AUTOMATIC CRACK BOX TECHNIQUE FOR BRITTLE AND DUCTILE CRACK PROPAGATION AND BIFURCATION CRITERIA

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ABSTRACT

In this paper, a numerical automatic Crack Box Technique (CBT) is developed to perform fine fracture mechanic calculations in various structures without complete remeshing. This technique aims to simulate the fatigue crack growth under mixed mode loading in 2-D medium and shells under ABAQUS code, in elastic and elastic-plastic materials. Using this technique, series of numerical calculations by FEM of the mixed mode crack growth are carried out. In order to compare the results of the proposed technique and those of existing methods, a special cracked specimen subjected to different mixed mode loads is studied. The crack growth paths are determined by using different elastic and elastic-plastic bifurcation criteria. It is shown that the proposed technique is an efficient tool to simulate the crack bifurcation under monotonic or cyclic loading in elastic materials and further experiments are needed in elastic-plastic materials.

1 INTRODUCTION

In industrial complex structures, the determination of the crack path is necessary to assess the fatigue life and the failure resistance. Bifurcation criteria are also needed to predict the crack path. Their choice depends on the mechanical material characteristics and the loading levels. In industrial purposes, two methods are commonly used. Either step-by-step complete remeshing of the global model is performed or a very simplified determination is made by choosing the crack path thanks to the maximum of the principal stresses [10]. The first approach is very time consuming and cannot be used easily for industrial purpose unless an optimized meshing is performed. Nevertheless it is necessary when the whole stiffness is affected by the crack path or in large scale plasticity.

Close to the crack tip, the local stress field is determined by the use of asymptotic analysis. This allows to predict the critical loading level to crack propagation and to determine the crack bifurcation angle. But, this local asymptotic stress field presents a very high gradient that's why a specific and regular finite element mesh is required in this zone.

Also during the crack propagation this mesh has to move with the crack tip and evolves as a function of the crack path in order to optimize the element number. Apart of crack failure and bifurcation criteria, two major problems remain, i.e. what is the mesh characteristics of the crack tip region and how to connect it to the overall structure?

2 METHODOLOGY

In order to use this technique one has to automatically create a transition zone between the "crack box" and the overall structural unchanged mesh (see figure 1).

Zone (A): Crack box (figure 2) : it contains a specific and regular mesh. It's affected by the asymptotic solution at the crack tip. For elastic calculations, few elements are needed. The crack tip is modelled with degenerated quadratic elements with one side collapsed and midside nodes are moved to the quarter point nearest the crack tip to create a strain singularity in $r^{-0,5}$ (r is the distance from the crack tip). For plastic calculations, more elements are needed to precisely determine the J-integral. To introduce a r^{-1} singularity for perfectly plastic material strains, degenerated quadratic elements are also used but crack tip nodes are allowed to move independently and midside nodes remain at the midside point. For Ramberg-Osgood materials, the latter mesh allows to globally approximate a $r^{-n/n+1}$ strain field (n is the hardening exponent). Quarter midside nodes can be used for low n values.

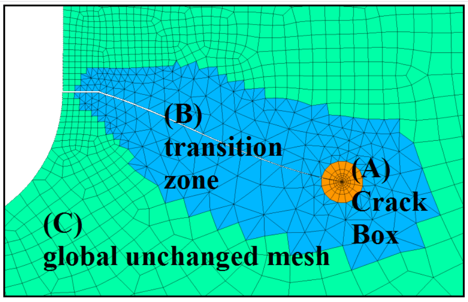

Figure 1: crack box in a structure (regions A, B and C)

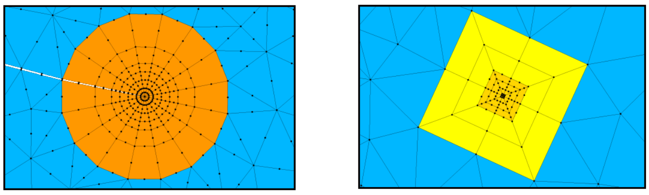

Figure 2: fine crack box (left) and coarse crack box (right)

Zone (B): Transition region. It contains an optimized linear (for elastic calculations) or quadratic (to increase precision for elastic and plastic calculations) triangular mesh obtained with the Delaunay triangulation procedure from NAG [14]. This allows to connect our specific crack box with the ABAQUS [15] model, which can be a 2D plane strain or stress and a 3D shell model.

