

## Numerical Modeling of Simultaneous and Sequential Multi-Site Impact Response of S-2 Glass/Epoxy Composite Laminates

L. J. Deka, S.D. Bartus and U. K. Vaidya\*  
Department of Material Science & Engineering  
The University of Alabama at Birmingham  
Birmingham, AL 35294-4461  
\*Corresponding Author

### Abstract

High velocity transverse impact to laminated fiber reinforced composites is of interest in military and structural applications. Recent advances in the field of numerical simulation provide a means of predicting the performance characteristics of layered materials for ballistic protection. The overall objective of this work was to investigate the response of laminated composites subjected to high velocity, multi-site impacts from an experimental and finite element modeling 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. During high velocity impact, composite laminates undergo progressive damage failure and this has been modeled using dynamic modeling software. These results were then compared with experimental data obtained from three layer laminates of Vacuum Assisted Resin Transfer Molding (VARTM) processed S-2 Glass/SC-15 epoxy, in which impact damage was characterized using optical nondestructive evaluation (NDE) techniques.

### Introduction

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 through 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),

COMPOSITES & POLYCON 2007

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. Various authors [6-8] 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. The objective of the current work is to understand the energy absorption and damage propagation of S2-glass/SC-15 composite laminates under sequential and multi-site spherical steel projectile high velocity impact using explicit commercial software LS-DYNA.

### 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. S-2 Glass/SC-15 epoxy resin was chosen for the composite system. This particular combination was used because it is a well established benchmark in regard to light weight armor materials. The preform consisted of a 24 oz. yd.<sup>-2</sup> 24K tow, plain woven S-2 glass with 933 sizing (epoxy). 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  $[0^{\circ}/90^{\circ}]_3$  with an average thickness of 2 mm  $\pm$  0.05 mm. Archimedes immersion density technique was used to determine the average fiber volume fraction, which was 40.1%  $\pm$  0.2%. Specimens of dimensions 20.3 x 20.3 cm<sup>2</sup> were cut from the panels and then post cured at 82°C for five hours.

## Experimental Set-Up

A single-stage light-gas gun was used for the impact experiments. The gas gun launches up to three projectiles near-simultaneously or sequentially with controlled impact locations. The gun has three barrels, equally spaced  $120^\circ$  apart on a 20 mm radius (approximately), Figure 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 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.

## Finite Element Modeling

Hypermesh (version 7) and Finite Element Model Builder (FEMB) computer code were used for pre-processing in the model development. LS-DYNA (version 970) was used to analyze perforation mechanisms, failure modes, and damage evaluation during high velocity impact projectile on the three layers, S-2 glass-epoxy target plates. Both the projectile and the composite plates have been meshed with eight node brick elements with a single integration point. The three layer plain weave composite plate was modeled using three layers of brick elements. Each layer has two elements through the thickness and represents one plain weave layer. The three spherical projectiles were made using 3150 brick elements per projectile. For simultaneous impact, the projectiles were placed 0.04 mm away from the target in order to minimize the computational time, whereas in the sequential impact series, the projectiles were staggered 50 mm normal to the target in order to minimize stress wave interactions (same relative impact positions were maintained). Materials properties [9] for the laminate and projectile are shown in Tables 1 and 2 respectively.

The spherical projectile was modeled using material model MAT 3 (MAT\_PLASTIC\_KINEMATIC) and the laminate using material model MAT 162 [10]. The contact between the projectile and laminate was defined using CONTACT\_ERODING\_SINGLE\_SURFACE. Penetration was handled using eroding elements with strain based failure criterion.

## Results and Discussion

Energy absorption and new surface creation due to delamination were estimated from the impact experiments. Energy absorption provides an indication of ballistic efficiency which is the energy absorption or ballistic limit velocity as a function of areal density. New surface creation, such as delamination is considered. In the assessment of the number of impacts, single and two projectile simultaneous and sequential impacts were carried out on the three layer laminates. The impact velocity was kept constant throughout all the impact events.

