Ballistic Properties of Polypropylene and Epoxy Based Glass Fiber Reinforced Composites: Experiments and Modeling

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ABSTRACT

In this paper, the ballistic properties of polypropylene and epoxy based glass fiber reinforced composites were investigated. Specimens based on woven Shield Strand S®/epoxy and E-glass fiber/polypropylene (Twintex®) were manufactured and prepared for testing under high velocity impact loading conditions. Experiments were performed using a single stage gas gun with spherical and sharp head steel projectiles. A high-speed non-contact strain measurement system was used to reveal global and localized 3D deformations, strain evolution and localization as well as failure mechanisms. Impact velocities ranged from 50 m/s to 175 m/s in order to determine the ballistic limit of each system. Experimental results were in very good agreement with the predictions offered by a numerical model. In addition, a clear relation between composite system, ballistic limit, and, failure mechanisms was highlighted.

1. INTRODUCTION

There are many composites, which are used in the manufacturing of components required for a wide range of applications. Polymer matrix composites are advanced materials based on thermoplastic and thermosetting resins reinforced with synthetic fibers. The matrix ensures proper bonding between the fibers, which acts as a load-bearing component. It also behaves as a medium that transfers the load to fibers [1]. These composites offer high specific strength and high specific stiffness when compared with metals. Furthermore, they also offer excellent corrosion resistance in combination with properties like excellent fatigue resistance and excellent impact resistance. Such properties make them ideal candidates to be used in high performance defense applications [2]. In addition, the manufacturing of components and the raw materials is becoming more cost efficient [3].

In order to evaluate the dynamic properties of composites, high-velocity impact tests are generally performed using apparatus such as the Hopkinson bar setup and a single stage gas-gun technique. It has been observed that in Hopkinson bar testing the shear stresses at gripping area

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are high and the dimensions of specimens should be large [4]. In contrast, in the newly developed gas-gun systems, these disadvantages are not present. They can be used to test specimens of various sizes and can be used to evaluate the high-velocity impact properties of number of materials [5]. Gower and Cronin studied the high-velocity impact behavior of Kevlar 29 and Kevlar 129 with conical and spherical projectiles at velocities of 130 m/s and 250 m/s. They observed that back face displacement of the specimen after impact of Kevlar 29 was more pronounced compared with Kevlar 129 [6]. Higuchi and Obake studied the high-velocity impact behavior on carbon fiber reinforced plastics and highlighted various failure modes that can occur in PMC's during ballistic testing [7]. Alireza and Nargis investigated the properties of glass fiber reinforced polymers with a sharp tip projectile at velocities ranging from 80 m/s to 160 m/s and revealed composite wave propagation and the ballistic performance of woven and cross-ply composites based on E-glass [8].

Gunnarsson and Ziemski performed ballistic testing on polycarbonate at velocities ranging from 50.1 m/s to 81.2 m/s using digital image correlation in order to monitor the maximum back face displacement of the plates during the impact event [9]. Kaboglu and Mohagheghian investigated the high velocity impact behavior of fiber metal laminates also using a digital image correlation system at velocities ranging from 116 m/s to 267 m/s in order to understand the full-field out-of-plane displacement, out-of-plane displacement profile during loading and unloading and as well as central maximum out-of-plane displacement of the material. They concluded that the energy absorption changes in FML's with increase in number of metal and fiber layers [10].

In this research work, polypropylene and epoxy based glass fiber reinforced composites were manufactured and tested under ballistic loading conditions. Here, high velocity impact testing was performed on woven thermoset and thermoplastic based composites using single stage gas-gun system. Composites with different thicknesses were impacted using 12 mm diameter spherical and sharp tip projectiles. The ballistic limit for these composites was established and the failure modes were revealed. Digital image correlation was used to determine the 3D deformation, maximum transient out of plane displacements and final back face displacements. Finally, numerical modeling was performed to predict the ballistic limit of these composite materials.