Zone (C): Whole mesh. It represents a usual finite element mesh. It's to be noted that this mesh is unchanged during the crack propagation.

The automatic crack box technique used in this paper is our own development using the ABAQUS code and consists in the following:

- Meshing of the three regions for the initial crack
- Performing FEM calculation associated to crack bifurcation criterion in order to determine the crack bifurcation angle.
- Taking a crack growth increment in this direction
- Updating of local crack tip region mesh and connecting it by the use of region (B) to overall structure.

Note: The region (B) works such a moving contour around the crack tip. It looks like a static condensation of the structural behaviour to the crack tip region. This technique is almost similar to boundary Integral Equations in which the contour is replaced by the transition zone [12].

3 CRACK PROPAGATION AND BIFURCATION CRITERIA

In order to determine the crack growth path under mixed mode loading, one can use various criteria to calculate the bifurcation angle. For example, the maximum circumferential stress $\sigma_{\theta\theta max}$ criterion (Erdogan and Sih [1]), the Maximum Energy Release Rate, MERR, criterion (Palasniswamy and Knauss [2]), the stationary strain energy density criterion (Sih [3]), the J_{II}=0

(Pawliska et al. [4]) and K_{II}=0 (Cotterell and Rice [5]) criteria (J_{II} is the value of the *J*-Integral corresponding to pure mode II and K_{II} is the value of the stress intensity factor corresponding to pure mode II), the crack tip opening displacement (or angle) criterion (Sutton et al. [6]), and so on. Recently we have developed the J-M_p based criteria (Li, Zhang, Recho [7]) to assess the propagation of a crack in elastic-plastic material under mixed mode loading.

The global scheme of the bifurcation criteria used for elastic and elastic-plastic purposes is developed in figure 3.

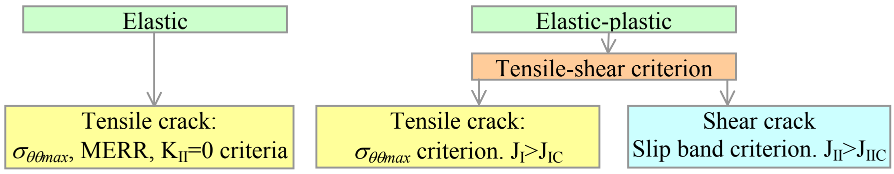

Figure 3: global scheme of bifurcation criteria

3.1. Elastic criteria

In the case of a crack in elastic material, the $\sigma_{\theta\theta max}$ criterion is more often used. According to this criterion, the crack propagates always in the direction of the maximum circumferential stress. Consider the equation of the circumferential stress $\sigma_{\theta\theta}$ as follow:

$$\sigma_{\theta\theta} = \frac{1}{4\sqrt{2\pi r}}\left[K_I\left(\cos\frac{\theta}{2}+\cos\frac{3\theta}{2}\right)-3K_{II}\left(\sin\frac{\theta}{2}+\sin\frac{3\theta}{2}\right)\right] \quad (1)$$

Where r and θ are the polar coordinates from the crack tip.

The bifurcation angle θ_0 can be obtained after calculating the stress intensity factors K_I and K_{II} :

$$\mathrm{tg}\left(\frac{\theta_0}{2}\right) = \frac{1}{4}\left(\frac{K_I}{K_{II}}\right) \pm \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2+8} \quad (2)$$

The numerical simulation of a crack growth is made in this work by using this criterion. Furthermore, the maximum energy release rate (MERR) and the K_{II}=0 criterion are also considered. The results are shown later.

