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Dynamic delamination in laminated fiber reinforced composites: A continuum damage mechanics approach

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ABSTRACT

Delamination causes a significant reduction in the load carrying capacity of fiber reinforced polymer (FRP) composites, which is a major concern to the aerospace and automotive industries. High performance FRPs are often subjected to dynamic loadings of different energy densities in their service life when strain rate, stress triaxiality, temperature, and mode of fracture can have a significant knock-down effect on the interfacial strength of plies in a laminate. This paper develops a predictive tool, in a continuum damage mechanics (CDM) framework, to assess delamination damage in FRPs under dynamic loading; the model takes into account the effects of dynamic energy density, mixed-mode fractures and temperature. The CDM model is formulated based on the fracture mechanics (FM) of decohesion and an advantage of the proposed model is that nearly all of the material parameters can be obtained directly through calibration to experimental data rather than numerical curve fitting of simulation results. The developed scheme is coded into a commercial FEA package (ABAQUS) through user-defined subroutines and the fidelity of the model is assessed by comparison with existing experimental data in the literature. The validated model is used to investigate delamination damage in a laminated FRP subject to projectile impact loading, where it will be shown that the extent of delamination damage through the thickness of the FRP structure is dependent upon different wave propagation scenarios. The proposed model provides a design platform for damage assessment caused by dynamic delamination and may be a useful tool for designing FRP composites with a greater impact tolerance.

1. Introduction

The common failure modes encountered in FRPs are delamination, transverse matrix cracking, fiber fracture, and fiber–matrix interfacial debonding (Voyiadjis et al., 2014, 2011, 2012a,b,c; Chaboche et al., 2001; Le Quang and He, 2008; Horstemeyer and Bammann, 2010; Azizi et al., 2011; Doghri et al., 2011; Kruch and Chaboche, 2011; Brassart et al., 2012; Li and Shojaei, 2012; Shojaei et al., 2012; 2014; Shojaei and Li, 2013; Shojaei et al., 2015; Shojaei, 2015; Voyiadjis and Shojaei, 2015a,b). Delamination is particularly pertinent to composite lay-ups with resin-rich interlaminar layers that have not been reinforced in the thickness direction. Due to the lower mechanical strength of the interlaminar layers, compared to their adjacent reinforced plies, interlaminar delamination can occur in any of the three basic modes shown schematically in Fig. 1. In reality, the state of the stress in the interlaminar layer is three-dimensional (3D) and delamination occurs under mixed-mode condition. Of particular concern to designers is delamination caused by local impact loading and free-edge stresses. A wealth of literature on the modeling of delamination damage in FRPs have already existed; only a selection of recent pertinent ones will be reviewed here. Readers are referred to (Hutchinson 1982; Wisnom 2012; Liu et al. 2013; Park and Paulino 2013) for a more complete review on recent developments in cohesive modeling methodologies.

Different approaches are followed to simulate delamination in composites, and they can be broadly classified into three categories, viz. (a) Virtual Crack Closure Techniques (VCCT), (b) Cohesive Zone Models (CZMs) (Li and Chandra, 2003; Zhang and Paulino, 2005; Xu and Lu, 2013), and (c) CDM models. The VCCT technique is based on Irwin's assumption that when a crack extends by a small amount, the energy released in the process is

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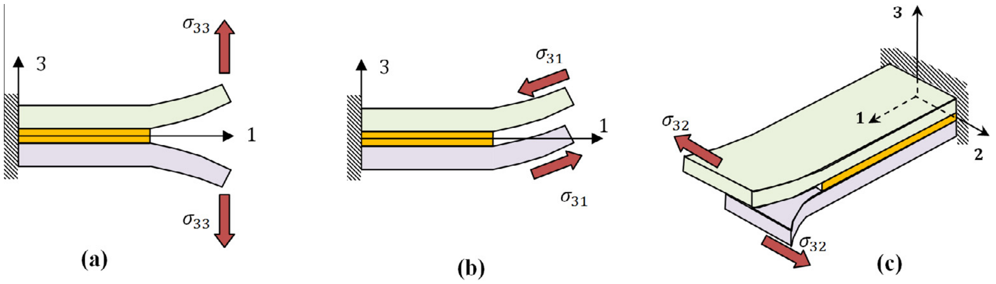

Fig. 1. Schematic of the three basic modes of loading, viz. (a) Mode I (b) Mode II and (c) Mode III, for inter-ply delamination.

