Investigation of High Velocity Impact Responses of a Glass/Epoxy Composite with a Gas Gun

A. VANDERKLOK, A. STAMM, M. AUVENSHINE, E. HU, J. DORER and X. XIAO

ABSTRACT

The single stage gas gun testing methodology was investigated. To provide data for computational model development, quantitative measurements of force and displacement were attempted. The transmitted impact force was measured with four load cells installed behind the target. The out-of-plane deformation was measured with a projection grating profilometry method using a high speed camera. The velocity of the projectile was determined using images from the high speed footage. The force and deflection measurements were successful for tests conducted below the ballistic limit. The improved gas gun experiment was used to investigate the high velocity impact behavior of a S2-glass/SC15 epoxy composite. The ballistic limit was found to be 329 and 381 m/s for the 3.8mm (6-ply) and 6.2mm (10-ply) composite panels, respectively. The failure modes of the composite panels were inspected with backlight. The area of damage and failure was found first to increase and then become localized with increasing velocity. As a result, the panels absorbed the same or even a slightly higher amount of energy beyond the ballistic limit, until damage localization. Finally, a new method to compare the ballistic protection capability of different materials is presented.

INTRODUCTION

Impact with an initial velocity between 250m/s to 1300m/s is classified as high velocity impact [1]. Understanding the material behavior and structure response within this range is important to improve designs against impacts generated by ballistic events, debris from explosion, bird strikes, and failure of high speed rotating machine components [2,3].

In laboratories, high velocity impact is often generated using gas guns [1,4-6]. The gas gun testing methodology is still under development. In the recent past, the
common outputs of such experiments are the level of damage to the material versus the impact velocity. With the advancement of 3D displacement measurement techniques, such as 3D digital image correlation (DIC) [7-9], moiré and fringe projection [10], the deformation field of the structure under impact can be recorded. The impact pulse measurement has been attempted with strain bars and an instrumented target [11], as well as an instrumented projectile [12]. These quantitative data will be useful in the validation of computational models for the prediction of high velocity impact response of the structures.

The objective of this work is to obtain data to assist the development of computational models for the prediction of high velocity impact of composite structures. This includes qualitative observations of the damage and failure modes of the composites, and quantitative measurements of force and displacement at locations which can be verified in computational models.

This paper presents some recent developments in gas gun experimental methodology towards this goal. A projection grating profilometry method was employed to measure the out-of-plane deformation. Resistance strain gage based load cells were used to measure the force transmitted to the testing frame. A S2-glass plain weave/SC-15 epoxy composite was investigated. Its post-mortem damage and failure modes were evaluated with images obtained with backlighting. The energy absorption with the evolution of damage and failure modes at different velocities was discussed.

EXPERIMENTAL

Gas Gun Set-Up

Figure 1 shows the schematic of the single stage gas gun used in this work. The major components are a pressure vessel, a gun barrel, and a poppet valve. The steel pressure vessel has a volume of 0.030 m³. The steel barrel is 4.7 m long with an inner diameter of 108 mm. The poppet valve between the pressure vessel and the gun barrel is made of a Mylar diaphragm, which consists of two layers of Mylar sheets of a total thickness 0.50 mm with embedded Nichrome wires, as shown in Fig. 2. Another thin Mylar sheet of 0.25 mm is installed at the exit end of the gun barrel which allows the barrel to be vacuumed to 1-5 kPa. The vacuum prevents the formation of a shock wave in front of the projectile [13] and thus allows the projectile to reach a higher velocity. The pressure is released by rupturing the Mylar diaphragm by resistance heating of the Nichrome wire at the instant of closing the electrical circuit.

In a gas gun experiment, a sabot carrying the projectile is placed in the barrel next to the poppet valve. At the instance of pressure release, the high pressure in the barrel accelerates the sabot down the barrel to reach a high velocity. A sabot arrester at the end of the barrel destructively stops the sabot and allows the projectile to pass to impact the target. The projectile used in this work was a solid aluminum cylinder of 38.1 mm diameter and 18.5 mm tall, with a nominal mass of 60 g.
Figure 1. The schematic of a single stage gas gun. Camera #1 phantom V12 for determining the projectile initial velocity and orientation. Camera #2 phantom V7 for determining the projectile residual velocity and the out-of-plane deformation using a projection grating profilometry method.

