# 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$^{o}$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 near-simultaneously or sequentially with controlled impact locations. The gas gun has three barrels, equally spaced 120$^{o}$ 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 $cm^2$ of exposed specimen and 180.6 $cm^2$ 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 $cm^2$. 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 $cm^2$ 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 ($cm^2$) 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.

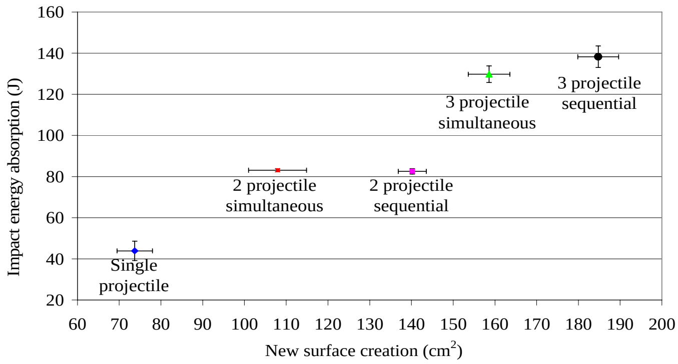


Figure 1. Impact energy absorption (J) vs. new surface creation ($cm^2$) for single projectile, two projectile and three projectile impact series showing an increase in new surface creation for the sequential impact event.

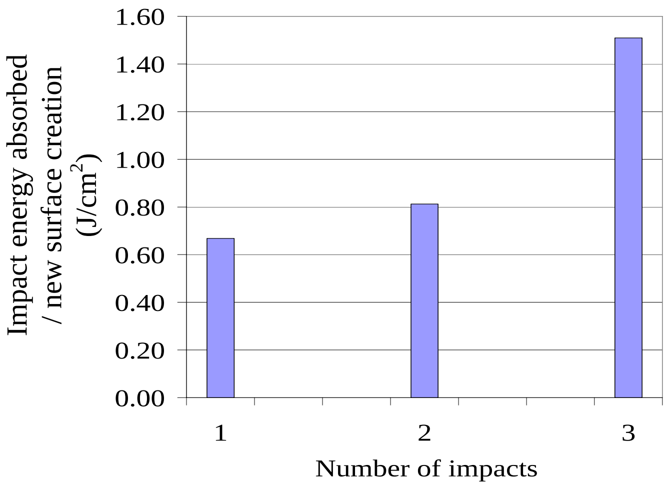


Figure 2. Impact energy absorbed/new surface creation (J $cm^{-2}$) vs. number of sequential impacts showing an increase in damage area while the energy absorbed remained relatively constant.

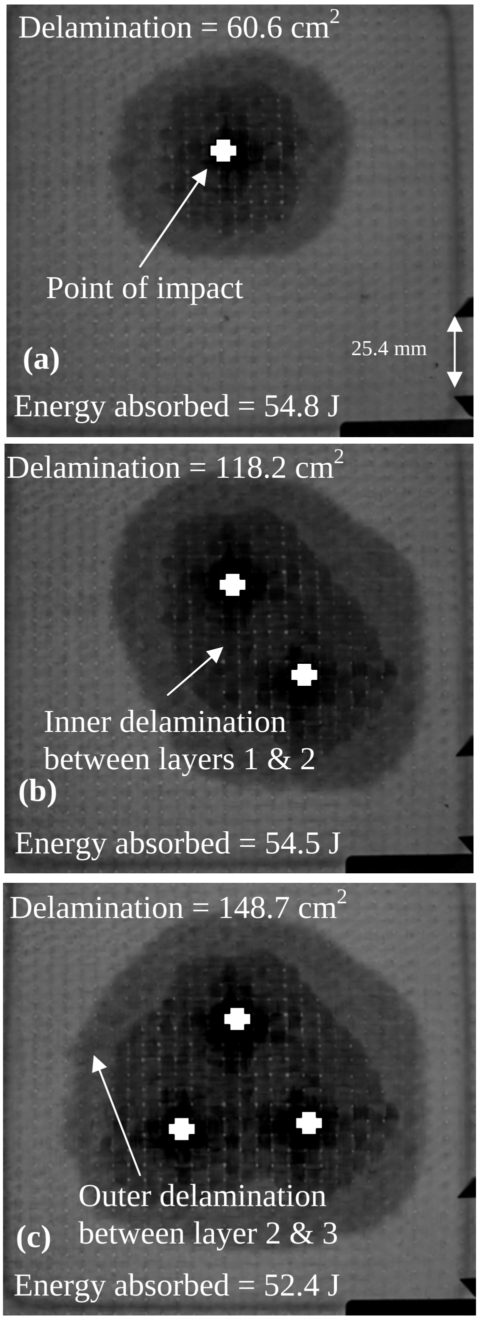


Figure 3. Sequential impact series with delamination damaged measured between impacts, (a) first impact, (b) second impact, (c) third impact.

The test program also analyzed projectile mass effects for three .50 caliber spherical $Al_2O_3$ (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 $Al_2O_3$ 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

[1] Abrate S., 1998. “Impact on Composite Structures”. Cambridge University Press, Cambridge, UK.

[2] Cantwell W.J. and Morton J., 1991. “The impact resistance of composite materials-a review”. *Composites* 22 (5), 347-362.

[3] Reid S.R. and Zhou G, Impact Behavior of fiber-reinforced composite materials and structures, Woodhead Publishing Ltd, Cambridge, England, 2000.

[4] Qian L., Qu M., and Feng G., International Journal of Impact Engineering, 31, 2005, pp. 755-767.

