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Point-wise evaluation of the growth driving direction for arbitrarily shaped delamination fronts using cohesive elements

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ABSTRACT

The identification of the delamination propagation direction in three-dimensional structures with arbitrarily shaped fronts is needed in many applications. In the cohesive element framework, the propagation direction may be computed as the normal direction to a numerical damage isoline. The damage isoline tracking requires to exchange information between neighboring elements, thus post-processing global data, which is computationally expensive. This work presents a novel approach for the evaluation of the growth driving direction, only using local element information. The method can be directly implemented in a user-defined element subroutine and be evaluated at the execution time of the analysis. The presented formulation and its implementation in the commercial Finite Element code Abaqus is validated by comparison to the damage isoline shape rendering using global information.

1. Introduction

Long fiber-reinforced polymers are layered materials produced by stacking plies which contain continuous fibers in different orientations. Fibers supply stiffness and strength to the material in the laminate plane. Although laminated composite structures are designed so that the highest stresses are in the fiber directions, out-of-plane stresses may also occur at many types of geometric discontinuities such as ply drops, skin-stiffener terminations, intersections, sandwich panels, free edges, holes, cut-outs, flanges, bonded and bolted joints or impacted zones. These load cases may damage the interface between plies, causing the failure mechanism called delamination. Delamination is considered the most detrimental failure mechanism in laminated composite structures because it occurs at relatively low load levels but still entails significant reduction of the structure's load carrying capacity. To address this problem without recoursing to impractical safe-life designs, damage-tolerant approaches are used. In that event, Finite Element (FE) analysis is an indispensable tool to predict delamination growth in complex laminated structures subjected to both static and fatigue loading.

The virtual crack closure technique (VCCT) is one of the most widely used FE techniques (Krueger, 2015). However, its application to realistic three-dimensional geometries with arbitrarily shaped crack front requires a continuous adaptive meshing technique in order to get a smooth front that fits with the instantaneous crack front curvature (FRANC3D; Schollmann et al., 2003; Iesulauro). Alternative methods, that allow the use of stationary meshes, consist of tracing a smooth virtual front around the stepped front (Xie and Biggers, 2006; Li et al. 2015; Liu et al., 2011). These techniques require the use of algorithms to determine the normal direction to the virtual delamination front using global information (or 18-noded elements as in (Xie and Biggers, 2006)). This direction is used to compute the virtually closed area and to define a local coordinate system that enables to calculate the energy release rate components according to it.

An alternative to VCCT, is the cohesive zone model (CZM), firstly developed by Dugdale (1960) and Barrenblatt (Barenblatt, 1962). In contrast with the VCCT approach, the application of the CZM is not limited to Linear Elastic Fracture Mechanics (LEFM). Indeed, it accounts for a large fracture process zone ahead of the crack tip where the material undergoes stiffness degradation until complete decohesion. This nonlinear material behavior is lumped into a surface, the cohesive zone, modeled by cohesive elements. Under static loading conditions, no crack tip tracking algorithm is required as long as the assumptions of identical fracture toughnesses for shear mode openings and independence of fracture toughness with propagation direction with respect to fiber orientation are made (Chabocheet al., 1997; Ortiz and Pandolfi, 1999; Alfano and Crisÿeld, 2001; Camanho et al., 2003; Goyal et al., 2004; Turon et al., 2006, 2010; Jiang et al., 2007). However, some of the existing methods for the simulation of fatigue-driven

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delamination using the CZM approach do require the identification of the propagation direction for its three-dimensional implementation (Bak et al., 2014a, 2016, 2017; Kawashita and Hallett, 2012; Wang and Xu, 2015), even making the same assumptions as in the static formulation. To the authors knowledge, the existing formulations to estimate the direction of crack propagation using CZM are nonlocal and, thus, require additional post-processing. In practice, these algorithms are computationally inefficient for the analysis of large structures.

Another and more recent approach presented by Van der Meer et al. (van Der Meer et al., 2012) uses the level set method to describe the crack front location. Like the VCCT, it is a fracture mechanics approach. Furthermore, its variant for large process zone simulation (van der Meer and Sluys, 2015) makes use of a stiffness degrading damage variable that allows a band of damaged material with predefined width. Conversely to most of the existing CZM formulations, the damage variable is not a function of the local properties but it is defined by the distance to the crack front, where the crack front is defined as the line that separates the damage process zone and the completely damaged interface.

In this work, a local algorithm to determine the growth driving direction in CZM is presented. It can be evaluated at any point within the cohesive zone at the same time the damage state is being computed. Therefore, it can be used to enhance the cohesive element formulation under static loading, preserving the local nature of the formulation. Moreover, it is an efficient alternative to the existing nonlocal propagation direction algorithms used in the methods for fatigue simulation.

The concept of growth driving direction applied to cohesive elements is presented in 2.1. Three different criteria for the growth driving direction identification are defined in Section 2.2. The formulation according to the first criterion is developed in Section 2.3. The formulation for the other two criteria is given in Appendix B. The three growth driving direction criteria are implemented for the particular case of the CZM presented in (Turon et al., 2006, 2010), which is summarized in Appendix A. However, it is worth to mention that the same criteria could be applied to any other CZM formulation. Sections 3 and 4 present the results from the application of the formulation to three one-element case studies under different loading conditions and a real three-dimensional composite structure, respectively. The work closes by discussing the obtained results and with the conclusions.