Figure 2. (a) The gas gun used in experiment. The gun barrel length is 4.7m (15.5 ft) long with an inner diameter of 108mm (4.25 in). (b) The poppet valve is made of Mylar with embedded Nichrome wire and a spent valve shown bottom. (c) The sabot is made of polylactic acid (PLA) and features a recess to hold projectile in position by press fit. (d) An aluminum 60g projectile machined to a flat on both ends.

**Projectile Velocity Measurement**

The velocity of the projectile at the instant of impact is determined from the high speed video footage using the PCC 2.7 software from Vision Research. An image of a scale ruler positioned in the flight path of the projectile is taken before the test. With this image, a calibration constant of distance per pixel can be determined which is then used to calculate the projectile velocity.

The compressed helium was used in this work. The helium was selected over other gases because it can accelerate the projectile to a higher velocity using less pressure.
Transmitted Impact Force Measurement

Unlike in low velocity instrumented drop tests, there are few established methods to measure the impact force in a high velocity gas gun experiment. In high velocity impact, the impact pulse can be measured directly with an instrumented projectile [12]. Nevertheless, such projectile is relatively expensive. Alternatively, the transmitted impact force (TIF) may be measured, such as an instrumented target made of a load cell attached to a deflector plate [11], used to measure the TIF of a soft projectile made of gel or rubber.

In this work, the measurement of TIF on the target was attempted with resistance strain gage based load cells mounted behind the testing frame which holds the target. The load cells were manufactured from 6061 aluminum rods in house. The finished load cell has a tubular configuration with an outer diameter of 38.1mm, an inner diameter of 19.1mm, and a length of 50.8mm. The diameter of the load cells was selected to give appropriate sensitivities for the estimated expected load. The length of the load cells was kept short to allow for maximum development of wave reflections within the load cell and hence to reduce the inertia effects seen in [11]. Each load cell was instrumented with four strain gages in a full bridge configuration as shown schematically in Fig. 3. The load cells were calibrated using an MTS loading frame with a load cell of 10kN. The strain gage signals were amplified with 100 kHz Vishay amplification cards, acquired by an NI 9223 module and recorded with NI LabView Signal Express.

Four load cells were used to measure the TIF in the gas gun experiment. The load cells were located at the four corners of a steel testing frame, as shown in Fig. 4. The load cells were secured between the testing frame and a rigid fixture with bolt and nuts, as shown in Fig.4. The testing frame has a circular opening. The composite testing panel was fixed to the testing frame with 24 bolts. During impact, the force was transmitted from the composite panel to the load cells through the testing frame. The TIF was calculated as the summation of the four load cells.
Figure 4. Isometric view of the testing frame with a panel installed. The thin wire in center of panel provides a switch for triggering and synchronizing of data acquisition equipment. On the right is a schematic of the circular frame with 24 count holes on a radius of 136.5mm (5.375in). The opening has a radius of 127.0mm (5in), and a test area of 0.05067m².

Figure 5. The schematic of the projection grating profilometry experimental setup for the out-of-plane deformation measurement.

**Velocity Measurement**

The projectile velocity at the instance of impact is referred to as the initial velocity. After interacting with and penetrating the testing panel, it is referred to as the residual velocity. A rebounding projectile will have a negative residual velocity.

As shown in Fig.1, two high speed video cameras were used in the experiment. Camera #1, a Phantom V12.1, was used to determine the velocity and orientation of the projectile before impact and the residual velocity of a rebounding projectile. Camera #2, a Phantom V7 was used to determine the residual velocity of the projectile that had perforated the target [17].

**Out-of-Plane Deformation Measurement**

The out-of-plane deformation was measured with a projection grating profilometry method. The experimental set-up includes a camera, a digital projector, and a
computer, as shown schematically in Fig. 5. By using the digital projector, only one frame of parallel fringe pattern with cosine function modulated intensity is projected onto the object with an incidence angle. The camera is placed normal to the reference plane, thus the deformed fringe patterns modulated by the surface profile of the object can be captured. After a calibration test, the surface profile can be extracted by calculating the fringe deformation between the reference and the detected surface. The details of the analysis are omitted here. The interested readers can refer to [18–20].