3.2. Elastic-plastic method

When a crack exists in an elastic-plastic material, the crack growth bifurcation angle depends on the competition between cleavage tensile fracture (T-type fracture), essentially related to the void growth and coalescence near the crack tip, and ductile shearing fracture (S-type fracture), which depends on the plasticity progression. Recently, we have developed the J-M^p based criteria [7] in order to determine this crack growth angle. The main idea of the J-M^p based criterion is as follows:

In the case of a crack in an elastic-plastic material under mixed mode loading, Shih (1981) [10] showed that the stresses, strains and displacements fields near the crack tip are dominated by the HRR singularity, and can be characterized by two parameters, the *J*-integral and the mixity parameter M^p. M^p varies from zero to one. When $M^p = 0$, it is the case of pure mode II and when $M^p = 1$, it is the case of pure mode I. A numerical method has been developed to determine these two parameters for a crack under mixed mode loading. M^p is defined as follows:

$$M^p = \lim_{r\to 0}\frac{2}{\pi}\tan^{-1}\left|\frac{\sigma_{\theta\theta}(\theta=0)}{\sigma_{r\theta}(\theta=0)}\right| \quad (3)$$

Experimental studies shown that, for an elastic-plastic material, it exists a transition from T-type fracture to S-Type fracture. This transition is controlled by the critical value of the mixity parameter M_c^p which can be determined by means of experiments according to the critical fracture toughnesses J_{IC} and J_{IIC} (J_{IC} is obtained from a pure mode I tensile test and J_{IIC} from a pure mode II shear test). If the mixity parameter M^p for a giving loading case is greater than M_c^p , the crack will propagate by T-type fracture. It means that it will propagate in the direction of the maximum circumferential stress $\sigma_{\theta\theta max}$. The $\sigma_{\theta\theta max}$ criterion can be used to determine the crack growth angle. On the other hand, if M^p is smaller than M_c^p , the crack will propagate by S-type fracture along one of slip bands. The crack growth angle can be determined according to the slip band criterion [7].
Note : In elastic medium, M^p leads to the ratio K_I/K_{II} and, consequently, the bifurcation angle is easily determined by (eqn 2).

4 NUMERICAL RESULTS AND DISCUSSIONS

In order to improve the proposed technique, we carry out some numerical calculations. The specimen is issued from Aoki et al.'s experimental work [8], which is called the compact-tension-shear specimen as shown in figure 4.

It is supposed that the specimens were made from 6061-T651 aluminium plates, with hardening coefficient about n = 7, Young's modulus E = 72GPa and yielding stress σ_0 = 288MPa. For this material, the two critical fracture toughness: J_{IC} = 14 N/mm and J_{IIC} = 46 N/mm, which were tested by Tohgo and Ishii [11]. According to the experimental critical values J_{IC} and J_{IIC}, we can get the critical mixity parameter M_c^p about 0.75.

A series of calculations for different loading cases have been done. We choose the loading angles α=60° and α=30°. For each loading angle, three simulations are carried out in order to determine the crack growth path. The first one is the elastic simulation, in which elastic criteria are used to calculate the crack growth angle. In the second simulation, the direction of crack propagation is predicted by J-M^p based criterion. The mixity parameter M^p must be calculated in each step of crack growth. The results are shown in figure 4.

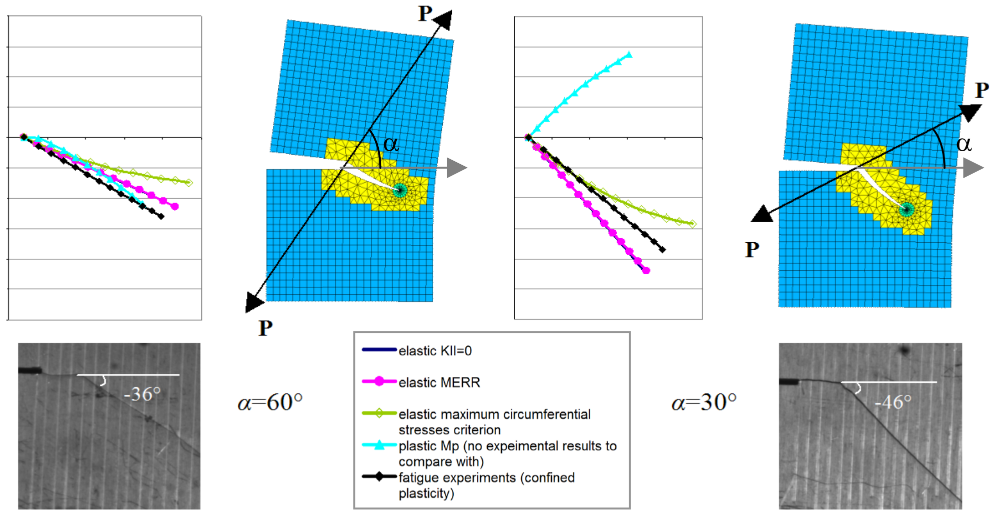

Figure 4: elastic and plastic calculation results (experimental results in endurance fatigue)

For these experiments, the crack was growing in fatigue endurance condition. As a consequence the plastic zone was very small at the crack tip. So the elastic calculations are in good agreement with experimental results.

