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A combined interface element to simulate interfacial fracture of laminated shell structures

Biao Li *, Yazhi Li, Jie Su

School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, PR China

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A new combined 8-node interface element is developed to simulate the interfacial fracture of shell-like structures such as composite laminates or adhesively bonded joints. It is composed of eight rigid bars and an 8-node zero-thickness cohesive element, each node of which possesses six degrees of freedom (DOFs). Layers of the shell structures are discretized by shell elements and the interface elements are embedded among them. The rigid bars are used to transfer mid-plane nodal displacements of the shell elements to the internal cohesive elements on which the interfacial fracture is actually occurred. The interface element is appeared as a solid one with its 4 nodes at each side connected with the adjacent 4-node shell element. No additional degree of freedoms is introduced by the new element in finite element (FE) model except those of shell elements. A bilinear mix-mode constitutive law is used to characterize the interfacial damages and a viscous regularization method is employed to treat the difficulty on the convergence of implicit FE algorithm. Parametric studies were conducted on double cantilever beam (DCB) specimen to investigate the effect of viscous coefficient and mesh size on the simulation results. The results indicate that the viscous regularization method is effective and the proposed shelled model is less mesh size sensitive than 3D solid model. An adhesively bonded single lap joint (SLJ) and a mixed-mode bending (MMB) specimen with various loading mode ratios were simulated to demonstrate the capability of the element to deal with interfacial fracture problems. The results show that the interfacial element and the simulation results agree well with the experimental results and those obtained through 3D solid models as well as analytical solutions.

1. Introduction

Fiber-reinforced composite laminate is a kind of shell structures and is utilized in a large variety of structural applications in aeronautical engineering. Despite its high intralaminar strength and stiffness, the laminate exhibits a low resistance to interlaminar damages, i.e. the interfacial fracture called delamination. Delamination frequently occurs in laminated composite structures, especially when the structures are subjected to transverse impacts. Delaminations can be dangerous since they result in significant loss in the structural stiffness and strength. Another kind of interfacial fractures often occurred in shell structures is the decohesion of adhesively bonded joints, such as the fracture of the bonding between longeron ends and skin sheet in aircraft skin panels, a typical site of the structural weakness due to the high stress concentration arisen by the interrupting of the load path. It is therefore very desirable to be able to predict the interfacial fracture by the use of advanced numerical methods.

Over the years, several methods have been used to predict the formation and propagation of interfacial fracture in composite structures. Cohesive zone model (CZM) approach is one of the appealing techniques. Compared with alternative analysis techniques directly based on fracture mechanics, such as the virtual crack closure technique (VCCT) [1–4], CZM incorporates both damage mechanics and fracture mechanics theories and allows investigating the onset and growth of delamination in the same analysis. The basic idea of such method can be traced back to Dugdale [5] and Barenblatt [6]. Afterwards, Hillerborg et al. [7] developed the concept of tensile strength for crack initiation and growth. Needleman [8] and Tvergaard [9] studied the mixed-mode crack growth. Camanho et al. [10] predicted crack onset and growth in mixed-mode with only a single damage variable to describe the damage process. CZM can be easily implemented by using cohesive elements which are embedded at potential delamination sites to model the adhesive interface. A softening constitutive law described by traction–displacement jump curve is introduced for the cohesive elements. Although several shapes of such curves

* Corresponding author. Address: Box 118, Northwestern Polytechnical University, No.127 Youyixilu, Xi'an, Shaanxi 710072, PR China. Tel.: +86 29 88460621.
E-mail addresses: libiao@mail.nwpu.edu.cn (B. Li), yazhi.li@nwpu.edu.cn (J. Su).

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have been proposed [11–13], the simplest bilinear law is often used since the structure's load–deflection response is relatively insensitive to the curve form [14–16]. The failure process with different jump curves is basically the same: irreversible softening process is initiated when the traction attains the maximum interfacial strength and delamination is fully developed when the local energy release rates approach their critical values. Numerous papers contribute to the use of this method in analyzing different laminate delamination problems, such as the simulations of low velocity impact [17,18], free edge delamination [19], delamination around bolt joints holes [20,21] and disbonding of adhesively bonded joints [22,23]. There are mainly three types of cohesive elements: zero thickness cohesive elements connecting 3D solid continuum elements, finite thickness cohesive elements connecting plate/shell elements, and 2D cohesive line elements connecting plane elements. In most cases, the finite element models were established in three dimensional forms in which zero thickness cohesive elements were commonly used in conjunction with solid continuum elements. In such models, cohesive elements worked well in predicting the onset and growth of delaminations. However, the large scale and the high computational cost of the 3D solid models are certainly the restrictive factors to the application of CZM approach.

Due to the nature of the material behavior, there exists a softening region known as the cohesive zone ahead of the crack front. The length of cohesive zone is a material property since the constitutive law does. It is on the order of 1 mm for typical polymeric matrix composite laminates [24]. It has been found that sufficient numbers of cohesive elements are needed in cohesive zone to describe the stress distribution ahead of the crack tip accurately. The least number of elements needed in cohesive zone ranges from 2 to 10 according to the authors [15,25,26]. As a consequence, extremely refined mesh is needed for conducting delamination analysis, which is computationally expensive, especially for 3D solid models mostly used in literature. Some researchers relaxed the requirement by artificially reducing the interfacial strength while keeping the critical energy release rate constant to increase the cohesive zone length. However, this might result in incorrect stress field at crack tip and may affect the onset and growth of intraply matrix cracks. Yang et al. [27] pointed out that such practice only adapts to the situation where the existing crack length is much larger than the cohesive zone length.