**Composite Panels for Testing**

The composite panels were made of S2-glass plain weave (5x5) fabric with areal weight of 0.81 kg/m² and API SC-15 toughened epoxy resin. The vacuum assisted resin transfer molding method (VARTM) was used to manufacture the panels. VARTM is a cost effective way to manufacture higher volume fraction composites [21]. The schematic of VARTM is shown in Fig. 9. The glass fabric layers were laid onto a flat tool plate to form a laminate with fibers in 0° and 90° orientations. The resin was introduced under vacuum. The composite was vitrified at 60°C for 2 hours, then post-cured at 94°C for 4 hours with a ramp rate of 1-2°C per minute. The manufactured composite plates had a nominal thickness of 0.62 mm/ply. The thickness of the 6-ply and 10-ply composite plates used in this study was 3.85±0.31mm and 6.19±0.05mm, respectively.

![Schematic of VARTM process](image)

**Figure 6. Manufacturing composite panels using VARTM Process.**

The manufactured composite plates were cut to 300mm x 300mm square panels for testing with an abrasive diamond face saw. Additionally, a 51mm x 102mm triangle was cut from each corner to allow the panel to fit in the testing fixture (Fig. 4). Each panel was drilled to have 24 equally spaced 6.4mm (0.25 in) holes and bolted to the testing frame, as shown in Fig.4. The bolts were carefully fastened with a torque wrench to a torque of 16.3 N-m (12.0 lbf-ft).

**Post-mortem Inspection**

The tested composite panels were inspected visually and with a backlighting photography method. The experiment set-up consists of a Cree CXA 1520 high density LED array with a Carclo 45° mirror reflector positioned 0.31m away from the backside of the panel. The photos were taken with a Nikon D3200 camera with a variable 18-55mm lens from a distance of 1.22m. The photos were post processed in
MATLAB where images were converted to gray scale using function rgb2gray and the contrast was enhanced with function imadjust. This method allows for easy observation of delamination damage in glass fiber composites.

RESULTS AND DISCUSSION

Table 1 provides a summary of the gas gun experimental results. A total of twelve panels were tested; four of them were 10-ply and the other eight were 6-ply. The measured initial projectile velocity $v_i$ ranged from 300m/s to 449m/s. From the initial velocity and the mass of the projectile, the initial kinetic energy of the projectile $E_{ki}$ was determined.

In nine experiments, the projectile perforated the panel where the residual velocity of the projectile $v_r$ had a positive value. The projectile rebounded in tests IT_8, IT_10, and IT_17. For these three cases, the maximum deflection was determined from the out-of-plane deformation measurement. The values are reported in Table 1. From $v_r$, the residual kinetic energy of the projectile $E_{res}$ can be determined.

The absorbed energy $E_{abs}$ is determined from the change in the kinetic energy of the projectile as

$$E_{abs} = E_{ki} - E_{res}$$

Since very little damage had occurred to the tested projectiles, $E_{abs}$ can be attributed to the energy absorbed by the panel. To compare the panels with different thickness, the specific energy absorption of the target panel was calculated by dividing $E_{abs}$ with the mass of the panel in unsupported area, i.e. the circular opening area shown in Fig. 4. These values are listed in Table 5. The average specific energy absorption was 7.69kJ/kg and 6.89kJ/kg for the 6-ply and 10-ply panels, respectively. The 6-ply panel was 12% more efficient than the 10-ply panel in this regard.