2. EXPERIMENTATION

The composite materials used in this project were based on Shield Strand S® and E-glass fibers (Figure 1) reinforcing epoxy and polypropylene resins respectively. Fiber volume fraction was 60% for both composites. Panels were manufactured with a dimension of 210 x 240 mm using an aluminum mold coated with Teflon® releasing agent to prevent the composite from sticking to the mold. Shield Strand S®/epoxy composites were manufactured using hand layup process. Here, layers of reinforcements were alternated with the epoxy resin and hand rolled to remove the excess resin and any air that could have been trapped. The mold was then placed in a hydraulic press preheated to around 100°C. A pressure of 7 MPa was applied for one hour according to the curing recommendations.

The manufacturing of E-glass fiber / polypropylene (Twintex®) composites consisted of placing prepreg layers in an aluminum mold. The mold was then placed in an oven until a temperature of 180°C was reached. Following this, the mold was subjected to a cold compression step using a hydraulic press.

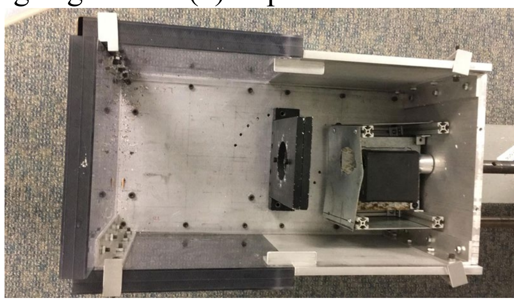
(a) (b)

Figure 1. Reinforcements used in the project based on (a) TPP 60 1485 E-glass fibers and (b) Shield Strand S® fibers.

In order to conduct high velocity impact testing, the manufactured panels were cut into specimens with dimensions of 100 x 100 mm using a diamond coated circular saw. The specimens were placed in an impact chamber located at the end of single stage gas-gun setup as shown in figure 3. The projectile velocity was measured using a velocity sensor located inside the impact chamber. In addition, bullet proof windows were added for in-situ investigations of the impact event. Here, high speed cameras (100,000 fps) were located at the back of the impact chamber along with pair of 250 W lamps and 150 W LED lights to investigate the impact event and reveal the deformation process and failure mechanisms

(a)

Figure 3. (a) Single stage gas-gun with (b) impact chamber for high velocity impact testing.



(b)

Figure 3 (continued) (a) Single stage gas-gun with (b) impact chamber for high velocity impact testing.

In addition in order to determine the 3D deformations, maximum transient out-of-plane displacements and final back face displacements, a digital image correlation system was used. Here, test specimens were spray painted with a combination of big black and white dots as shown in figure 4.

(a) (b)

Figure 4. Optical micrographs showing (a) calibration panel for DIC, and (b) the Speckle pattern applied to the specimen before ballistic testing.

Finally, in order to predict the ballistic limit of the composite materials, the Reid and Wen model was used [11]. This model has been specifically used to estimate ballistic limit of a number of composites. Here, the ballistic limit is given by:

$$V_b = \frac{\pi \Gamma \sqrt{\rho_t \sigma_e} D^2 T}{4m}\left[1 + \sqrt{1 + \frac{8m}{\pi \Gamma^2 \rho_t D^2 T}}\right] \quad [1]$$

Where,

V_b = Velocity at ballistic limit

D = Diameter of the projectile

T = Total laminate thickness

m = Mass of the projectile

σ_e = Quasistatic linear elastic compression limit

Γ = 1.5 (for spherical head projectile), 0.03 (for sharp head projectile)

ρ_t = Density of laminate

Here, for the quasi-static linear elastic compression limit, three point bending tests were performed on the composite materials. The dimensions of the specimens for testing were considered according to the ASTM D7264 standards. Testing was performed using a universal testing machine (Instron 5967) shown in figure 5.