2. Determination of the growth driving direction

In the framework of LEFM, the propagation direction is assumed to be the normal direction to the crack front, where the crack front is the line separating the uncracked and cracked parts (see Fig. 1.a). In contrast to LEFM, the CZM technique accounts for a band of damaged interface of variable length, called the fracture process zone, FPZ (light grey band in Fig. 1.b). Therefore, the propagation direction, understood as the normal to the crack front line, can not be defined in the CZM framework. In this work, the concept of "growth driving direction" is introduced for CZM as the analogous to the propagation direction. It is assumed to be normal to a given damage isoline and can be calculated at any point within the FPZ. This definition follows naturally from the LEFM definition and provides the exact same result in the limiting case where the length of the fracture process zone goes to zero.

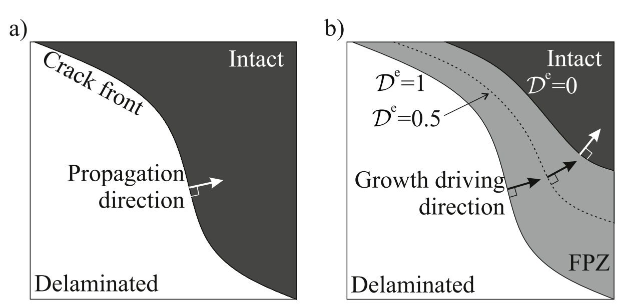

Fig. 1. a) The propagation direction is assumed to be the normal direction to the crack front in the LEFM framework. b) The growth driving direction is assumed to be the normal direction to a damage isoline in the CZM framework. The energy-based damage variable, $\mathscr{D}^e$, is defined in Appendix A.

2.1. Growth driving direction using cohesive elements

Consider a laminated structure undergoing a delamination crack restricted to propagate in the interface between two adjacent plies. The degradation process of the material ahead of the crack tip is modeled in this work using the bilinear CZM formulation developed by Turon et al. in (Turon et al., 2006, 2010). As detailed in Appendix A, the process of the degradation of the interface properties is governed by an energy-based damage variable, $\mathscr{D}^e$, defined in Equation (A.16) as the ratio between the specific dissipated energy, ω_d, and the fracture toughness, $\mathscr{G}_c$. Thus, $\mathscr{D}^e$ is a scalar quantity that measures the degree of crack development: when $\mathscr{D}^e$ equals 0, the degradation process is yet to start, while, when $\mathscr{D}^e$ equals 1, the crack is completely developed. The total specific work, ω_{tot}, corresponding to a given state of damage is the sum of the specific dissipated energy, ω_d, and the specific elastic energy, ω_e.

To ensure the proper energy dissipation under mixed-mode conditions, a one-dimensional cohesive law relates the equivalent mixed-mode traction, μ, to the equivalent mixed-mode displacement jump, λ. Such constitutive law is formed by an initial elastic region, before damage initiation, and a softening region. When the area under the one-dimensional traction-displacement jump curve is equal to the fracture toughness, $\mathscr{G}_c$, a new crack surface is formed. The Benzeggagh-Kenane criterion (Benzeggagh and Kenane, 1996) is used to define the mixed-mode displacement jumps at which the onset of damage, λ_o, and propagation, λ_c, occur. A sketch of the equivalent one dimensional bilinear law is represented in Fig. 2 for a given mode-mixity, B.

Complying with the cohesive element definition, the interfacial tractions and displacement jumps are evaluated at the interfacial deformed midsurface, $\overline{S}$, and determined by its local orientation. Thus, the normal and tangential traction components, acting on a unit deformed interfacial midsurface area, are conjugated to the normal and tangential displacement jumps across the material discontinuity. For the analysis of delamination propagation in three-dimensional structures, the interfacial midsurface is defined by the Cartesian coordinates $\overline{x}_i$, with $i = 1,2,3$. The local Cartesian coordinate system located on the deformed midsurface is defined by two tangential unit vectors, $\hat{\boldsymbol{e}}_1$ and $\hat{\boldsymbol{e}}_2$, and a normal unit vector, $\hat{\boldsymbol{e}}_3$. Assuming that the crack propagation is confined to the interface, the vector defining the growth driving direction must belong to the plane spanned by the tangential vectors $\hat{\boldsymbol{e}}_1$ and $\hat{\boldsymbol{e}}_2$ at the point $\overline{p}_i$ where the direction is evaluated. Thus, the three-dimensional problem, can be solved in a two-dimensional space defined by the local Cartesian coordinates (e_1, e_2), where e_l, with $l = 1,2$, are the coordinates spanned by the unit vectors $\hat{\boldsymbol{e}}_l$.

Then, for any given distribution of $\mathscr{D}^e(e_1, e_2)$, the growth driving

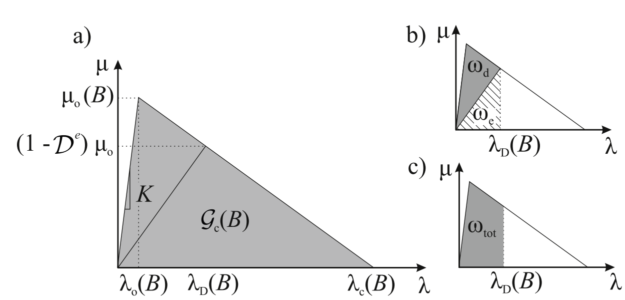

Fig. 2. Equivalent one-dimensional cohesive law for a given mode-mixity, B. The shadowed area in a) represents the fracture toughness, $\mathscr{G}_c$, in b), the specific dissipated energy, ω_d, and the specific elastic energy, ω_e, and in c), the total specific work, ω_{tot}, for a given state of damage.