NEAR-SIMULTANEOUS AND SEQUENTIAL MULTI-SITE IMPACT RESPONSE OF S-2 GLASS/EPOXY LAMINATES

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Abstract

This work investigates the response of laminated composites subjected to high velocity, multi-site impacts. The 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 damage. While the energy absorption for the two impact conditions remained relatively constant in the experimental study, an increase in new surface creation was noted for specimens impacted sequentially in contrast to those impacted simultaneously.

1.0 Introduction and Literature Review

Military and civilian structures are frequently subjected to impact loading by secondary blast debris, primary blast debris (shrapnel), and multiple bullet impacts. When laminated composites are subjected to ballistic impact, the material response is determined by interaction of multiple stress waves generated at the laminate interfaces [1]. Cantwell and Morton [2], Reid and Zhou [3] and Abrate [1] have provided extensive reviews on impact behavior of composite and laminated structures for single point impacts. Qian et al. [4] investigated fragment cloud impact (FCI) of thin metallic armor plate. Their results indicated that fragment cluster density and the fragment hit-time interval were the main parameters distinguishing cumulative and additive damage mechanisms. Cantwell and Morton [2] reported a 50% reduction in compression-after-impact properties for composite laminates, illustrating the influence of impact induced stress waves that cause detrimental damage producing mechanism in composite laminates.

Preliminary work by Bartus and Vaidya 2004 [5] and Bartus [6] reported that there was an increase in energy absorption in carbon-epoxy specimens subjected to random multi-site simultaneous impact when compared to single projectile impact.

2.0 Materials and Processing

All specimens were processed using resin infusion of S-2 glass fabric with SC-15 epoxy resin. The S2-glass preform consisted of a 24 oz. yd.\(^2\) 24K tow, plain weave with 933 sizing. SC-15 rubber toughened epoxy resin (Supplier: Applied Poleramic Inc.) was used as the matrix because of its low viscosity and high toughness relative to other epoxy systems. The average lay-up thickness was 2 mm ±0.05 mm. Immersion density technique was used to determine the average fiber volume fraction, which was 40.1% ±0.2%. Specimens of dimensions 20.3 x 20.3 cm\(^2\) were cut from the panels and then post cured at 82°C for five hours.

3.0 Experimental

A single-stage light-gas gun was designed and constructed in-house for the impact experiments. While the design of the gas gun was conventional with respect to other projectile launchers of this type, the unique capability of this gun lies in its ability to launch up to three projectiles nearly simultaneously or sequentially with controlled impact locations. The gas gun has three barrels, equally spaced 120° apart on a 20 mm radius (approximately). 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 ensures 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. The plugs 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. In addition, the projectile
velocity through each barrel (single projectile) was
found to extremely consistent for a given pressure
indicating that assumption of a near-simultaneous
impact condition is valid. The current means of
measuring projectile velocity is using photoelectric
chronographs (Model: Oehler 35 chronograph and
Oehler Sky Screens). The boundary conditions were
fully clamped on four sides with 232.3 cm² of
exposed specimen and 180.6 cm² of clamped area.

4.0 Results and Discussion

The results were based on nine specimens
impacted with a 0.30 caliber alloyed steel ball
bearing with a mass of 2.04 g, above ballistic limit
in sequential and near-simultaneous impact. In this
series of impact tests, the energy absorption
remained fairly constant in both the sequential and
near simultaneous impacts. The impact velocity was
223.3 m s⁻¹ and on average with a standard deviation
of 7.6 m s⁻¹. The average energy absorption for the
sequential series was 45.7 J with a standard
deviation of 3.6 J. The new surface creation was
on average, 187.6 cm². The average energy absorption
for the sequential impact tests was 40.4 J with a
standard deviation of 2.7 J. The new surface
creation was 158.6 cm² with a standard deviation of
10.0 J. The difference in average energy absorption
and new surface creation for the sequential and near
simultaneous impact scenarios was 13.1% and
18.3%, respectively.

Average energy absorption (J) versus new
surface creation (cm²) is shown in Figure 1 for
single projectile, two and three projectile
simultaneous and sequential impact series. The
impact energy absorption was similar for the
simultaneous and sequential impact series. However,
specimens subjected to sequential impact by either
two or three projectiles exhibited a greater amount
of new surface creation (Figure 3). This is attributed
to an increase in compliance as a result of incipient
damage. The specimen compliance changes the
specimen-projectile contact duration, back-face
displacement and affects the failure mode. Figure 2,
showing energy absorption normalized by the new
surface creation (J cm⁻²) for the sequential impact
series illustrates a change in failure modes as
incipient damage increases. Even though the energy
absorbed remained relatively constant, delamination
damage increased as the amount of preexisting
damage increased. In the case of near-simultaneous
impact, stress wave interactions (constructive or
destructive interference) are presumed to influence
the penetration process. In addition, dynamic crack
interactions can further affect penetration in the case
of simultaneous impact.
The test program also analyzed projectile mass effects for three .50 caliber spherical Al₂O₃ (3.94 g), and tungsten carbide (16.08 g) projectiles at constant incident energy (200 J/projectile). A factor of four increase in projectile mass corresponded to 22.4% (sequential increases in delamination damage). Energy absorption increased 11.9% (sequential impact) and 8.7% simultaneous impact for laminates subjected to tungsten carbide projectiles over Al₂O₃ projectiles. Energy absorption in laminates subjected to sequential impact was 20.0% higher (average) than those impacted simultaneously (Figure 4). Impact energy absorption increased with increasing cumulative damage. New surface creation did not play a significant role as an energy absorption mechanism however; its influence on compliance dominated the target response (Figure 5).

5.0 Summary

High velocity impact experiments were conducted on S-2 glass/epoxy laminates at three locations, which were maintained constant, under two conditions: simultaneous and sequential. While the energy absorption for the two impact conditions remained relatively constant experimentally. However, an increase in new surface creation was noted for specimens impacted sequentially in contrast to those impacted simultaneously. The experimental results were then compared with LS-DYNA 3D simulations of the same impact events. In the models, impact energy absorbed was similar, however, the residual velocity of the projectile was dependant on stress wave interaction, particularly along the primary yarns and on the amount of delamination damage. As projectiles impacted damaged regions, the decrease in contact stiffness reduced the ability of the laminate to absorb energy resulting an increase in exit velocity. This was noted in both cases. The model under predicted energy absorption and future work will be in varying damage parameters in order to better model this type of impact. Damage, however, was modeled effectively.

6.0 References


Figure 3. Sequential impact series with delamination damaged measured between impacts, (a) first impact, (b) second impact, (c) third impact.

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Figure 4. Impact energy absorption for thin S-2 glass laminates subjected to near-simultaneous and sequential impact by three Al$_2$O$_3$ and tungsten carbide, .50 caliber (12.7 mm) diameter spherical projectiles

Figure 5. New surface creation (delamination) for thin S-2 glass laminates subjected to three projectile near-simultaneous and sequential impact by 3.94 g (Alumina/Al$_2$O$_3$) and 16.08 g (WC) .50 caliber (12.7 mm) diameter spherical projectiles.