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Multi-site impact response of S2-glass/epoxy composite laminates

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ABSTRACT

High velocity transverse impact to laminated fiber reinforced composites is of interest in marine, military and civilian applications. Most studies in literature have addressed single point isolated impact events; while this work draws distinction in that we consider multi-site sequential and simultaneous impacts to composite structures. The overall objectives of this work were to investigate the response of laminated composites subjected to high velocity, multi-site impacts from a modeling and experimental viewpoint. Energy absorption, new surface creation, and failure mechanisms from sequential and simultaneous multi-site high velocity impacts are compared to assess additive and cumulative effects of these scenarios. Finite element modeling (LS-DYNA 3D) was used to gain insight into failure modes, energy absorption, and damage prediction. The modeling results correlated well with experimental data obtained from three layer laminates of vacuum assisted resin transfer molding (VARTM) processed S2-glass/SC-15 epoxy. The impact damage has been characterized using optical nondestructive evaluation (NDE) techniques. Specimens subjected to sequential impact exhibited average of 10% greater energy absorption and 18% increase in damage than specimens impacted simultaneously.

1. Introduction

Marine, military and civilian structures are frequently subjected to impact loading by secondary blast debris, primary blast debris (shrapnel), and multiple bullet impact. Under ballistic impact, the kinetic energy of the projectile is dissipated in the form of several mechanisms. The predominant energy absorption mechanisms of laminates under high velocity, small mass impact are: kinetic energy imparted to the specimen, namely cone formation on the distal side of the laminate and/or spall formation, and energy absorption as a result of shear plugging, tensile fiber failure of the primary yarns, fiber debonding, fiber pull-out, elastic deformation of the secondary yarns, matrix cracking (intralaminar), interlaminar delamination, and frictional energy absorbed during interaction of the penetrator and laminate [1–3]. Most studies reported in open literature only address single point impacts with little consideration given to the effect of multi-site projectile impact. When laminated composites are subjected to ballistic impact, the material response is determined by interactions of multiple stress waves generated at the laminate interfaces [4]. In the case of a simultaneous multiple projectile impact scenario, stress waves interact with one another or with newly formed delaminations from adjacent damage zones, causing constructive/destruction interference and/or wave scattering [5]. This can change the peak stress witnessed by a target, specimen compliance, and damage mechanisms resulting in a change in the extent of damage and energy absorption when compared to a single projectile impact. Cantwell and Morton [6], Reid and Zhou [7], and Abrate [8,9] have provided extensive reviews on impact behavior of composite and laminated structures, however, none of the work cited discusses the effect of multi-site impact.

Fragment cluster impact (FCI) is a common scenario arising from the fragmentation of a metallic case containing a high explosive (HE) charge (bursting munitions). The most damaging result is the ejection of high velocity projectiles from the charge. In FCI, the material response is thought to be governed by synergistic effects such as the propagation and interaction of stress/shock waves (additive effects) and dynamic cracks/damage (cumulative effects). The situation where multiple fragments impact a structure simultaneously within a local area has been studied recently [5–7,9–14]. Qian et al. [12] and Qian and Qu [13] investigated FCI of a thin metallic armor plate. The study by Qian et al. [12] focused on an analytical model to distinguish between cumulative and additive effects on specimens subjected to impact by an explosive fragment generator. Qian and Qu [13] used numerical simulation (LS-DYNA code) of FCI to reproduce the experimental results in Qian et al. [12]. The modeling results indicated that fragment cluster density and the fragment hit-time interval were the main parameters distinguishing cumulative and additive damage mechanisms. Riedel et al. [11] conducted a limited study of a carbon–epoxy aircraft wingbox subjected to blast and impact from a fragmenting HE

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warhead. Commercial hydrocode AUTODYN was used to simulate the entire loading situation. The primary fragments of the warhead were accurately modeled with respect to fragment sizes, distribution angles and velocities but the extent of the delamination in the areas of high impact densities was underpredicted.

A substantial amount of work has been done to model the failure mechanism of composites due to transverse impact loading [15–21]. But limited studies have been done on the progressive failure of composites under high strain rate loading. However, it is generally expected that composites fail in a progressive manner. Ladeveze et al. [22,23] used a damage mechanics approach to describe matrix cracking and fiber/matrix debonding by introducing damage variables associated with the material stiffness reduction in their plasticity model. Johnson et al. [24] reported a numerical method to predict composite damage using the framework outlined by Ladeveze et al. [22]. Matzenmiller et al. [25] developed a continuum damage mechanics (CDM) model for unidirectional composites. On the basis of CDM, Williams and Vaziri [26] wrote material subroutines for matrix/fiber failure in LS-DYNA. Yen [27] developed Material Model 161 and 162 (MAT 161/162) for LS-DYNA that captures the progressive failure mode of composite laminates (both unidirectional and plain weave laminates) during transverse impact. Because of the inherent ability to model progressive damage MAT 161/162 has been used successfully in predicting energy absorption and damage [27–31].