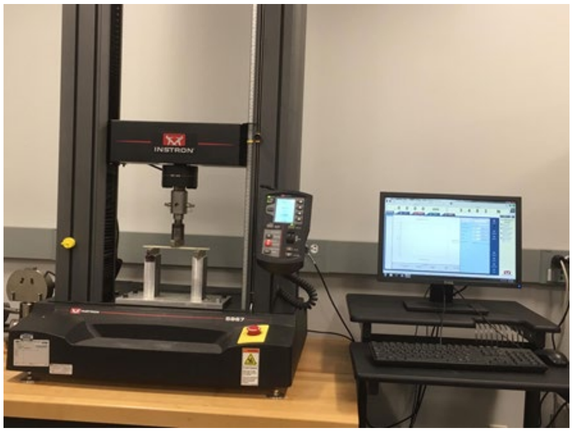


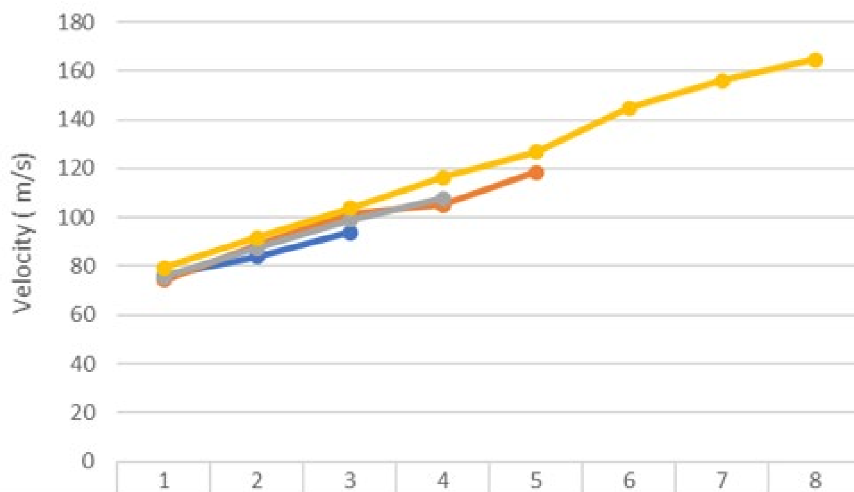
Figure 5. Three point bend testing on composite using an Instron 5967 universal testing machine.

3. RESULTS

In this project, the ballistic properties of woven composites based on Shield Strand S® / epoxy and E-glass fiber / polypropylene (Twintex®) were investigated. Here, impact velocities ranging between 50 m/s and 175 m/s were used in order to determine the ballistic limit of each composite with different projectiles and different thicknesses. First, in order to estimate the velocity of the projectile required for the test, the pressure and velocity calibration relationship was established.

Spherical head and sharp nose projectiles were propelled under different pressures towards wood blocks placed in the impact chamber until the pressure vs. velocity calibration relationship was established. It was noticed that for the spherical head projectile the pressure required to attain the certain velocity was higher than the pressure required to reach that velocity for the sharp nose projectile.

Figure 6 shows the impact response of the woven composites used in this project after ballistic testing with a spherical head projectile. In the figure, the highest velocity value of each specimen corresponds to the Ballistic limit. These experimental results indicate that the Shield Strand S® / epoxy composites offer more impact resistance compared to the Twintex® based composites with the same thickness. Furthermore, the Shield Strand S® / epoxy composites with a thickness of 2.5 mm exhibited higher impact resistance even when compared to the Twintex® based composites with a 4.5 mm thickness.