### TABLE 1. GAS GUN EXPERIMENTAL RESULTS

<table>
<thead>
<tr>
<th>Test (#)</th>
<th>Areal Weight (kg/m²)</th>
<th>Target</th>
<th>Projectile Mass (g) v_i (m/s)</th>
<th>v_r (m/s)</th>
<th>E_{ki} (kJ)</th>
<th>E_{res} (kJ)</th>
<th>E_{abs} (kJ)</th>
<th>Target Specific Energy (kJ/kg)</th>
<th>Result/Max Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT_6</td>
<td>6.53</td>
<td>6ply</td>
<td>60</td>
<td>360</td>
<td>94</td>
<td>3.89</td>
<td>3.62</td>
<td>10.95</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_7</td>
<td>6.53</td>
<td>6ply</td>
<td>60</td>
<td>374</td>
<td>211</td>
<td>4.20</td>
<td>2.86</td>
<td>8.63</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_8</td>
<td>6.53</td>
<td>6ply</td>
<td>60</td>
<td>321</td>
<td>-23</td>
<td>3.09</td>
<td>3.08</td>
<td>9.30</td>
<td>28.3</td>
</tr>
<tr>
<td>IT_10</td>
<td>10.66</td>
<td>10ply</td>
<td>58.84</td>
<td>375</td>
<td>-23</td>
<td>4.14</td>
<td>4.12</td>
<td>8.63</td>
<td>23.0</td>
</tr>
<tr>
<td>IT_11</td>
<td>10.66</td>
<td>10ply</td>
<td>58.75</td>
<td>458</td>
<td>346</td>
<td>6.16</td>
<td>2.65</td>
<td>4.90</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_12</td>
<td>6.53</td>
<td>6ply</td>
<td>58.51</td>
<td>449</td>
<td>370</td>
<td>5.90</td>
<td>1.89</td>
<td>7.72</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_13</td>
<td>6.53</td>
<td>6ply</td>
<td>60.44</td>
<td>359</td>
<td>199</td>
<td>3.89</td>
<td>2.69</td>
<td>6.14</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_14</td>
<td>10.66</td>
<td>10ply</td>
<td>60.93</td>
<td>443</td>
<td>270</td>
<td>5.98</td>
<td>3.76</td>
<td>6.76</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_15</td>
<td>10.66</td>
<td>10ply</td>
<td>58.33</td>
<td>438</td>
<td>206</td>
<td>5.60</td>
<td>4.36</td>
<td>8.07</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_16</td>
<td>6.53</td>
<td>6ply</td>
<td>60.94</td>
<td>383</td>
<td>268</td>
<td>4.47</td>
<td>2.28</td>
<td>6.79</td>
<td>Perforation</td>
</tr>
<tr>
<td>IT_17</td>
<td>6.53</td>
<td>6ply</td>
<td>59.04</td>
<td>300</td>
<td>-9</td>
<td>2.66</td>
<td>2.65</td>
<td>5.31</td>
<td>Rebound**</td>
</tr>
<tr>
<td>IT_18</td>
<td>6.53</td>
<td>6ply</td>
<td>57.65</td>
<td>387</td>
<td>325</td>
<td>4.32</td>
<td>1.27</td>
<td>3.85</td>
<td>Perforation</td>
</tr>
</tbody>
</table>

* $v_i$-initial projectile velocity, $E_{ki}$-initial projectile kinetic energy, $v_r$-residual velocity of projectile, (-) implies rebound. The target specific energy absorption was calculated by $E_{abs}$/mass of the test area. The test area =506.7cm². The mass of the test area is 331g for the 6-ply and 540g for the 10-ply panels.

**IT_17 Max Deflection unavailable.
Ballistic Limit

The ballistic limit is the velocity required for a particular projectile to penetrate a particular target. In this work, the ballistic limit was defined as the velocity that results in a residual velocity of zero. The residual velocities were plotted against the initial velocities for the twelve experiments in Fig. 7. The ballistic limit was determined by the line connecting the point with the fastest velocity that caused rebound and the point with the slowest velocity that had no rebound. The interception of the line with the x-axis yielded the ballistic limit. The value was 329 m/s and 381 m/s for the 6-ply and 10-ply composites, respectively. It is interesting to note that the ballistic limit did not increase proportionally with the panel thickness. The ballistic limit of the 10-ply panel is only 16% higher than that of 6-ply. The lower efficiency in the energy absorption as well as in the ballistic limit of the 10-ply panel may be caused by the change in the structural rigidity of the panel and the damage mechanisms and dominate failure modes at higher speeds.

In testing of various heat treated metals, the estimated error in the determination of the ballistic limit was approximately ±3% [22]. The ballistic limits of the composite targets reported here could have a higher error due to manufacturing variability of the composite panels.