equal to the work required to close the crack to its original length (Krueger et al., 1999). Whilst this method is computationally efficient, there are numerical difficulties associated with it, say, utilizing re-meshing techniques, identification of the delamination front after each crack 'pop-up' and prescribing the delamination path. Cohesive zone models, on the other hand, treat the fracture formation as a gradual phenomenon in which the separation of the crack surfaces takes place across an extended crack tip, or cohesive zone, resisted by cohesive tractions (Needleman, 1987, Needleman and Tvergaard, 1987). Different types of cohesive elements have been proposed to model cohesive fracture with the finite element method, ranging from zero-thickness volumetric elements connecting solid elements (De Moura et al., 1997), finite-thickness volumetric elements connecting shell elements (Reedy et al., 1996), to line elements (Chen et al., 1999). (Kubair and Geubelle, 2003) have argued that intrinsic cohesive delamination models may result in numerical instabilities and give rise to unrealistic results as the crack opening velocity becomes negative at the cohesive zone tip. A decohesion element, capable of dealing with crack propagation under mixed-mode loading, has been proposed and its efficacy has been demonstrated by Benzeggagh and Kenane (1996), Kenane and Benzeggagh (1997), Camanho et al. (2003). The main disadvantages of using cohesive elements in FEA are (1) difficulties associated with obtaining converged solutions (Alfano and Crisfield, 2001), and (2) the *a priori* identification and prescription of likely fracture path(s). (Corigliano, 1993) discussed the difficulties concerning the use of interface models in numerical analyses. (Schellekens and De Borst, 1993) simulated the free edge delamination of uniaxially stressed layered specimens, using non-linear FEA. CDM models have been developed to model delamination process in FRPs by a number of researchers, including (Allix and Ladevèze, 1992; Li et al., 1998; Zou et al., 2002; Li et al., 2006; Maimi et al., 2008). The CDM framework outperforms the conventional VCCT and CZM by (1) CDM utilizes regular solid elements whilst CZM or VCCT requires that specific types of element to be used for meshing the fracture path, (2) CDM can be coupled with plasticity theories to provide a more realistic representation of the fracture mechanisms in ductile materials, and (3) fracture path in CDM approach evolves naturally based upon damage dissipative energies while in the case of CZM and VCCT the fracture path needs to be prescribed.

The topic of dynamic crack growth has been investigated by many researchers including (Glennie 1971a,b; Freund and Hutchinson, 1985; Tvergaard and Hutchinson, 1996; Landis et al., 2000; Chen and Ghosh, 2012). In general, higher crack velocity results in higher strain rate hardening effect within the fracture process zone, leading to increased toughness of the interface (Wei and Hutchinson, 1997). Dynamic crack growth along the interface of a FRP composite has been investigated experimentally and numerically by Tzaferopoulos and Panagiotopoulos (1993), Brunner (2000), Corigliano and Allix (2000), Espinosa et al. (2000), Hashagen and de Borst (2000), Sprenger et al. (2000), Coker et al. (2003), Khan and Khraisheh (2004), Mariani and Corigliano (2005), Khan and Farrokh (2006), Ahmed and Sluys (2014). Slepyan (2010) has studied the non-uniform dynamic crack growth in a homogeneous isotropic elastic medium subjected to the action of remote oscillatory loads and (Remmers et al. 2008) carried out FE analyses, using cohesive segments, of the dynamic decohesion. Response of an infinite orthotropic material with a semi-infinite crack under impact loads has been investigated by Rubio-Gonzalez and Mason (2000) and X-FEM has been utilized by Grégoire et al. (2007) to study the dynamic crack growth problem. Asymptotic crack tip stress–strain fields have been developed by Zhu and Hwang (2008) for the case of dynamic fractures. Rate-dependent models for damage and plastic deformation of brittle and ductile materials under dynamic loading have also been extensively investigated (Zuo et al. 2010; Shojaei et al., 2013). The stability problem of a dynamically propagating crack has been studied by Obrezanova et al. (2002a,b). Bazant and co-workers have studied the size effect of cohesive cracks (Zi and Bažant, 2003; Caner and Bažant, 2009). Despite the developments, nearly all the delamination models for FRPs in the literature consider only a subset of possible failure mechanisms. Their approach is typically limited to using traction separation laws (cohesive laws) or CDM models that have been developed based on quasi-static experimental data (Ouyang and Li 2009a,b). One of the problems associated with these simplified approaches is that they do not account for the complete state of the applied stress when investigating the delamination mechanism. In other words, in dynamic problems with different energy densities, the applied deviatoric and hydrostatic stress waves may be significant and need to be accounted for in order to accurately predict fracture (Bao and Wierzbicki, 2004, 2005; Hooputra et al., 2004; Dey et al., 2007; Crowell et al., 2012). It is conventional to classify dynamic problems into the low and high energy density cases where different deformation and damage mechanisms may operate in each case (Shojaei et al., 2013). In the case of high dynamic energy density problems, the induced hydrostatic stress may be several times the material strength and the temperature, due to the dissipative mechanisms, may reach the melting temperature of the material (Eftis and Nemes, 1991, 1996; Eftis et al., 2003). Furthermore, when the compressive shock waves induced by the loading is reflected from any free surfaces as tensile waves, delamination damage can occur by spalling (Eftis et al., 2003; Shojaei et al., 2013). In the case of lower dynamic energy densities, the shear stress is the dominant driving force for the delamination damage (Chen and Ghosh, 2012) even though hydrostatic stress could still have a significant effect on the delamination process. In this paper, a comprehensive delamination model is developed within the CDM framework that accounts for the influence of shear stress and hydrostatic stress effects, as well as the fracture mode-mixity effects, on the delamination of FRPs. Several attempts have been made to correlate the micromechanics of damage mechanisms in composite materials to the continuum level,