### Single Projectile Impact

The single projectile impact study was conducted on three layer laminate in order to establish a benchmark for the multiple impact study. Fiber breakage and delamination were found to be main energy absorbing mechanisms during the impact. Table 3 shows the single projectile impact result of 3 layer s2-glass/epoxy laminate above the ballistic limit. The impact velocity was held constant at  $223.1 \text{ m.s}^{-1}$  (standard deviation =  $19.1 \text{ m.s}^{-1}$ ), which is above the ballistic limit. The average energy absorption was 43.9 J with a standard deviation of 3.4 J, Table 3. The average new surface creation was  $73.7 \text{ cm}^2$  with a standard deviation of  $8.5 \text{ cm}^2$ . Numerical predictions of energy absorption and delamination area at impact velocity of  $223.1 \text{ m s}^{-1}$  were found to be  $42.36 \text{ cm}^2$  and  $70.1 \text{ cm}^2$  which are within 95-96% of corresponding experimental results. Delamination at the interface is one of the major failure mechanisms at the matrix mode. Delamination is caused by interlaminar stresses ( $\sigma_z, \tau_{yz}, \tau_{zx}$ ) which initiate matrix microcracks which span the fiber-matrix interface and propagate along the fiber. Figure 2 shows the typical delamination damage during a single projectile impact with impact velocity  $221.8 \text{ m s}^{-1}$ .

### Two Projectile Impact

The two projectile impact positions for simultaneous and sequential impact are shown in Fig. 3. The two projectile simultaneous and sequential impacts were at the A and C positions, along the primary yarns. These positions were chosen because the highest wave speed is along the primary yarns and to examine damage interaction along the primary yarns. For sequential impact second projectile (position C) was staggered at 50 mm away from the target to minimize the stress wave interaction generated from the impact points. Damage modes were investigated under two different velocities. ( $\sim 200 \text{ m.s}^{-1}$  and  $220 \text{ m.s}^{-1}$ ). These velocities resulted in impact conditions near the ballistic limit (below the threshold velocity for complete penetration) and above the ballistic limit. The experimental and simulated results

for simultaneous and sequential two projectile impact for three layer laminates are given in Table 4. The impact velocity for the two projectile impact was  $201.2 \text{ m.s}^{-1}$  (standard deviation =  $4.2 \text{ m.s}^{-1}$ ) for sequential impact and  $201.9 \text{ m.s}^{-1}$  (standard deviation =  $1.9 \text{ m.s}^{-1}$ ) for near-simultaneous impact (referred to as simultaneous impact). This velocity was closer to the single projectile ballistic limit for the three layer laminate. For the two projectile sequential impact experiments, position A was the first to be impacted, followed by position C. The average impact energy per projectile was 41.3 J (standard deviation = 1.71 J) and 41.6 J (standard deviation = 0.80 J) for simultaneous and sequential two projectile impact, respectively. This corresponded to an average new surface creation of  $107.9 \text{ cm}^2$  (standard deviation =  $13.99 \text{ cm}^2$ ) and  $140.29 \text{ cm}^2$  (standard deviation =  $6.79 \text{ cm}^2$ ) for simultaneous and sequential impacts, respectively. Although the average impact energy for the simultaneous and sequential two projectile impacts were within 0.7 % of one another, sequential impact resulted in a 23 % increase in new surface creation. Simultaneous and sequential simulations were performed with impact velocities  $201.2 \text{ ms}^{-1}$  and  $201.9 \text{ ms}^{-1}$  respectively to compare with the experimental data. Predicted impact energy absorbed per projectile was 38.76 J and 35.6 J for simultaneous and sequential two projectile impact respectively. Predicted delamination for simultaneous and sequential two projectile impact was found to be  $127.50 \text{ cm}^2$  and  $145.2 \text{ cm}^2$  respectively. Figure 4 and 5 show the experimental and corresponding simulation prediction of delaminated region for two projectile simultaneous and sequential impact events. As can be seen from these figures the damage modes and size of delamination is accurately captured by the model.

