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Numerical investigation of energy absorption mechanisms in unidirectional composites subjected to dynamic loading events

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A B S T R A C T

This work serves as an initial investigation, which is purely numerical, of three energy absorption mechanisms of severe dynamic loading events using a finite element model of a cross-ply unidirectional (UD) composite laminate. In this study, the inelastic energy absorption mechanisms associated with damage at the interfacial and constituent levels were numerically characterized through three admissible failure modes: fiber breakage, matrix shearing, and fiber/matrix debonding (delamination) (i.e., cohesive failure). The UD composite was constructed of ultrahigh molecular weight polyethylene (UHMWPE) fibers separately reinforced with a polymer matrix material. The energy absorption capacities of these damage mechanisms were contrasted for three different dynamic loading cases including blast, shock, and ballistic impact at three different energy levels. Energy loss due to cohesive failure was observed in all three loading cases and energy levels. Furthermore, energy loss due to matrix failure was observed at all energy levels for the blast case, but only for the highest energy level in the shock and ballistics. There was energy loss due to fiber failure in the blast and in the highest energy ballistics impact case. However, there was not any fiber damage in the shock case.

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1. Introduction

Fiber-reinforced composites have become an integral part of commercial, recreation, and defense markets. The proliferation of applications for fiber-reinforced composite technology can be in large part attributed to tailorability, the single most advantageous aspect of fiber-reinforced composites. Specifically, tailorability provides the designer with unique levels of customization, such as selection of the fiber and matrix materials, lamina architecture, and laminate stacking schedules and orientations—all of which facilitate the design of a composite with optimal product performance with minimal weight.

The diverse requirements for various military/defense composite applications demonstrate (1) how challenging it is to design a functional composite that offers optimum protection for vehicles, vessels, buildings, and even personnel and (2) how critical tailorability is to that design process. For example, military land vehicles are often suited with hard armor composites to withstand ballistic impacts from enemy combatants and blasts from improvised explosive devices (IEDs); marine vessels, however, require protection from blast overpressures, shock, wave slap, electromagnetic threats, and corrosion. Blast-resistance composites and fabrics are being deployed in building construction, temporary shelters, and spall liners as barriers for defeating fragment threats. The National Aeronautics and Space Administration (NASA) uses ballistic composite laminates and fabrics for its deep-space habitats to protect against micrometeor orbital debris (MMOD), which travel at hyper velocities (3 km/s). Personnel armor, both soft and hard, range from stab-resistant vests, to vests designed to withstand armor-piercing ammunition, to blast-resistance diapers for vehicle personnel and for demolition and mine-clearing troops. Cavallaro et al. [1–3] provides an overview of personnel armors and research that has been conducted on plain-woven soft body armors.

The tailorability features afforded by composites include hosts of different fiber materials (for example, aramids, polyethylene, polyesters, glasses, and ceramics) and matrix materials (for example, polymers, ceramics, and metals) from which the designer can choose. Also available are ranges of mechanical properties for the fiber and matrix materials, such as density, strength, elongation, modulus, toughness, strain rate dependencies—all of which have the propensity to influence the stress wave propagations and energy absorption capacities at the meso-scale. Crimp imbalance, which represents one architectural modification that can be specified/tailored in woven composites and fabrics, can be used to selectively alter stress wave dynamics [2,4]. Similarly, lamina stacking schedules (for example, 0/90, 0/45/90/−45, 0/45/0, etc.) and thicknesses [5–7] can be changed to alter (1) how the stress

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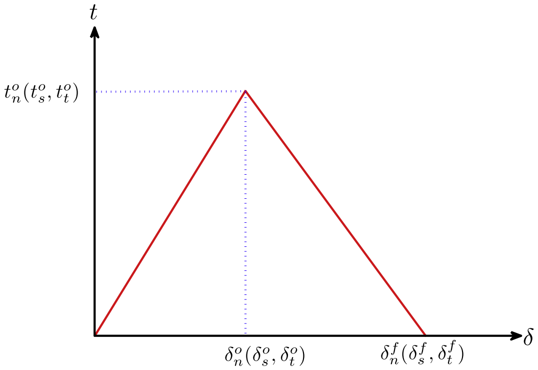

Fig. 1. Surface-based cohesive behavior to model the interfacial zone. The contact stresses at damage initiation are $t_n^o(t_s^o, t_t^o)$ and effective separation at damage initiation in the normal and two shear directions are $\delta_n^o(\delta_s^o, \delta_t^o)$. The separations at failure are $\delta_n^f\left(\delta_s^f, \delta_t^f\right)$ where subscripts *n*, *s*, and *t* refer to the normal and tangential directions, respectively.

waves propagate along the in-plane and through-thickness directions of the laminate and (2) the extent that reflections occur at the lamina boundaries at the macro-scale.