The plastic calculations show two different behaviours of the crack growth in α=60° and α=30° loadings. Indeed in 60° the crack will begin to propagate in shear mode 0° and then will follow the $\sigma_{\theta\theta max}$ direction, unlike in 30° loading, the crack will always follow a 45° slip band direction.

Large scale plasticity experiments have to be carried out to validate our plastic calculations and to precisely study the transition between tensile and shear fracture types.

The Crack Box Technique (CBT) has also been used for two other configurations:

4.1. Crack from a fillet in elastic material

This example shows the capability of the CBT to predict crack path in various geometries and loading conditions. It's important to note that only the crack zone is remeshed during iterative calculations. The bending stiffness is modified by varying the size *h* of the bottom I-beam [13]. For low h values, there is a large bending component so the crack direction highly changes. For large h values, the crack tends to go straight (figure 5).

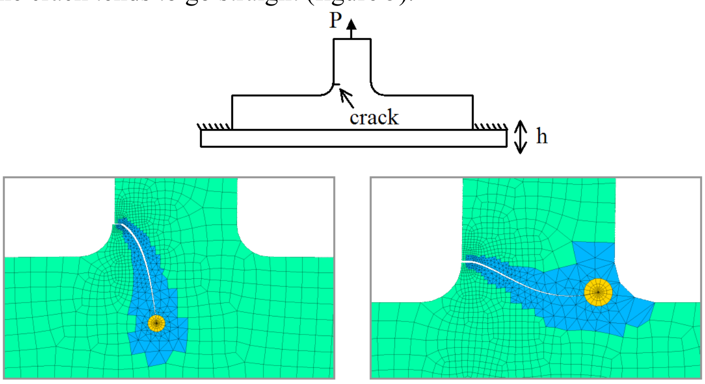

Figure 5: fillet loading, and crack growth result (left: h low values, right: h large values)

4.2. Crack growth near two holes in elastic-plastic material

This example shows the different paths for elastic and elastic-plastic materials. In the latter material, the crack will follow a 45° slip band and failure will occur in the first hole, whereas in elastic calculations the crack propagates between the two holes (see figure 6).

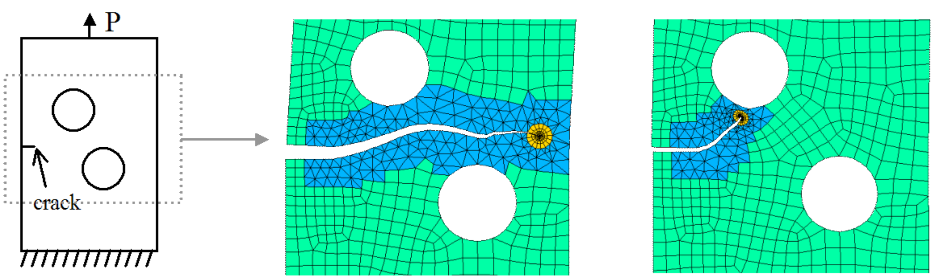

Figure 6: geometry and crack growth results (elastic (left), elastic-plastic (right) materials)

5 CONCLUSIONS

An automatic Crack Box Technique (CBT) has been developed. It can be used under ABAQUS code. In a global structure, only the crack region has to be remeshed. A transition zone allows to connect the refined specific crack tip mesh to the global structural discretization. So this technique can be used for complex industrial structures. Various criteria can then be used in order to predict the crack path: elastic criteria and specific elastic-plastic criteria based on a mixity parameter. The CBT will allow us to study the influence of plastic material characteristics (particularly the shear-tensile transition criterion) on the crack growth path. It's to be noted that this crack path has a significant influence on the fatigue life duration, in particular under variable loading. Indeed an overload can modify locally the material behaviour and as a consequence completely change the crack direction when mode-II is dominating.

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