## Summary

High velocity impact experiments were conducted on S-2 glass/epoxy laminates at two projectile locations under two conditions namely, simultaneous and sequential. The energy absorption for the two impact conditions remained relatively constant in the experiments. However, an increase in new surface creation was noted for specimens impacted sequentially in contrast to those impacted simultaneously. In the dynamic simulation, progressive damage model, MAT 162 was used to model the composite plates. The residual velocity of the projectile was influenced by 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, which resulted in an increase in exit velocity. This was noted for both sequential and simultaneous impact scenarios. Specimens subjected to sequential impact exhibited 10.1% greater energy absorption than specimens impacted simultaneously.

New surface creation, i.e. delaminated region was well predicted by the model.

## References:

1. Goldsmith W. et al., 'Quasi-static and ballistic perforation of carbon fiber laminates', *International Journal of Impact Engineering*, Vol. 32(1), 1995, pp. 89-103.
2. Cantwell W.J. and Morton J., The impact resistance of composite materials-a review. *Composites*, Vol. 22 (5), 1991, pp. 347-362.
3. Reid S.R. et al. 'Impact Behavior of fiber-reinforced composite materials and structures', Woodhead Publishing Ltd, Cambridge, England, 2000.
4. Riedel W. et al., 'Vulnerability of composite aircraft components to fragmenting warheads-experimental analysis, material modeling and numerical studies', 20th International Symposium on -Ballistics, 23-27 September, Orlando, Florida, 2002.
5. Parga-Landa B., Vlegels S., Hernández-Olivares F., and Clark S.D., Analytical simulation of stress wave propagation in composite materials. *Composite Structures*, 45, 1999, pp. 125-129.
6. Abrate S., 'Impact on Composite Structures', Cambridge University Press, Cambridge, 1998, UK.
7. Cantwell et al., Impact perforation of carbon fiber reinforced plastic. *J comp. scie Tech*, 38, 1990, pp. 119-40.
8. Richardson et al., Review of low velocity impact properties of composite materials. *Composites*, 27 (A), 1996, pp. 1123-1131.
9. Xiao et al. 'Progressive damage and delamination in plain weave S-2 glass/SC-15 composites under quasi-static punch shear loading', *Composite Structures*, (2005) (Article in press).
10. LS-DYNA Theoretical Manual, version 950, Livermore Software Tech. Corp., May 1998.

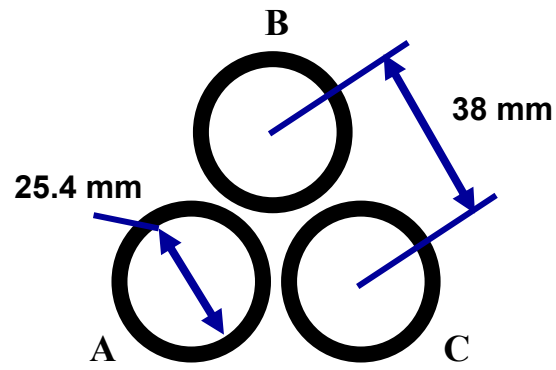


Figure 1. Illustration showing the dimensions, configuration, and firing order of the tri-fire gas gun barrels.