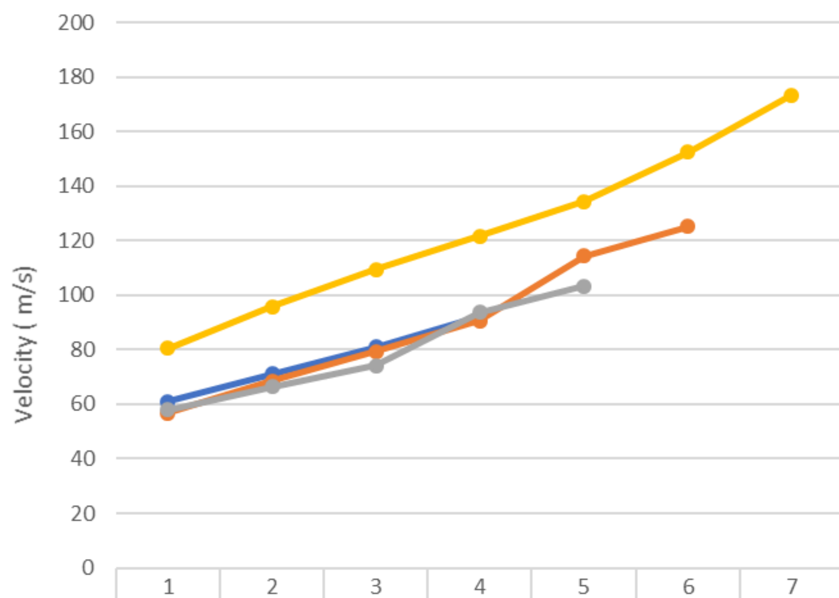
	1	2	3	4	5	6	7	8
Twintex 2.5 mm thickness	76.12	83.78	93.86					
Shield Strand S / Epoxy 2.5 mm thickness	74.32	88.4	101.5	105	118.5			
Twintex 4.5 mm thickness	75.42	87.45	98.88	107.8				
Shield Strand S / Epoxy 4.5 mm thickness	79.35	91.58	103.7	116.3	126.7	144.8	156.1	164.5

Figure 6. Impact behavior of Shield Strand S®/epoxy and E-glass fiber/polypropylene composites under ballistic loading with a spherical head projectile.

Figure 7 shows the impact response of the woven composites used in this project after ballistic testing using a sharp nose projectile. From the figure, it is evident that once again the thermosetting based composites offer higher levels of impact resistance than the thermoplastic based composites.

It is interesting to note that the E-glass fiber reinforced polypropylene in a woven configuration exhibited similar values of ballistic limit when subjected to ballistic loading using either a spherical head or sharp nose projectile, highlighting the excellent energy absorbing capabilities of the composite to localized impact loading.

Furthermore, the Shield Strand S® fiber reinforced epoxy exhibited an improved impact response when subjected to ballistic loading using a sharp nose projectile compared to when impacted with a spherical head projectile. These results suggest the presence of an increased number of failure and energy absorbing mechanisms when loaded with a sharp nose projectile under ballistic loading conditions.



	1	2	3	4	5	6	7
Twintex 2.5 mm thickness	60.96	71.22	81.09	92.1			
Shield Strand S / Epoxy 2.5 mm thickness	56.7	68.5	79.28	90.57	114.4	125.1	
Twintex 4.5 mm thickness	58.07	66.35	74.29	93.77	103.25		
Shield Strand S / Epoxy 4.5 mm thickness	80.5	95.69	109.4	121.6	134.24	152.4	173.4

Figure 7. Impact behavior of Shield Strand S®/epoxy and E-glass fiber/polypropylene composites under ballistic loading with sharp nose projectile.

During the impact event, a high speed non contact digital image correlation system was used to reveal local and global 3D deformation as well as strain evolution of the woven composite materials under ballistic loading conditions. It is worth nothing that at the ballistic limit, complete 3D deformation data could not be captured since there were damages in the speckle pattern due to the perforation of the projectile. Therefore, 3D deformation and maximum transient out-of-plane displacement data of the composites at the velocity just before the ballistic limit velocity are presented in this paper.

Figure 8 shows the Impact behavior of the Twintex® based 2.5 mm thick specimen impacted with sharp nose projectile at a velocity of 81.09 m/s. From the figure, it is evident that on the point of contact of projectile, fiber ruptures were noticed along with matrix cracks near the point of impact. On the opposite side, heavy fiber ruptures are present with petaling. This type of failure occurs when the tensile stresses on the backside exceed the tensile strength of the composite.

