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Shock loading of three-dimensional woven composite materials

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Abstract

The effect of shock loading on three-dimensional (3-D) woven composite materials has been experimentally studied. The preform materials used in this work, known under trademark 3Weave™, were manufactured by 3TEX using S-2 glass fiber roving. Four different preforms, having areal weights 93, 98, 100, and 190 oz/yd^2, were used in fabrication of single-layer and two-layer composites. The respective composites were made using VARTM process with Dow Derakane epoxy/vinyl ester resin. A shock tube was used to create the shock loading for the study and was chosen for its ability to provide highly consistent and repeatable levels of shock loading. The material's resistance to shock loading was evaluated using such parameters as surface and internal visual damage, the magnitude of permanent (i.e., after-shock, residual) deflection, and post-mortem compressive strength. The observed visual damage consisted of surface discolorations at low shock load levels and progressed to surface fiber breakage accompanied by internal delaminations and breakage of the through thickness (Z-directional) fibers at higher shock load levels. The onset of permanent deflection in the form of bulging was observed in the panels tested at pressures of 5.65 MPa and higher with maximum values of 8–9 mm found in the 93 and 100 oz/yd^2 preform composites tested at a pressure of 8.1 MPa. The compressive strength of the materials was also found to decrease in both the warp and weft fiber directions with increasing test pressures. Over the range of shock pressures applied in this series of tests, the 98 oz/yd^2 preform composite was found to perform best in terms of a smaller amount of visual damage, lower permanent deflection, and higher post-mortem compressive strength.

Keywords: Shock loading; Shock resistance; Composite materials; Residual stress; Permanent deformation

1. Introduction

The interest in the response of plates, shells and other structures to dynamic impulse loading has been renewed in recent years. Most of the studies have focused on homogeneous materials because of their traditionally widespread use in transportation, defense, building, and shipping. However, the advent of composite materials has channeled the interest toward these new materials. Particularly, reference book [1] presents geometrically nonlinear theory, dynamic deformation and failure analysis methods for laminated composite cylindrical shells exposed to longitudinal and lateral blast-type loadings.

Traditionally, two methods have been used to experimentally study the response of various structures subjected to shock loading: the direct use of explosives and the use of a shock tube. The use of explosives to create blast loading has been widely adopted due to the relative ease of use [2,3]. However, this methodology is plagued with some deficiencies such as the generation of spherical wave fronts and complex pressure signatures that are hard to model. Additional difficulties arise from the complexity of the instrumentation needed to capture the propagating wave. The alternative use of a shock tube is adopted in this study.

Shock tubes have been widely used in the study of supersonic gas dynamics and they allow the creation of either shock or expansion waves. Shock tubes also offer the advantage of generating plane wave fronts and experimental parameters that can be easily controlled and measured.

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Previous studies of blast-loaded plates have featured fully clamped or built-in edges [4,5]. Depending on the magnitude of the impulse, three distinct failure modes have been identified. Mode I failure is regarded as large deformations (elastic/inelastic) with the critical factor being the displacement of the center of the plate. Within Mode I failure, there are two deformation patterns, as described by Ross [6]. The first is a continuous deformation pattern, which is found in near-static loading cases and the second is the development of a plastic hinge, in which the initial deflection of the plate is a traveling plastic hinge. Mode II failure has been defined as a combination of the deformation and tearing of the material along the clamped edges. Mode III failure consists of shearing failure at the boundary with minimal deformation of the plate itself.

Previous studies have considered mostly metallic plates, but recently many researchers have refocused on composites and concrete. The aim of these recent studies was to analyze damage area, midpoint transient deflection, permanent deflection, and other characteristics of dynamic response.