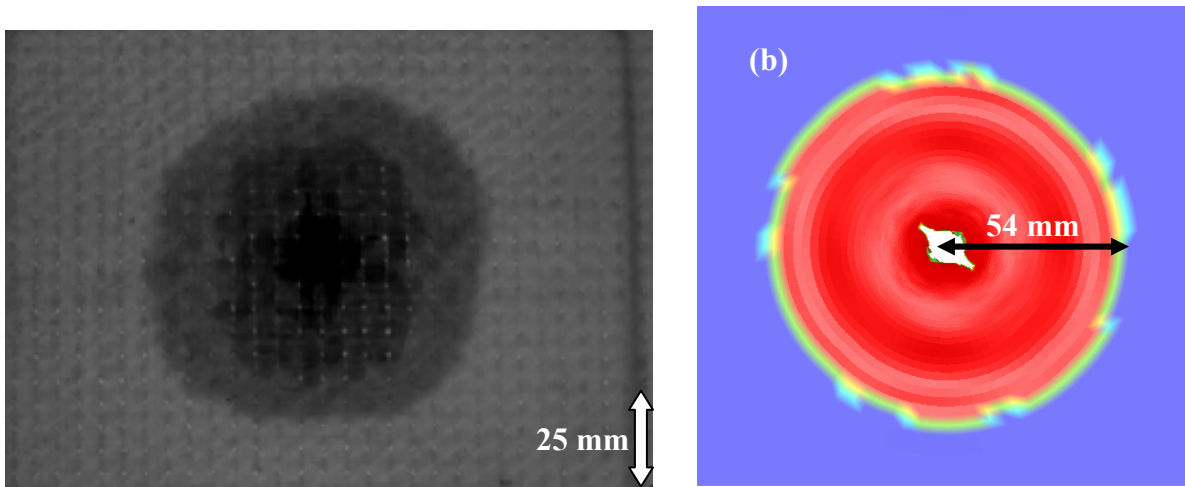


Figure 2. Delamination under single impact condition at velocity  $221.8 \text{ m s}^{-1}$   
 (a) Experimental (b) Simulation

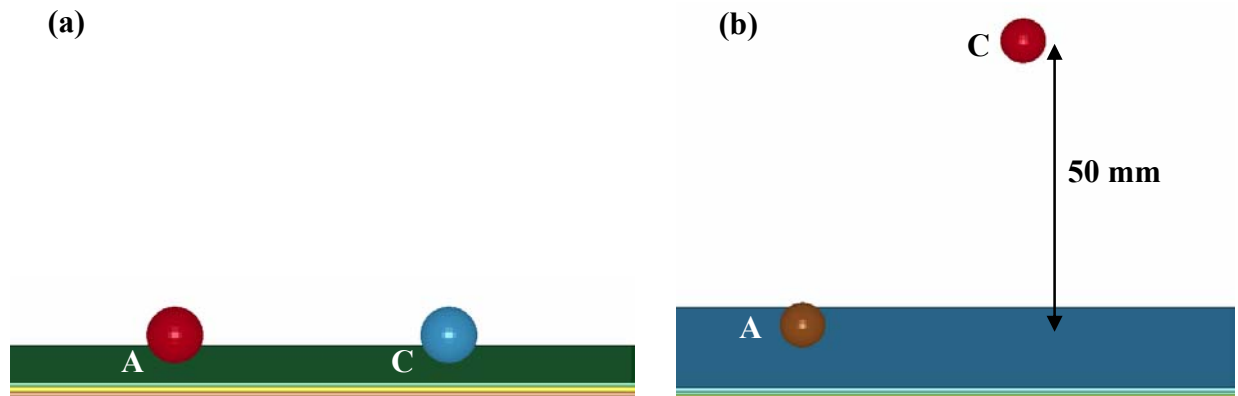


Figure 3. Impact positions (A, C) of the two projectiles (a) Simultaneous impact (b) Sequential impact