![Residual Velocity vs Initial Velocity](image)

Figure 7. Material ballistic limit is determined at the x-axis intercept of a linear trend line from residual vs. initial velocities.

Force and Deformation Histories

Figure 8 plots the force history curves from the load cell measurement. Figure 9 presents the value of the peak force versus the impact velocity of the projectile. As seen, the highest forces were recorded for the two panels tested under the ballistic limit, with a maximum value of 38kN and 30kN for IT_10 (10-ply) and IT_8 (6-ply), respectively. For the tests above the ballistic limit, the force registered by the load cell decreased with the velocity of the projectile. At 449 m/s, the recorded maximum force on IT_12 was only 454 N, merely 1.5% of the force recorded from IT_8. The lower
recorded force values at higher projectile speeds indicate that the failure in the panel became more localized and independent of the boundary condition. As suggested by Roberts et al [23], in a high velocity impact scenario, the failure modes observed from panels of simple geometries may closely match the failure modes seen on a complex structure.

Figure 8. The force history traces recorded by the load cell. The force is the summation of four load cells.

Figure 9. The recorded peak force versus the impact velocity of the projectile.
The out-of-plane deformation measurement using the projection grating profilometry was successful with the two panels tested under the ballistic limit (no perforation). The results are shown in Fig. 10. Under the impact of a cylindrical projectile, the panel displayed a cone shaped deformation. The cone expanded in size and then retreated.

A comparison between the force and deformation measurements helps to identify the origin of the peak forces registered by the load cells. Fig. 11 plots the out-of-plane displacement history at the center of the two panels. For IT_10, the panel reached the maximum deflection at 216 μs and then reflected back, passing zero at 1134 μs and then reached the maximum in the opposite direction at 1458 μs. In Fig. 8, the first peak force for IT_10 occurred at 352 μs, corresponding to the maximum deflection of the plate. The delay of the load cell signal was therefore estimated to be about 136 μs. Therefore, the peak force at 1700 μs is likely to relate to the maximum deflection in the opposite direction. On the other hand, the peak force for IT_10 at 760 μs cannot be associated to a particular deformation stage and therefore it was likely caused by the reflected wave within the load cell.

In the tests above the ballistic limit, failure occurred through the thickness of the composite panels. In the experiment, upon initial impact, a bright lighting phenomenon was observed. This degraded the initial fringe pattern to be useful in the analysis. Soon after, the matrix resin disintegrated into dust which obstructed the view of the video camera and fringe projector. The out-of-plane deformation measurement, therefore, was not successful for the panels that were perforated.

---

Figure 10. 3D profile of the back side of the panel during impact testing under the ballistic limit.
Energy Absorption

Figures 12a and 12b plot the energy absorption versus the initial velocity for the 6-ply and 10-ply panels, respectively. It shows that above the ballistic limit, a panel can still absorb the same or even a slightly greater amount of energy with increasing velocity. The same phenomenon has been reported for woven fabrics [24] and carbon fiber composites [25]. Literature data indicates that this region would end at a critical velocity where the energy absorption reaches a peak value [24,25]. Accordingly, the energy absorption behavior may be divided into three regions: Region I - below the ballistic limit; Region II - from the ballistic limit to the critical velocity; and Region III – above the critical velocity, as indicated in Fig. 12. Judging from the energy absorption, the impact test at 449m/s for the 6-ply panel might have exceeded the critical velocity.
Damage and Failure Mode Analysis

The damage and failure in the glass fiber composite was inspected visually and with the backlighting photography technique. It reveals that the failure modes change depending on the impact velocity. Fig. 13 presents the backlighting images of tested panels and a summary of the visually observed failure modes. In all images, the fiber tows in the composite panel were oriented in the vertical and perpendicular directions.

Figure 13. Inspection of tested panels with backlight. The surface shown is the impact face.
In Region I, the dominating failure modes were matrix cracking and crushing. For the 6-ply panel, four major cracks, each with minor fiber pull out, were observed on the top surface. Delamination occurred but was limited to the top layer only. On the backlighted panels, delamination regions are seen visibly as fringes. A single fringe indicates that delamination occurred at one interface. There was no visible damage at the backside of the panel. The 10-ply panel had a few more short cracks and a similar delamination area.