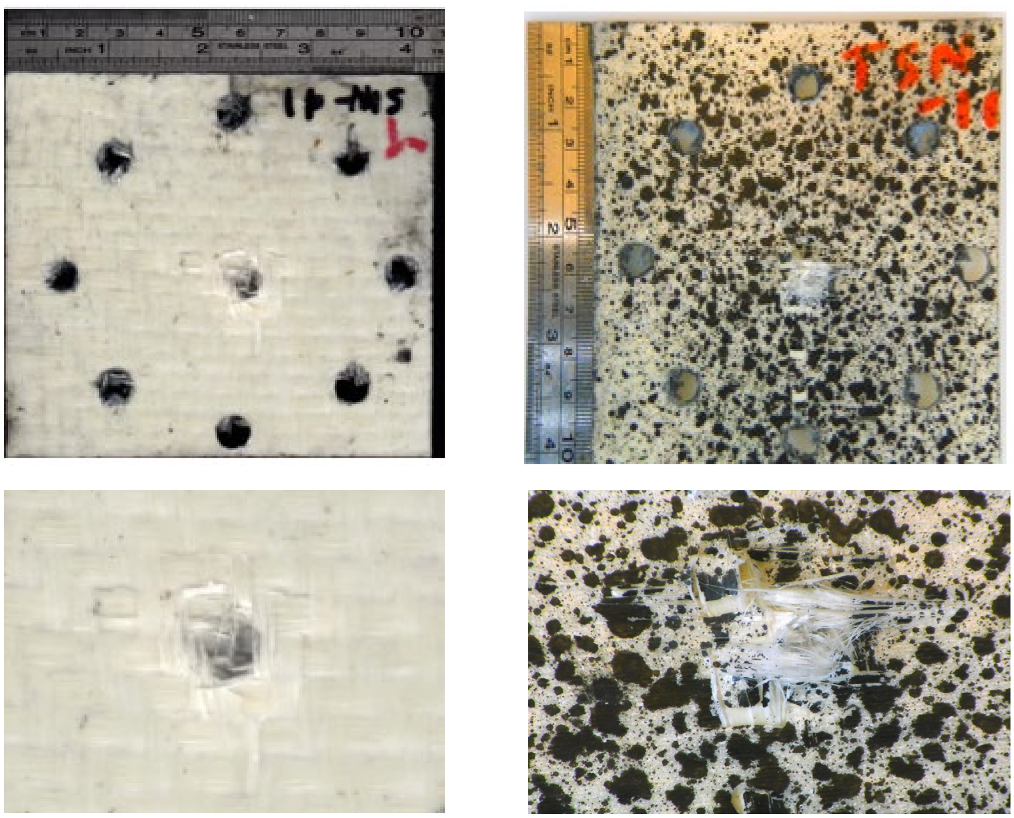


Figure 8. Twintex® based 2.5 mm thick composite impacted at velocity of 81.09 m/s with a sharp nose projectile.

Figure 9 shows the variation of the maximum transient out-of-plane displacement with stage time for the specimen illustrated in figure 8. For this case, the maximum out of plane displacement was measured as 12.64 mm. Figure 9 also highlights a number of serrations due to the heavy fiber ruptures at the point of contact of the projectile and multiple elastic deformations are also noticed

