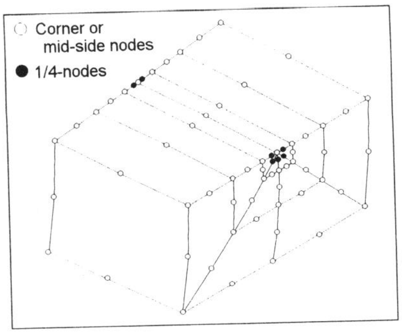

Figure 2 An element block at crack-tip

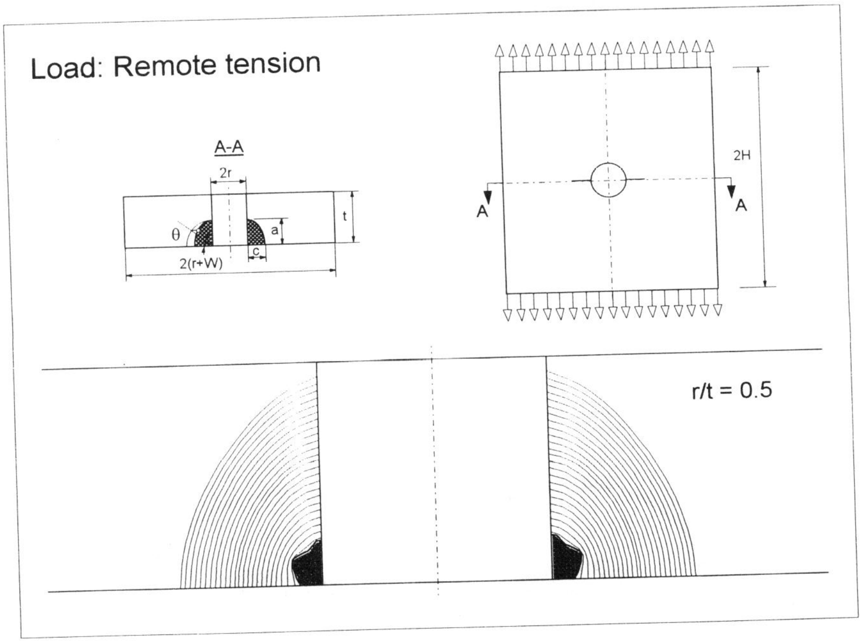

Figure 3 Crack shape evolution for a pair of corner cracks emanating from a fastener hole

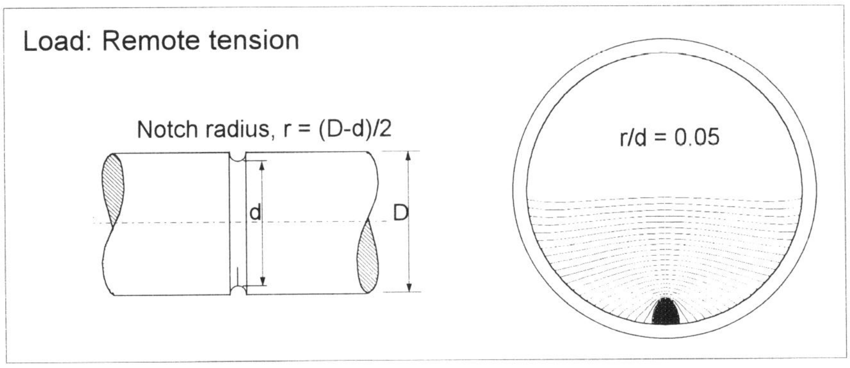

Figure 4 Fatigue shape development for a surface crack at notch

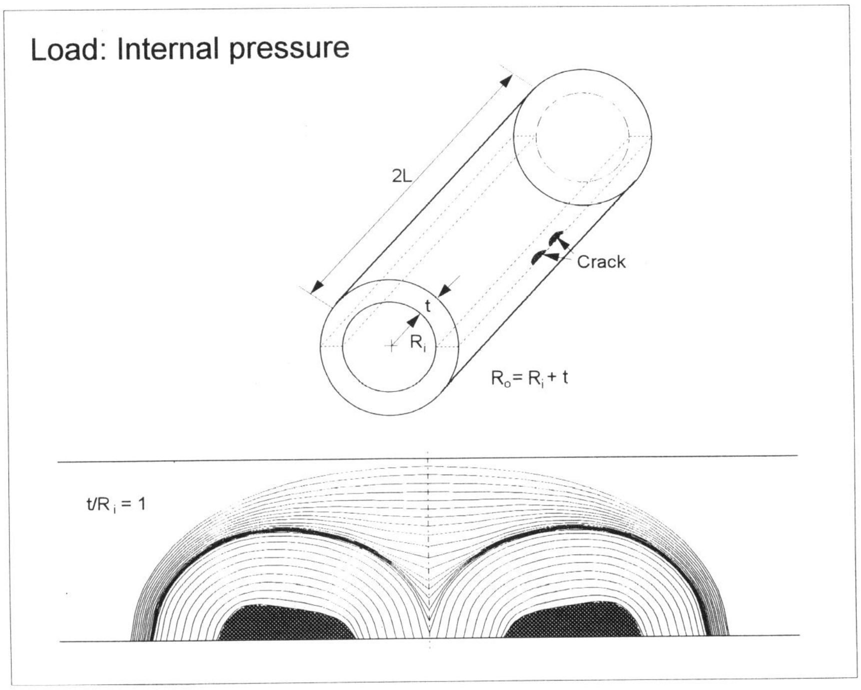

Figure 5 Interaction and coalescence of two adjacent external surface cracks in a cylinder