In Region II, the projectile perforated the panel. The dominate failure mode was shear failure. A shear plug or circular cutout was observed on the top layers. At the back side, fiber tows were protruded out of the panel and formed a hut, as shown in Fig. 14. These fiber tows had little resin on them. As mentioned above, in the impact tests above the ballistic limit, the matrix resin disintegrated into dust at the back side of the panel. The post-mortem confirmed this observation. The second characteristic failure mode is delamination at multiple interfaces. Multiple fringes are visible in the backlight images. In these panels, the outer most fringes correspond to the back side of the panel where the projectile exits. The images at different impact velocities show that delamination increased with velocity. Furthermore, the number of the major cracks increased with impact velocity.

Test IT_12 might mark the beginning of Region III. The dominate failure mode was still shear but the failure was rather localized. The shear failure went all the way through the panel. At the back side, the protruded fiber tows formed a taller hut, Fig. 17. The major cracks were shorter and the delamination areas were smaller.

The tested panels were no longer flat but slightly warped. The depth of the deformed shape was largest at the center of the panel. This depth was designated as $dp$. Its value for each test was measured and reported in Fig. 13. All panels except IT_8 bulged towards the back side and the measured $dp$ ranged from 3.3mm to 8.8mm. IT_8 bulged towards the impact side with $dp=-9.2$mm.

Figure 14. The back side of the composite panel from IT_12, 6-ply panel tested at 458m/s: dry fiber tows are protruded and form a hut shaped sub-structure.

**Comparison of Energy Absorption at Ballistic Limit**

The ballistic limit depends on the shape and mass of the projectile and the configuration of the target. Although ballistic limit data are available for a variety of materials in literature, it is difficult to compare the ballistic protection capability of different materials. In this work, different materials are compared by $E_{BL}$, the
projectile kinetic energy at the target ballistic limit normalized by the contact area of the projectile with the target, versus the areal weight of the target, as shown in Fig.18. The data compared here are for projectiles with a blunt head, such as a flat face or a semispherical shape. The contact area is defined as the maximum cross section of the projectile. This plot allows one to determine the required areal weight for a specific material to stop a blunt projectile of certain mass and velocity.

Figure 15 shows that the S2-glass plain weave/SC-15 epoxy composite has excellent ballistic protection capability compared to other materials. Other high efficiency materials are Inconel 718 heat treatment (HT) B and HTA.

![Figure 15. Comparison of E_{BL}, the energy absorbed by the target material at the ballistic limit normalized by the contact area, versus the areal weight of the target. Material tested in this work is identified by arrows. Data source: S2-glass areal weight 3.2 (kg/m²) [26], Inconel 718 [22], AS4 [27], E-glass and T300 [28,29], Al [30].](image)

**CONCLUSIONS**

To improve the gas gun experiment, several new techniques were explored. The measurement of the transmitted impact force (TIF) was attempted with four load cells attached to the testing frame. The out-of-plane deformation of the target panel was measured using a projection grating profilometry method with a high speed camera. This deformation measurement was successful for tests conducted at velocities below the ballistic limit but failed for those above the ballistic limit.

The high velocity impact behavior of S2-glass plain weave/SC15 epoxy composite panels was investigated. With a cylindrical aluminum projectile of 60g, the ballistic
limit was 329 m/s and 381 m/s for the 6-ply and 10-ply, respectively. In terms of the specific energy absorption, the 6-ply panel was 12% more efficient than that of 10-ply. In the range of impact velocity from 300 m/s to 458 m/s, the energy absorption of the composite panels maintained and even increased with velocity. The failure modes of the panels evolved with the velocity. The damage and failure first increased in size with velocity and then became more localized. In 458 m/s impact, the force registered by the load cells is only 1.5% of that at 321 m/s, indicating that failure was localized and independent of the boundary condition.

By plotting $E_{BL}$, the projectile kinetic energy at the target ballistic limit normalized by the contact area of the projectile, versus the areal weight of the target, the ballistic protection capability of different materials can be compared. S2-glass/epoxy composite is ranked high in ballistic capability.

ACKNOWLEDGEMENTS

This work is supported by NASA Glenn Research Center through grant number NNX12AL14A.

REFERENCES