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Peridynamic modeling of composite laminates under explosive loading

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ABSTRACT

High velocity impact and shock or blast responses are a critical design characteristic determining sizing of composite parts and, ultimately, weight savings. This study demonstrates the applicability of peridynamics to accurately predict nonlinear transient deformation and damage behavior of composites under shock or blast types of loadings due to explosions. The peridynamic predictions correlate well with the experimental results available in the literature. Therefore, peridynamics provides the ability to predict residual strength and durability for improving structural designs of composites under such loading conditions.

1. Introduction

During the service life of an aircraft composite component, damage due to high velocity impact or blast may occur, which leads to catastrophic failure of these structures. However, component-level structural testing and analysis of advanced composites is prohibitively expensive and time consuming. Therefore, using robust and accurate computational tools complemented by experiments at key stages is a viable and cost-effective option.

High velocity impact and blast loads cause nonlinear structural deformation and multifaceted failure mechanism in composite laminates. However, it is a very challenging task to predict all possible failure modes because damage initiation and its progressive growth is very complex, and commonly accepted methods have had limited success. It is evident that the inhomogeneous nature of composites must be retained in the analysis to predict the correct failure modes. Aside from the complex loading conditions, the deformation of a laminate is dependent on the lamina properties, thickness, and stacking sequence. There exists, usually, a resin-rich and extremely thin layer between the laminae; an inherent source for cracking and delamination. Therefore, transverse normal and shear deformations especially play a critical role in the initiation and growth of delamination.

High velocity impact and shock or blast responses are a critical design characteristic determining the sizing of composite parts and, ultimately, weight savings. Deformation and failure characteristics of composite materials under shock loading conditions were considered in the past as part of many computational/analytical and experimental investigations. Rabczuk et al. [1] developed a simple model with two lumped masses to analyze sandwich structures subjected to dynamic underwater loads. Motley et al. [2] numerically investigated initial failure loads of fully submerged composite plates subjected to explosion by employing Hashin's criteria for failure initiation. A more complex study was performed by Batra and Hassan [3] for a composite laminate subjected to underwater shock loading by using a finite element method (FEM) while incorporating a rate-dependent damage evolution equations. Also, LeBlanc [4] used LS-DYNA, a commercially available FE software, which permits specific material models while incorporating progressive damage property. Wei et al. [5] proposed a progressive degradation model in order to analyze different damage mechanisms in composite structures, and they compared their results with experimental observations obtained from an underwater shock tube. Later, these results were improved by considering strain-rate effects on the mechanical behavior of constituents of composites [6]. Experimental investigations were also carried out in order to gain a better understanding of the dynamic and damage behavior of composite structures under shock loadings. In general, experiments were performed under either direct explosions or with laboratory-scale shock tubes. Using shock tubes is more favorable than using explosives [7] because field experiments can be expensive, dangerous, and harmful to the environment [8]. In

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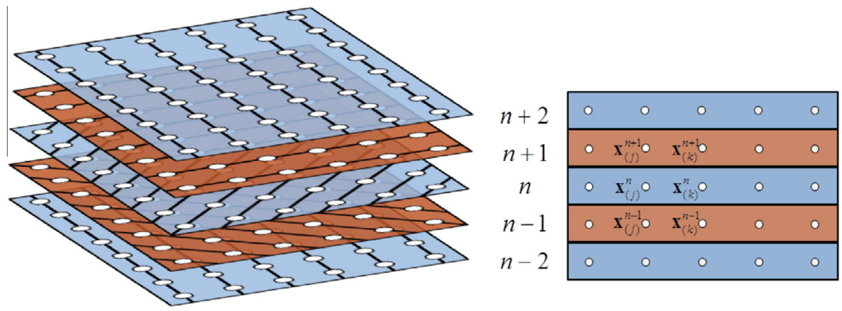

Fig. 1. Elevation of each lamina in a laminate and PD material points.

experiments, small target dimensions may lead to small impacted regions and, subsequently, localized damage [9].

Therefore, scaling relations involving plate dimensions, explosive intensity, and other parameters are rather important. Bachynski et al. [8] derived scaling relations for composite structures to conduct laboratory-scale experiments. Espinosa et al. [10] developed a novel experimental setup, which is based on scaling analysis, in order to represent full field experiments on a laboratory scale. Other shock tube test setups have been used in the literature [4,11–13] to understand deformation and failure characteristics of composite structures. Mouritz [13] carried out prototype-scale experiments and showed the effect of stitching on improving damage characteristics, especially delamination damage, of glass/vinyl ester composites. Arora et al. [7] carried out large-scale field experiments and investigated failure mechanisms of E-glass fiber-reinforced sandwich panels and laminated tubes. Latourte et al. [9] investigated failure modes and damage mechanisms of composite laminate and sandwich structures using a shock tube defined by Espinosa et al. [10]. Avachat and Zhou [14] used a novel gas-gun based Underwater Shock Loading Simulator (USLS) for investigating damage characteristics of composite structures, and comparisons were done with FE simulations performed by Avachat [12].

