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Delamination and transverse crack growth prediction for laminated composite plates and shells ☆

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ABSTRACT

Based on the extended layerwise method (XLWM) (Li, 2016; Li et al., 2015) and virtual crack closure technique (VCCT), a VCCT-XLWM method is proposed to predict the delamination and transverse crack growth of laminated composite plates and shells. In the VCCT–XLWM method, the laminated composite plates and shells with delamination and transverse crack are simulated by the XLWM method, and the strain energy release rate (SERR) along the delamination front is calculated by the VCCT. The moving delamination front with an arbitrary and changing shape is traced by an algorithm presented by Xie and Biggers (2006), and delamination growth is predicted by a mixed-mode fracture criterion.

1. Introduction

Delamination and transverse crack are the typical interlaminar failure mode of composite laminates caused by the low strength of the resin-rich interface between single layers and the lack of reinforcement in the thickness direction. The onset and growth of delamination are critical in applications of composite structures. Over the past years, many methods and models have been proposed for the prediction of delamination growth [4] and transverse crack [5–11].

Whitcomb [12] studied the delamination growth problem caused by local buckling for composite plates based on a three-dimensional (3D) geometrically nonlinear finite element model and the fracture criterion governed by the strain energy release rate (SERR). Chen [13] analyzed the elastic buckling and postbuckling using the shear deformation theory (SDT) and Giffith-type fracture criterion for an axially loaded beam plate with across-width delamination. This conforms the lowering effect of shear deformation on the critical buckling load and ultimate load. On the basis of a kinematically nonlinear finite element formulation, Nilsson and Giannakopoulos [14] analyzed the configurational stability phenomenon and finite growth of a buckling-driven, initially circular, delaminated thin film loaded in equal biaxial compression. It was found that from their analysis the configurational instability is highly associated with the fracture mode and dependence in the crack growth law, and the two perturbation methods can result in quite different shapes of the advancing buckled thin film. Robinson and Ronald [15,16] presented the results of the effect of stacking sequence on energy release rate (ERR) distributions for the laminated carbon fiber reinforced epoxy end-notched flexure (ENF), double cantilever beam (DCB) and single leg bending (SLB) test specimens. Hitchings et al. [17] presented an efficient finite element technique of the arbitrarily shaped delamination growth for the laminated composite. The LEFM assumptions and an SERR criterion ($\gamma = 1$) were used, where γ is a function of SERR, and this criterion is satisfied at all points along the delamination front. Aymerich et al. [18] used the virtual internal bond (VIB) [19] model to predict delamination initiation and growth in unidirectional laminated composites, including the DCB, ENF, and mixed-mode bending (MMB). Meer et al. [20] presented a new method to model progressive delamination by implicitly describing the crack front with a level set field. Weak discontinuities are introduced to simulate the sharp transition between the cracked and uncracked parts of the crack front. Crack growth is handled by an explicit energy-based relation, in which the configurational force is computed as the jump in the Eshelby tensor. Sprenger et al. [21] presented a 3D-shell formulation with an extended eight-node brick element for simulation of delamination in composite structures. The delamination behavior and growth were calculated by a rate-dependent plasticity-based softening material law and critical energy release rate (G_c), respectively. Rinderknecht and Kröplin [22] investigated the delamination growth problem using the Reissner–Mindlin plate

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theory and the so-called front control method with a moving mesh technique adapting the mesh successively to the delamination front. Xie and Biggers [3,23] presented an algorithm to trace the moving delamination front with an arbitrary and changing shape. The crack front is defined by two basic vectors, each denoting the beginning and ending of the completely bonded region. Hossein et al. [24] extended the layerwise theory by jump discontinuity conditions at the interfaces for analyzing delamination growth. The SERRs were calculated by the virtual crack closure technique (VCCT). Hu et al. [25] presented a new approach for modeling delamination growth using peridynamics. The interlayer bonds were assumed to fail once their SERR reaches a critical value. Shen et al. [26] developed a 3D finite element model based on VCCT for circular delaminations in woven and nonwoven composite laminates. They found that fiber orientation of the plies plays an important role in the distribution of the local SERR, and hence the commonly used quarter models to reduce computational effort are unjustified and will produce erroneous results. Elmarakbi and Fukunaga [27] developed a fully 3D model using a new adaptive cohesive element to overcome the numerical insataibility of the bilinear cohesive model, and implemented LS-DYNA as a user-defined material subroutine (UMAT). In this model, a pre-softening zone, in which the initial stiffness and interface strength were gradually decreased, is developed on front of the existing softening zone. The methodologies based on the combined use of the VCCT and a fail release approach might not be robust because of the mesh and load step size dependency. Pietropaoli and Riccio [28,29] proposed a novel approach (SMART), which allows an automatic definition of load step size adjustment. It has been implemented as user subroutines in ANSYS. In addition, there have been several studies focusing on the fatigue delamination growth problem via experiments and numerical methods [30–34].