The objective of the current work is to understand the energy absorption and damage propagation of S2-glass/SC-15 composite laminates subjected to simultaneous and multi-site high velocity impact using explicit commercial software LS-DYNA. The results are then compared to the experimental work detailed in [32–36].

2. Materials and processing

All specimens were processed using vacuum assisted resin infusion/transfer molding (VARTM). VARTM is considered an affordable process because tooling costs; high temperature and pressure cycles, closed-molds, and post-machining operations incurred in traditional autoclave processing are eliminated. With VARTM, resin is infused into dry fabric preform assembled on single-sided tooling that is covered with an inexpensive vacuum bag film. Large structural parts with inserts or multiple layers can be produced rapidly. Other advantages of VARTM are low process volatile emissions, high fiber-to-resin ratios, and good repeatability.

S2-glass/SC-15 epoxy resin was chosen for the composite system. This particular combination was used because it is a well established benchmark as an impact resistant material [20,21, 37–39]. The preform consisted of a 24 oz. yd.$^{-2}$ 24K tow, plain woven S2-glass with 933 sizing. Applied Poleramic Inc. SC-15 rubber toughened epoxy resin was used as the matrix because of its low viscosity and high toughness relative to other epoxy systems. The lay up scheme was $[0°/90°]_3$ with an average thickness of 2 mm ± 0.05 mm. Archimedes immersion density technique was used to determine the average fiber volume fraction, which was 40.1 ± 0.2%. Specimens of dimensions $20.3 \times 20.3\ \mathrm{cm}^2$ were cut from the panels and then post cured at 82 °C for 5 h.

3. Experimental set-up

A single-stage light-gas gun was designed and constructed in-house for the impact experiments. The unique capability of this gun lies in its ability to launch up to three projectiles near-simultaneously or sequentially with controlled impact locations. The gas gun has three barrels, equally spaced 120° apart on a 20 mm radius (approximately), Fig. 1. The 25.4 mm ID barrels are breach loaded and connected to a single 63.5 mm diameter butterfly valve via a common 200 mm ID manifold. This insures that the sabot assisted projectiles will be subjected to the same firing pressure, while the mass and dimensional tolerances of the sabots are maintained to very high standards to insure the near-simultaneous impact condition. One or two of the barrels can be plugged allowing a two projectile or single projectile test condition, respectively. These plug(s) can be rotated such that the near-simultaneous and sequential impact series can be contrasted while maintaining constant impact locations. Pressure versus velocity studies were conducted prior to testing in order to obtain calibration curves for single, two, and three projectile test conditions.

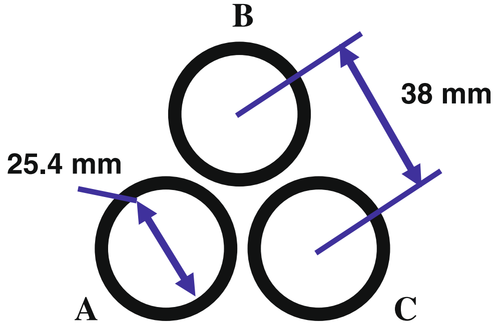

Fig. 1. Illustration showing the dimensions, configuration, and firing order of the tri-fire gas gun barrels.

The projectiles used in the study were 7.94 mm diameter (≅0.30 caliber), grade 25, alloyed steel ball bearings with a hardness of 63–67 Rockwell C, and a mass of 2.039 g. The projectile velocity through each barrel (single projectile) was found to be extremely consistent for a given pressure indicating that assumption of a near-simultaneous impact condition is likely valid. This will be verified in future work via high-speed photography since the only current means of measuring projectile velocity is using photoelectric chronographs (Model: Oehler 35 chronograph and Oehler Sky). The boundary conditions were fully clamped on four sides with $232.3\ \mathrm{cm}^2$ of exposed specimen and $180.6\ \mathrm{cm}^2$ of clamped area. This provided a large enough area to ensure that the delamination damage did not interact with the boundaries.

Delamination damage was characterized using an optical nondestructive evaluation (NDE) technique. The S2-glass/epoxy specimens are translucent and when damaged, present very distinct delaminations. In order to characterize the delamination area, a light box was constructed. It consists of specimen supports, a reflective tunnel to provide for even illumination, a 25.4 mm scale and a 150 W halogen light source. Digital images were taken normal to the back lit specimen with the scale placed within view. The images were then post processed using Image-Pro Plus (Media Cybernetics Inc.). The same software was then used to trace out and measure the delaminated areas, in which case the number of delaminations is equal to the number of plies minus one. Once the delaminated area is traced out, the software calculates the encircled area based on the calibration with respect to the scale. The goal in the 0.30 caliber projectile impact study was to investigate the effect of number of impacts. In the assessment of the number of impacts, single, two and three projectile simultaneous and sequential impacts were carried out on the three layer laminates. The impact velocity was kept constant throughout all the impact events.

4. Modeling approach

4.1. Numerical tools and model development

Hypermesh (Version 7) and finite element model builder (FEMB) computer code have been used for pre-processing in the