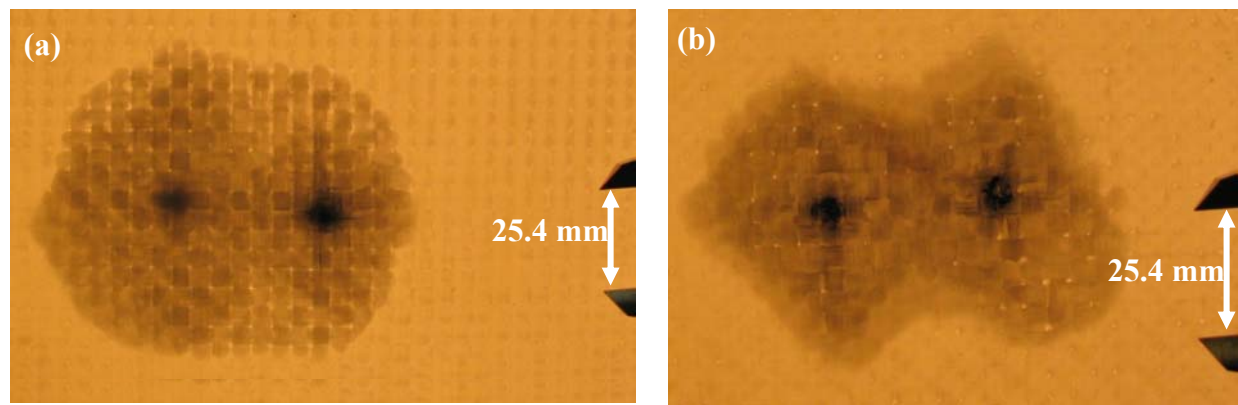


Figure 4. Experimental delamination (a) Simultaneous impact at impact velocity of  $203.3 \text{ m s}^{-1}$  (b) Sequential impact at impact velocities of  $203 \text{ m s}^{-1}$  (A) and  $203.9 \text{ m s}^{-1}$  (C)

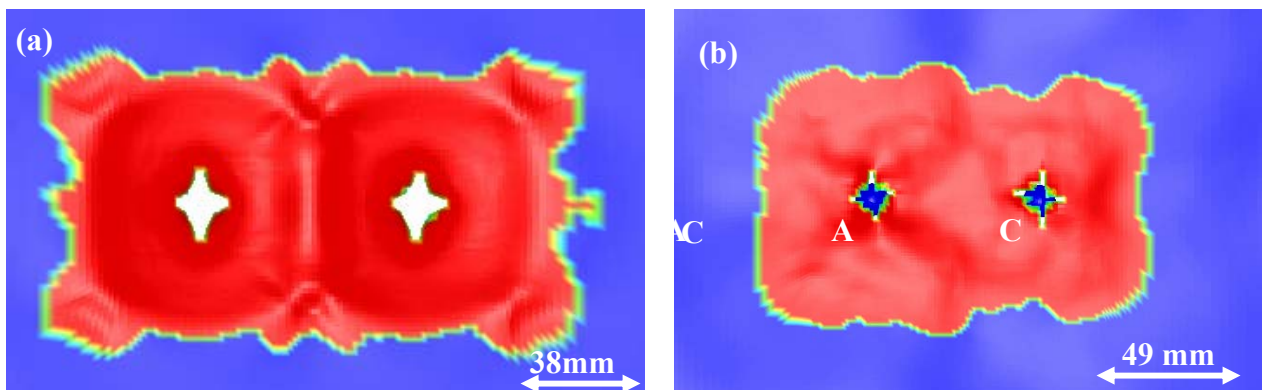


Figure 5. Predicated delamination (a) Simultaneous impact at impact velocity of  $203.3 \text{ ms}^{-1}$  (b) Sequential impact at impact velocities of  $203.9 \text{ ms}^{-1}$  (A) and  $203 \text{ ms}^{-1}$  (C)

