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Note

Analysis of mixed-mode dynamic crack propagation by interface element based on virtual crack closure technique

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Abstract

An interface element tailored for the virtual crack closure technique (VCCT) was used to study an example of dynamic crack propagation under mixed mode loading. Through this interfacial element approach, VCCT can be implemented into a commercial finite element analysis (FEA) code having user subroutines without interrupting the main code. Further, with the implementation of relevant fracture criteria, this interface element can be used to simulate a wide range of fracture problems by utilizing the enhanced capabilities available by the commercial FEA codes. For illustration, this element has been implemented with the commercial FEA software ABAQUS® through the user defined element (UEL). One example of fast crack propagation at constant speed and under mixed-mode loading was examined by comparison to the other's numerical results using singular moving elements. No convergence difficulty was encountered for all the cases with different values of crack velocity. Neither singular element, nor the collapsed element was required. Therefore, due to its simplicity, the VCCT interface element as demonstrated could be a potential tool for engineers to practice dynamic fracture analysis in conjunction with commercial FEA codes.

Keywords: Virtual crack closure technique; Dynamic fracture; Strain energy release rate; Mixed-mode fracture; Interfacial element; Finite element analysis

1. Introduction

Dynamic crack propagation and arrest are of great interests for some engineering structures such as pipe lines, nuclear reactors, airplane fuselages and ship hulls [1–4]. Within the frame of finite element analysis (FEA) and linear elastic fracture mechanics (LEFM), Atluri and Nishioka [5–15] developed moving singular elements equipped with stress intensity factor computation and several classic examples were analyzed. Sun et al. [16,17] used their own code to study the pure mode I dynamic propagation examples. Virtual crack

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closure technique (VCCT) was used to compute the strain energy release rate and node release technique was used to advance the crack growth. Ingraffea et al. [18–20] at Cornell Crack Group developed FEA based fracture software: FRANC2D and FRANC3D. With adaptive mesh technique, this fracture software can simulate crack growth without the crack path prescribed. Their work has provided fundamental understandings for the simulation of dynamic crack propagation based on FEA.

VCCT is particularly convenient when it is used in conjunction with FEA since it involves only the evaluation of the nodal forces and displacements without any special treatment of the region around the crack tip. It was first introduced by Rybicki and Kanninen [21] for line type cracks, and was extended to surface type cracks by Shivakumar et al. [22]. Raju [23] developed the general procedure for this technique and extended it to any type of elements. Recently, a review over VCCT was presented in Ref. [24].

VCCT can be easily implemented during the process of FEA code development to simulate crack propagation as shown in Refs. [16–20]. For stationary cracks, VCCT can also be easily used in conjunction with commercial FEA codes. However, some extra efforts are necessary to compute the strain energy release rates based on the information of nodal forces and displacements provided by the FEA codes. For propagation cracks, this extra computation becomes problematic when VCCT is used with commercial FEA codes. In this case, users have to break a propagation analysis into a series of consecutive steps at each load increment: running analysis, conducting extra computing for VCCT, making a judgment on crack advances, and restarting the analysis. Obviously, this process is tedious and mistakes prone. To address this issue, Refs. [24,25] suggested to developing interfacial software to communicate with the commercial FEA codes. However, this requires sophisticated skills of code programming and comprehensive knowledge of computer system beyond the capability of the FEA code users, let along the time spending on validation and verification.

Alternatively, Xie and Biggers [26–28] introduced an interface element tailored for VCCT so that the VCCT procedure can be seamlessly integrated into any commercial FEA codes having user access subroutines. Within the element, very stiff spring is placed between the node pair at the crack tip to hold the nodes together and meanwhile to compute the nodal forces. Therefore, these nodes at the crack tip have contributions to the stiffness matrix. The nodes around the crack tip are also collected to extract the information from the commercial FEA code and to compute the displacement opening behind the crack tip and crack jump ahead of the crack tip. These nodes are dummy nodes since they do not contribute to the stiffness matrix and they are introduced only to extract information. So far, all the information required to compute the strain energy release rate is ready within the element. Once the criterion is satisfied, the spring stiffness at the crack tip are set to zero (removal of the spring), the crack tip advances. Within this type of elements, VCCT can simulate crack propagation simultaneously as commercial codes perform FEA without any pauses. This interfacial element does not damage the integrity of the commercial FEA codes and minimizes the programming efforts. It also avoids the repetition of the extra computations and, therefore, it is also beneficial to the stationary crack problems. It has been practiced with the commercial FEA code ABAQUS® through its user element subroutine UEL and used to study crack kinking [29,30], failure of adhesively bonded joints [31] and crack response to impact loading [32].

In this technical note, the VCCT interface element was reported to study a 2D example of dynamic crack propagation under mixed mode loading at the crack tip. The results were examined by comparison to the other's numerical results [11]. Although, the analyses were performed with ABAQUS®, this element approach is universal and can be applicable to other commercial FEA codes having user subroutines.

2. VCCT interface element

The details for this interfacial element for VCCT can be found in Refs. [26–28]. Here, only the outline is presented. Fig. 1 shows the definition and node numbering of a typical VCCT interface element for 2D fracture problems. Each element has five nodes. When such element is applied, it is placed in such a way that the nodes 1 and 2 are located at the crack tip, with nodes 3 and 4 behind and node 5 ahead of the crack tip. The element contains two sets of node groups: the top set (nodes 1, 3 and 5) and the bottom set (nodes 2 and 4).

Very stiff spring is placed between nodes 1 and 2 to compute the nodal forces at the crack tip by

$$F_x = K_x(u_1 - u_2), \quad F_y = K_y(v_1 - v_2) \tag{1}$$