However, almost all the aforementioned methods are based on the observed macroscale material behavior, but not on an understanding of the micro-mechanics underlying the delamination growth. Many studies were conducted on the delamination growth, but only very few of them focused on the delamination growth problems together with the transverse cracks. Petrossian and Wisnom [35] developed a special interface element to deal with the delamination growth problem of composites with a cut, which can be considered as a transverse crack. Yielding of the element depended on an interactive stress-based criterion and final failure depended on a mixed-mode fracture mechanics criterion. In composite laminates, the intraply matrix cracking is the initial damage mode resulted from the impact. As the matrix cracks induce local stress concentrations at crack tips, the delaminations start to occur once the matrix cracks reach the interface between the ply groups having different fiber orientations [36,37]. Because the tensile failure strength of the fiber is high, and the damage induced by fiber breakage is generally very limited and confined to the region under and near the contact area between the impactor and the composite laminates, the main part of damage in the composite laminates is caused by the matrix cracks and delaminations [38]. Therefore, a method which can accurately predict the delamination growth together with the arbitrary growth of the thick through or non-thick through transverse cracks needs to be developed. Furthermore, almost all the existing methods and investigations deal with delamination growth resulted from the in-plane loads, and the numerical results of the out-plane loads were very few. All the aforementioned drawbacks have been addressed in this study.

The typical damage pattern of composite laminated structures is a complex three-dimensional crack with layered characteristics. Since it is very difficult to apply XFEM directly to deal with complex 3D crack, this complex 3D crack can be decoupling into two 2D crack (delaminations and transverse crack) by using an appropriate displacements model along thickness direction. There are a large number of displacements field along the thickness direction applied to the composite laminated structures, such as the equivalent single layer theory, 3D elasticity theory and multiple model methods. For three-dimensional problems, such as the composite laminated structures with delaminations and cracks, the layerwise theories [39–46] established by assuming that the displacement field exhibits only C_0-continuity through the thickness should be the most suitable. The layerwise theories can represent the zigzag behavior of the in-plane displacements through the thickness, and providing an effective way to accurately calculate the inplane and transverse stresses.

In our previous studies [2], an extended layerwise method (XLWM) was developed for the composite laminated beams with multiple delaminations and transverse cracks. The displacement field of the XLWM is constructed with the linear Lagrange interpolation functions, the one-dimensional (1D) weak discontinuous function and strong discontinuous function. The strong and weak discontinuous functions are applied in the displacement field along the thickness direction to model the displacement discontinuity induced by the delaminations and strain discontinuity induced by the interface between the layers, respectively. The transverse cracks are simulated in the in-plane displacement discretization. Recently, the XLWM was extended to the laminated composite plates and the doubly curved laminated composite shells [1]. The XLWM of laminated composite shells can not only perfectly describe the multiple delaminations together with the thick through or non-thick through transverse cracks, but also accurately obtain the displacement and stress fields of the transverse crack tips and delamination front. The weak discontinuous function is used to ensure the C^0 continuous condition at the interlaminar interfaces. Because the XLWM is quasi-3D and the transverse cracks of each single layer are independently described, the distribution of the stress intensity factor (SIF) along the thickness direction can be calculated, and the predicted crack growth angle is different for each mathematic layer. This serves an important advantage compared with the existing shell elements enriched by XFEM. The XLWM expanded the application of the XFEM in the damage analysis and prediction of composite laminated structures. In addition, the modeling capabilities of the XLWM are essentially the same as the conventional 3D displacement finite element method. Therefore the existing fracture mechanics method based on the conventional 3D displacement finite element method can be conveniently applied to XLWM.

The existing XLWM of composite beams and plates can only simulate the stress singularity and arbitrary growth of the transverse cracks. Therefore, in this study, we proposed a VCCT–XLWM method, which can predict the simultaneous propagation of transverse cracks and delaminations. The remainder of this article is organized as follows: Section 2 presents the mathematic formulations of the proposed VCCT-XLWM were presented, including the displacement field assumption, Hamilton principle, Euler equations, and finite element formulations of XLWM for composite plates and shells, VCCT based on XLWM, algorithm to determine the delamination front and the mixed-mode fracture criterion used to predict delamination growth. Section 3 presents some numerical examples to demonstrate the capabilities of the VCCT–XLWM. A comparison of the numerical results of SERR obtained for the composite beams with straight delamination and the square plates and spherical shells with circular delamination, and the results of the composite beams with those in the references was made to validate the proposed method. In addition, the influences of the transverse crack on the distribution of SERR along the delamination front were also investigated for the laminated composite beam