Table 1: Material properties of a plain weave s2-glass/sc15 epoxy laminates [9]		Table 2: Material properties for .30 caliber the tool steel spherical projectile	
Density, $\rho$ , kg mm <sup>-3</sup>	1.85E-06	Density, $\rho$ , kg mm <sup>-3</sup>	7860
Tensile Modulus, EA, EB, EC, GPa	27.1, 27.1, 12.0	Young's modulus, E, GPa	210
Poissons ratio, $\nu_{21}, \nu_{31}, \nu_{32}$	0.11, 0.18, 0.18	Poissons ratio	0.28
Shear modulus, GAB, GBC, GCA, GPa	2.9, 2.14, 2.14	Yield strength, GPa	1.08
Inplane-Tensile strength, SAT, SBT, GPa	0.604		
Out of plane tensile strength, SCT, GPa	0.058		
Compressive strength, SAC, SBC, GPa	0.291		
Fiber crush, SFC, GPa	0.85		
Fiber shear, SFC, GPa	0.3		
Matrix mode shear strength, SAB, SBC SCA, GPa	0.075, 0.058, 0.058		
Residual compressive scale factor, SFFC	0.3		
Friction angle, PHIC	10		
Damage parameter, AM1, AM2, AM3, AM4	0.6, 0.6, 0.5, 0.2		
Strain rate parameter, C1, C2, C3, C4	0.1, 0.0001, 0.0001, 0.0001		
Delamination, S_DELM	5,7		
Eroding strain, E_LIMIT	1.2		

*In the table, A, B and C correspond to the 3-orthotropic directions; density, tensile modulus, shear modulus, in-plane tensile strength, out-of-plane tensile strength and compression strength, matrix mode shear strength are standard parameters; Fiber crush occurs at the point of the contact of the projectile with the plate; Fiber shear occurs during penetration; residual scale factor corresponds to partial strength of a failed region in compression; friction angle corresponds to the Coulomb-Mohr friction between the fiber and matrix; damage parameters represent the progressive strain softening of the laminate; strain rate parameter corresponds to strain rate dependency of the plate; delamination criteria guides the in-plane matrix failure mode, and eroding strain corresponds to eroding of the failed element(s) when the strain limit is exceeded.*

Table 3 : Three layer laminate, single projectile results above the ballistic limit

Specimen	Test configuration	Incident velocity (m s <sup>-1</sup> )	Residual velocity (m s <sup>-1</sup> )	Impact energy (J)	Energy absorption (J)	New surface creation (cm <sup>2</sup> )	Predicted average energy absorption (J)	Predicted average new surface creation (cm <sup>2</sup> )
1	Center impact	215.1	0	47.2	47.2	73.2		
2	Center impact	224.6	63.3	51.4	47.3	82.3		
3	Center impact	213	0	46.3	46.3	59.8	43.26	70.1
4	Center impact	221.8	95.9	50.2	40.8	77.7		
5	Center impact	264.7	174.4	71.5	40.5	68.6		
6	Center impact	221.5	92.5	50	41.3	80.7		

Table 4 : Three layer laminate, simultaneous and sequential two projectile impact results

Specimen	Test configuration	Incident velocity (m s <sup>-1</sup> )	Residual velocity (m s <sup>-1</sup> )	Impact energy (J)	Energy absorption (J)	New surface creation (cm <sup>2</sup> )	Predicted average energy absorption (J)	Predicted average new surface creation (cm <sup>2</sup> )
Simultaneous impact								
1	A, C	200.5 <sup>†</sup>	0.0	82.0	82.0	98.1	77.52 <sup>†</sup>	102.4 <sup>†</sup>
2	A, C	203.3 <sup>†</sup>	0.0	84.2	84.2	117.7		
3	A, C	232.2 <sup>‡</sup>	101.1	110.0	89.1	138.9		
4	A, C	230.2 <sup>‡</sup>	113.5	108.0	81.8	109.5	76 <sup>‡</sup>	106.5 <sup>‡</sup>
5	A, C	220.6 <sup>‡</sup>	105.9	99.2	76.4	107.3		
Sequential impact <sup>†</sup>								
1	A	193.2	0	38.1	38.1	NA		
	C	198.7	0	40.3	40.3			
2	A	203.9	0	42.4	42.4	147.7		
	C	203	0	42.0	42.0		71.2	145.2
3	A	207.5	0	NA	NA	137.8		
	C	199.9	0	40.7	40.7			
4	A	201.1	0	NA	NA	135.1		
	C	202.1	0	41.6	41.6			

<sup>†</sup> = Near the ballistic limit, <sup>‡</sup> = above the ballistic limit