[5] Bartus S.D. & Vaidya U.K., 2004. “Fragment cloud impact response of carbon-epoxy plates”.

45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. 19-22 April, Palm Springs, CA.

[6] Bartus S.D., 2006. "Simultaneous and sequential multi-site impact response of composite laminates". A Ph.D. Dissertation, The University of Alabama at Birmingham.

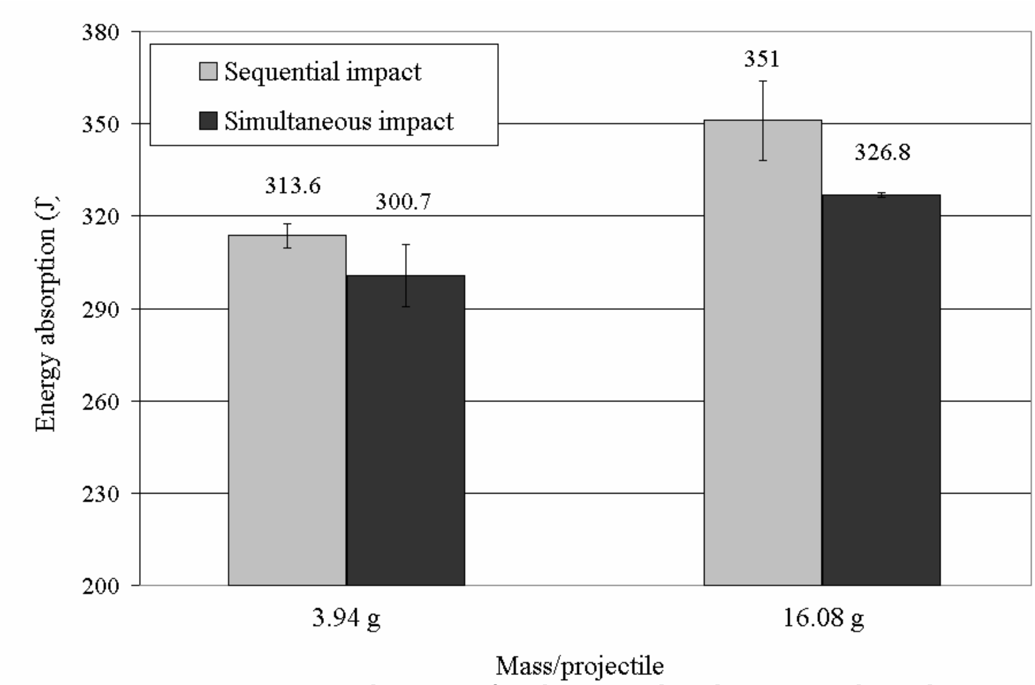


Figure 4. Impact energy absorption for thin S-2 glass laminates subjected to near-simultaneous and sequential impact by three $Al_2O_3$ and tungsten carbide, .50 caliber (12.7 mm) diameter spherical projectiles

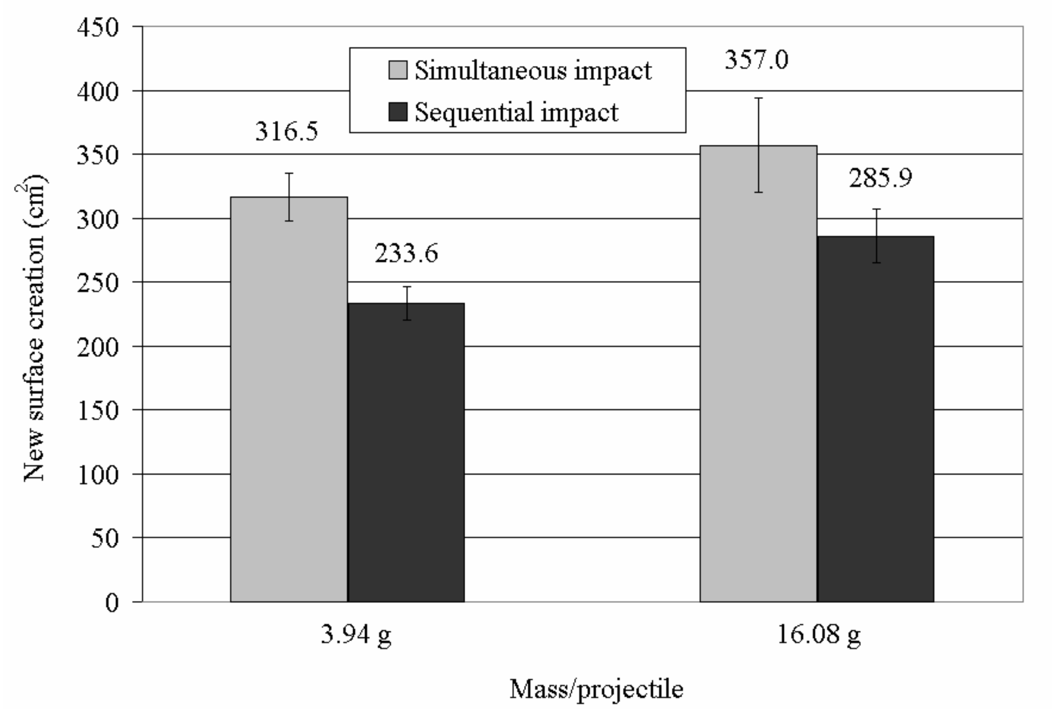


Figure 5. New surface creation (delamination) for thin S-2 glass laminates subjected to three projectile near-simultaneous and sequential impact by 3.94 g (Alumina/$Al_2O_3$) and 16.08 g (WC) .50 caliber (12.7 mm) diameter spherical projectiles.