Experimental studies that have been recently performed on metal plates have measured dynamic response, failure modes, and permanent deformations. Studies by Jacinto et al. [3] and Stoffle et al. [2] have focused on the dynamic response of plates when subjected to varying levels of blast and shock loading. Particularly, Jacinto et al. [3] attached accelerometers to the non-impact face of the plates in order to measure the dynamic response, whereas Stoffel et al. [2] used a capacitance scheme to measure central deflection during loading. Experimental studies performed by Nurick et al. [4,5] and Wierzbicki and Nurick [7] examined the large deformations and failure modes of thin plates subjected to blast loading. The plates were loaded with a pressure pulse of short duration generated by a shock tube.

Composite studies have focused on damage area and on the mechanical properties of the plate material before and after loading [8,9]. Three types of damage have been observed: matrix cracking, delamination/debonding, and penetration. Matrix cracking consists of circumferential cracks at varying distances from the blast center and radial cracks propagating from the center of the plate. Delamination/debonding damage consists of a discoloration of the area immediately surrounding the central point. This damage mode has been found to be the predominant mechanism in thicker specimens due to high flexural rigidity. Penetration consists of complete fiber failure and, therefore, rupture of the plate.

Recent progress in design, manufacturing and applications of 3-D woven fabrics and composites based on 3-D woven preforms is described in Bogdanovich et al. [10], Mohamed et al. [11]. Particularly, improved experimental results have been obtained in applications of 3-D woven fabrics and composites for various personal and vehicle protection systems (see [12–15]). Due to their characteristic reinforcement architecture, where through-thickness fibers effectively bridge in-plane cracks, 3-D woven composites do not delaminate and do not allow the initiated micro-cracks to grow into macrocracks, which makes a strong positive effect on the damage tolerance, ability to withstand multiple shots, and resistance against impact and blast loads.

3TEX manufactures a variety of proprietary 3-D woven fabrics for use in high performance, light-weight, multi-hit, and multi-threat armor systems. These 3-D woven fabrics allow for unique engineered armor systems capable of defeating wide variety of threats that include armor piercing projectiles and projectiles from improvised explosive devices. 3TEX's 3Weave™ fabrics can be woven using almost any high performance fiber type and can be hybridized by including several different fibers types in a single preform to take advantage of each fiber type performance capabilities. In spite of their relatively large thickness, 3Weave™ fabrics are sufficiently conformable and extremely permeable for common epoxy and epoxy-vinyl ester resin systems. Therefore, 3Weave™ fabrics are ideal materials for pre-pregging, RTM and VARTM technologies. As demonstrated by extensive experimental studies in the last 5 years, 3Weave™ fabrics are very suitable and cost effective materials for manufacturing armor products such as body armor inserts, helmets, vehicle armor systems, ballistic shields and barriers, etc.

The present work is a new experimental investigation of the effects of shock loading on composite plates made of 3Weave™ fabric preforms. The composite plates are subjected to increasing shock loads applied by a shock tube. Real-time measurements of the pressure pulses affecting the plates are recorded and documented for future numerical modeling. Post-mortem studies are used to evaluate the effectiveness of the materials to withstand these shock loads. This testing consists of visual damage observations, compressive strength measurements, and permanent deformation mapping. In the following sections, the methods used to carry out these experiments are presented, and the obtained experimental results are discussed in detail.

2. Composite materials for experimental studies

The schematic fiber architecture in a typical 3Weave™ fabric is illustrated in Fig. 1a. Here, red yarns run in warp, dark blue yarns in fill and light blue yarns in through thickness (Z) directions, respectively. This idealized model assumes rectangular cross-sections of the yarns. Such assumption, though supported by visual observations, is not imperative; the yarn cross-sections can be considered, for example, as elliptical or lenticular. The yarn paths in this idealized fabric model run along the three Cartesian orthogonal coordinates, with the Z-yarns placed nearly perpendicular to the fabric mid-plane in the fabric interior, and parallel to the warp direction at the fabric surfaces.

Next, Fig. 2 shows (by rectangular contours on the top, front and side surfaces) the position of a Unit Cell within