Batra and Hassan developed custom FE software [8] to subject UD composites to dynamic loading events such as blast [9] and shock [10] for various geometric, loading, and material properties. For UD composites subjected to blast, it was shown that approximately 15% of the work done by external forces were dissipated through failure modes and the stacking sequence strongly influenced the energy dissipation. The failure modes considered here were matrix cracking, fiber breakage, and fiber/matrix debonding. A failure envelope was used to model the initiation of delaminations between adjoining layers. The same conclusions were drawn for shock loading, with the addition that fiber orientation influenced both the time and location of failure mode initiation and its direction of propagation. In both models, delamination served as the damage mechanism that absorbed the most energy; however, Batra and Hassan pointed out that (1) the software homogenized the damage energies so that the energies associated with each failure mode were easily obtained and (2) not all potential failure modes were included. Other failure modes could include, but are not limited to, fiber pull-out, fiber kinking, fiber buckling, and matrix crushing.

Dolce et al. [11] developed a three-dimensional (3-D) FE model of a carbon fiber-reinforced plastic composite plate subjected to blast loads from C4 explosive charges along with experimental testing. The model, which agreed reasonably well with experimental data, considered only delamination based on the Dycoss Discrete Crack Model [11] (references within) between the layers in the composite and the Chang–Chang failure criteria [11] (references within) for modeling in-plane failure of the UD layers.

Will et al. [12] investigated the effects of laminate stacking of carbon fiber-reinforced polymers subjected to projectile impact. Under high speed impacts, it was found that a minimal amount of energy was used to deform the fibers. However, a significant amount of energy was dissipated in delamination, debonding, and fiber pull-out.

Other researchers [8,13–15] developed cohesive elements to model damage initiation and damage evolution in the fiber/matrix interfacial zone. Karahan [16] compared the ballistic performance and energy absorption in woven and UD aramid fabrics. Although the fibers used were not the same, this study concluded that UD fabric panels absorbed 12.5–16.5% more energy of the projectile than did the woven fabric for unit panel weights.

Table 2
Isotropic material properties for polymer matrix [19].

E (psi)	ρ (lb/in^3)	ν	Ultimate strength (psi)	$\bar{\epsilon}^p$ (in/in)	δ^f (in)
435,113.0	1.68E−4	0.4	13,900	2.5	2.0E−5

Table 3
Isotropic material properties for UHMWPE fibers [19].

E (psi)	ρ (lb/in^3)	ν	Ultimate strength (psi)	$\bar{\epsilon}^p$ (in/in)	δ^f (in)
17.1E7	1.3E−4	0.3	5.8E5	0.36	1.0E−5

Extensive research has been conducted to address energy absorption behaviors in rigid UD composites subjected to various dynamic loads. Researchers have investigated, both numerically and experimentally, energy mechanisms such as: fiber breakage, fiber pull-out, fiber kinking, fiber buckling, matrix cracking, matrix crushing, fiber/matrix debonding and delamination, and interlaminar delamination. However, little research has been devoted to the investigation of how the energy absorbed by these mechanisms varies with different dynamic loading events and different energy levels.

In a purely computational setting, the purpose of this research was to quantify how the energy absorbed in each considered failure mode changes per dynamic loading event and energy level. The failure modes considered in this paper are fiber breakage, matrix cracking, and fiber/matrix debonding (delamination). In the remainder of the paper, the authors refer to fiber/matrix debonding (delamination) as cohesive failure. Although there is no experimental work to correlate these computational models, the authors are actively planning experimental testing.

2. Failure modes

Fiber-reinforced composites are often designed so that the fibers bear the in-plane normal forces if the composite is impacted in the longitudinal direction. If the composite is loaded along the fiber direction, a shear stress will develop down the length of the fiber in the interfacial (cohesive) zone. If the shear stress induced from the loading event is greater than the shear strength of the cohesive bond, the bond will fail and will release strain energy—leading to a higher concentration of shear stress in that region. This will eventually lead to the delamination and possible fiber breakage from the matrix which is elaborately discussed in shear lag theory [5,7]. Once the fiber is completely delaminated from the matrix, the matrix transfers the load to the surrounding fibers. There are many theories describing the process of load transfer to neighboring fibers, a review of which can be found in Mishnaevsky's article [5]. On the other hand, if the shear stress is larger than the strength of the bond, the matrix will fail due to shear and the failure will extend along the matrix parallel to the fiber.

Table 1
Stiffness and displacement properties for the cohesive surfaces.

K_n (psi)	K_s (psi)	K_t (psi)	δ_n^0 (in.)	δ_s^0 (in.)	δ_t^0 (in.)	δ_n^f (in.)	δ_s^f (in.)	δ_t^f (in.)
8.0E5	8.0E5	8.0E5	1.7E−5	1.7E−5	1.7E−5	3.0E−5	3.0E−5	3.0E−5