In summary, several numerical investigations have been performed in collaboration with experimental studies in order to develop the most suitable and accurate numerical modeling technique. However, the previous numerical studies utilized FE analysis, which suffers from mesh sensitivity in the case of impact analyses [15]. Although the use of Cohesive Zone Elements (CZE) is suitable for pure mode I or II type failures, it is still a topic of research for mixed-mode type failure. It requires a priori knowledge of the crack propagation path for CZE placement. In the case of composites, it is also not practical to place CZEs in between each ply for delamination and in-plane matrix cracking. Moreover, they require remeshing for accurate predictions, which is computationally challenging. While the eXtended Finite Element Method (XFEM) has been successfully applied to numerous applications with a moderate number of cracks, its application to complex fracture patterns as they occur in blast events of composite structures remains a challenge. Furthermore, although XFEM is capable of modeling crack growth without remeshing, it still requires a criterion for crack branching and coalescence, and robust criteria for such cases are still missing.

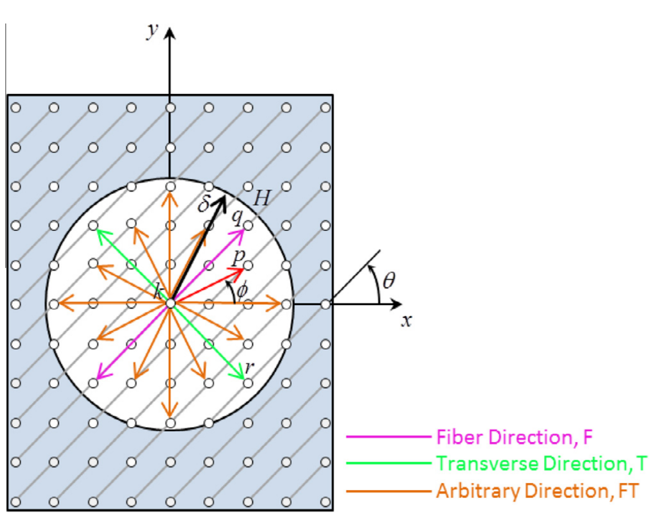

Fig. 2. PD horizon for a family of material points and their interactions in a lamina.

Meshfree methods [16] have been shown to be a good alternative to the finite element method for problems involving large deformations, fracture, and fragmentation. They can handle changes in the 'nodal connectivities' more naturally. For example, modeling perforation during impact requires the deletion of elements. Meshfree methods have been extensively applied to dynamic fracture and fragmentation since the nineties [17–19]. They have been used to model shear bands in metals [20–23], concrete fragmentation [24–26], dynamic fracture in thin shells [21,27,28], and fluid structure interaction [29,30], among others.

Early approaches were based on Eulerian kernels, where fracture is modeled through a natural separation of particles. However, it was shown for instance in [31] that the use of Eulerian kernels lead to numerical fracture—that could be avoided by formulations based on Lagrangian kernels [32]—and would, in turn, require fracture criteria and a representation of the crack topology. A simple and robust method to treat dynamic fracture that does not require a representation of the crack topology was presented by Sulsky et al. [33]. The Cracking Particles Method (CPM) [24,34] was specifically designed for complex fracture patterns such as crack branching and coalescence. In the CPM, the crack path is represented by a set of cracked particles. The crack kinematics, which is assumed to be piecewise constant, is obtained through enrichment, though a simple particle splitting [35,28] can achieve the same objective.

Silling [36,37] introduced a nonlocal theory that does not require spatial derivatives, the peridynamic (PD) theory. This theory provides nonlinear material response with respect to displacements. Furthermore, the material response includes damage in the PD theory. The PD theory is formulated by using integral equations, and this feature allows damage initiation and propagation at multiple sites, with arbitrary paths inside the material, without resorting to special crack growth criteria. In the PD theory, internal forces are expressed through nonlocal interactions between the material points within a continuous body, and damage is part of the constitutive model. Interfaces between dissimilar materials have their own properties and damage can propagate when and where it is energetically favorable for it to do so.

The PD methodology overcomes the weaknesses of the existing methods, and it is capable of identifying all of the failure modes