Thin walled composite structures are preferably modeled with more computationally efficient plate/shell elements. Several delamination models using shell elements have been proposed. Borg et al. [28] presented a shell delamination model using a mixed-mode adhesive penalty contact algorithm. The thickness offset and rotational degrees of freedom (DOFs) in the shells were taken into account. Zou et al. [29] adopted interface elements to impose the continuity conditions between adjacent shell elements. Each node pair of an interface element was equivalently generated by a set of stiff springs. Bruno et al. [30] used rigid links to offset the node pair from the shell mid surface to the interface between the layers, and the interface was simulated by three translational springs at every node pair. Reedy et al. [31] developed shell models for discrete delamination, using volumetric elements to connect adjacent sublaminate shell elements. Davila et al. [32] adopted 3D cohesive element to simulate the bonded shells and plates.

In this paper, we aim to develop another kind of interface element comprised of a zero-thickness cohesive zone element and a number of rigid bars. The combined element is best being used in shell delamination model. Double cantilever beam (DCB) tests were simulated to figure out relevant parameters. The experiments of mixed-mode bending (MMB) under various mode ratios and adhesively bonded joints were analyzed to show the capability of the proposed interface element.

2. Shell delamination model

2.1. Model description

In the shell delamination models, laminated structures are divided into several sublaminates through the thickness. A sublaminate is a set of adjacent physical layers among which debonding is unlikely to occur. All sublaminates are modeled with four-noded quadrilateral shell elements on middle planes of them. The finite-thickness interface elements are used to connect shell elements belonging to adjacent sublaminates, as shown in Fig. 1b. Thus the laminates could be considered as sandwich shells stacked by shell elements and the interface elements. In this way, intralaminar and interlaminar damages could be considered separately with both kinds of elements.

As shown in Fig. 2, an interface element is composed of eight rigid bars and a zero thickness cohesive element. Each rigid bar possesses a master node and a slave node. The master nodes are used to connect external shell nodes, and the slave nodes are used to connect internal cohesive element nodes, respectively. The rigid bars transfer the translational and rotational movements of the shell nodes to the internal cohesive element. Interlaminar fracture will be denoted by the failure of the internal cohesive element. Although being composed of discrete rigid bars and cohesive element, the interface element presents itself as a solid one in which DOFs of the internal nodes have been eliminated by deduction of its kinematic formulae. Therefore, no additional DOFs are required in the shell delamination models except those of shell elements. The interface element has been implemented in the commercial finite element (FE) code ABAQUS via its user defined element subroutine (UEL). Newton–Cotes full integration scheme is adopted which has shown superior to other integration techniques [33]. According to the way that ABAQUS names its in-built elements, we name the new interface element as CRC3D8, namely the 8 node and three dimensional combined rigid bar-cohesive element.

2.2. Interface element formulation

In a CRC3D8 element shown in Fig. 2, lower rigid bars are numbered from 1 to 4 and upper fours are 5 to 8. The relation of the nodal displacements between two nodes of a rigid bar can be expressed as follows:

$$\boldsymbol{u}_{\mathrm{S}}^{i} = \boldsymbol{t}_{\delta}^{i}\boldsymbol{u}_{\mathrm{M}}^{i} \quad (i = 1, \ldots, 8) \tag{1}$$

where $\boldsymbol{u}_{\mathrm{M}}^{i} = (u_{\mathrm{M}}^{i}, v_{\mathrm{M}}^{i}, w_{\mathrm{M}}^{i}, \theta_{\mathrm{Mx}}^{i}, \theta_{\mathrm{My}}^{i}, \theta_{\mathrm{Mz}}^{i})$ and $\boldsymbol{u}_{\mathrm{S}}^{i} = (u_{\mathrm{S}}^{i}, v_{\mathrm{S}}^{i}, w_{\mathrm{S}}^{i}, \theta_{\mathrm{Sx}}^{i}, \theta_{\mathrm{Sy}}^{i}, \theta_{\mathrm{Sz}}^{i})$ are the displacement vectors at master and slave nodes of the ith rigid bar respectively, and both of them contain six DOFs. $\boldsymbol{t}_{\delta}^{i}$ is the displacement transformation matrix of the two nodes:

$$\boldsymbol{t}_{\delta}^{i} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{\mathrm{S}}^{i} - z_{\mathrm{M}}^{i} & -(y_{\mathrm{S}}^{i} - y_{\mathrm{M}}^{i}) \\ 0 & 1 & 0 & -(z_{\mathrm{S}}^{i} - z_{\mathrm{M}}^{i}) & 0 & x_{\mathrm{S}}^{i} - x_{\mathrm{M}}^{i} \\ 0 & 0 & 1 & y_{\mathrm{S}}^{i} - y_{\mathrm{M}}^{i} & -(x_{\mathrm{S}}^{i} - x_{\mathrm{M}}^{i}) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where x, y, z are coordinates. Lower subscripts S and M denote the slave and master nodes respectively.

Similarly, the nodal force relation between master and slave nodes of a rigid bar can be expressed as:

$$\boldsymbol{F}_{\mathrm{S}}^{i} = \boldsymbol{t}_{\mathrm{F}}^{i}\boldsymbol{F}_{\mathrm{M}}^{i} \tag{3}$$

where $\boldsymbol{F}_{\mathrm{M}}^{i}$ and $\boldsymbol{F}_{\mathrm{S}}^{i}$ are the nodal force vectors of the master and slave nodes in ith rigid bar. $\boldsymbol{t}_{\mathrm{Fi}}$ is the nodal force transformation matrix.