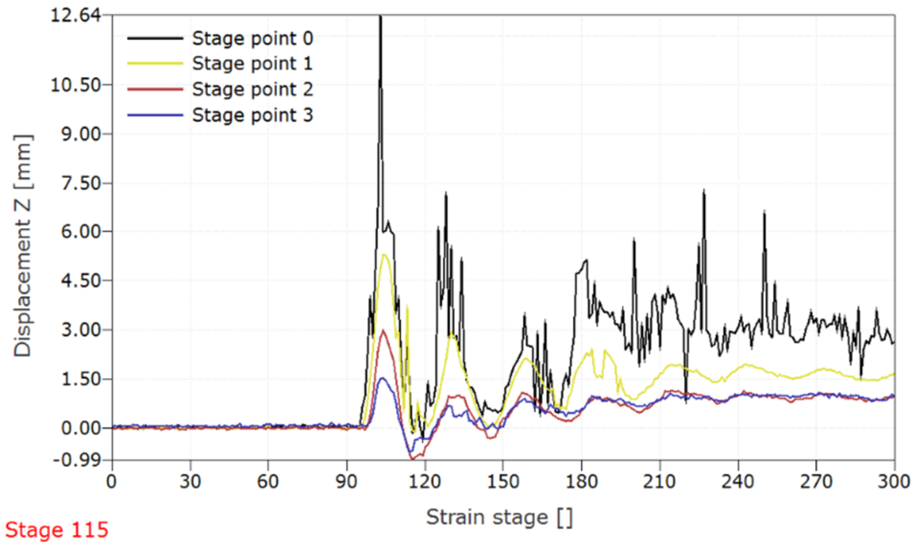
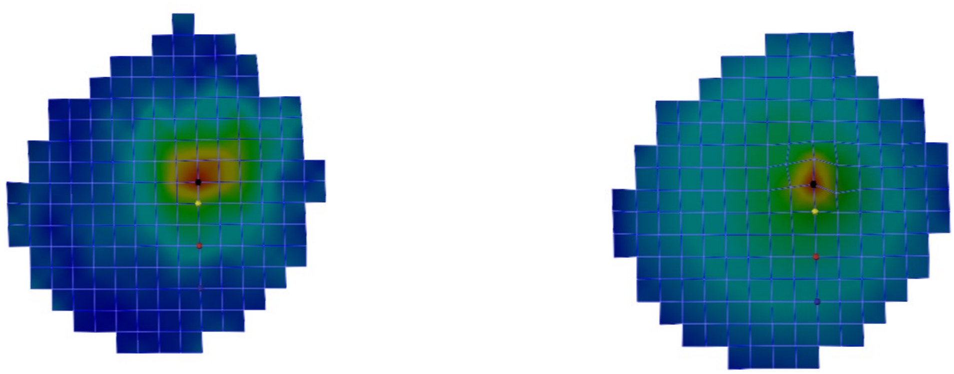


Figure 9. Displacement vs stage plot for a Twintex® based 2.5 mm thick specimen impacted at velocity of 81.09 m/s with a sharp nose projectile.

Figure 10 shows a number of deformation stages representing the impact event on the 2.5 mm thick Twintex® based composites tested at velocity of 81.09 m/s with sharp nose projectile. From the figure, it is evident how the out-of-plane deformation increased until the maximum transient out-of-plane displacement was reached in stage 103 with a value of 12.64 mm. Following this, the displacement decreased in stage 122 with the final displacement taking a value close to 3.00 mm in the region of impact.



Stage 98 Stage 103

Figure 10. 3D deformation data of a Twintex® based 2.5 mm thick specimen impacted at velocity of 81.09 m/s with a sharp nose projectile.

Stage 122 Stage 300

Figure 10 (Continued) 3D deformation data of a Twintex® based 2.5 mm thick specimen impacted at velocity of 81.09 m/s with a sharp nose projectile.

Figure 11 shows the impact behavior Shield Strand S®/epoxy based 2.5 mm thick specimen impacted with sharp nose projectile at a velocity of 114.4 m/s. From the figure, it was evident that on the point of contact of the projectile fiber ruptures are present and close to the point of impact delaminations are also present. On the opposite side (speckle pattern) of the point of contact of projectile, fiber ruptures and petaling are evident along with delaminations. In addition, heavy fragmentation was observed during impact.

The maximum transient out-of-plane displacement with stage time for specimen presented in figure 12. In this case, the maximum out-of-plane displacement reached a value of 12.16 mm. Figure 12 also highlights a number of serrations due to fiber ruptures and deformations associated with the impact waves.

Figure 13 shows a number of deformation stages representing the impact event on the thermosetting-based composite tested at velocity of 114.4 m/s with a sharp nose projectile. From the figure, it is evident how the out-of-plane deformation increased until a value of 12.16 mm was reached. Following this, the displacement decreased as shown in stage 44. Here, due to the fragmentation, a small region of speckle pattern was obstructed and complete 3D displacement data for this specimen at this stage was affected. The final displacement was close to 5.00 mm at the point of impact.

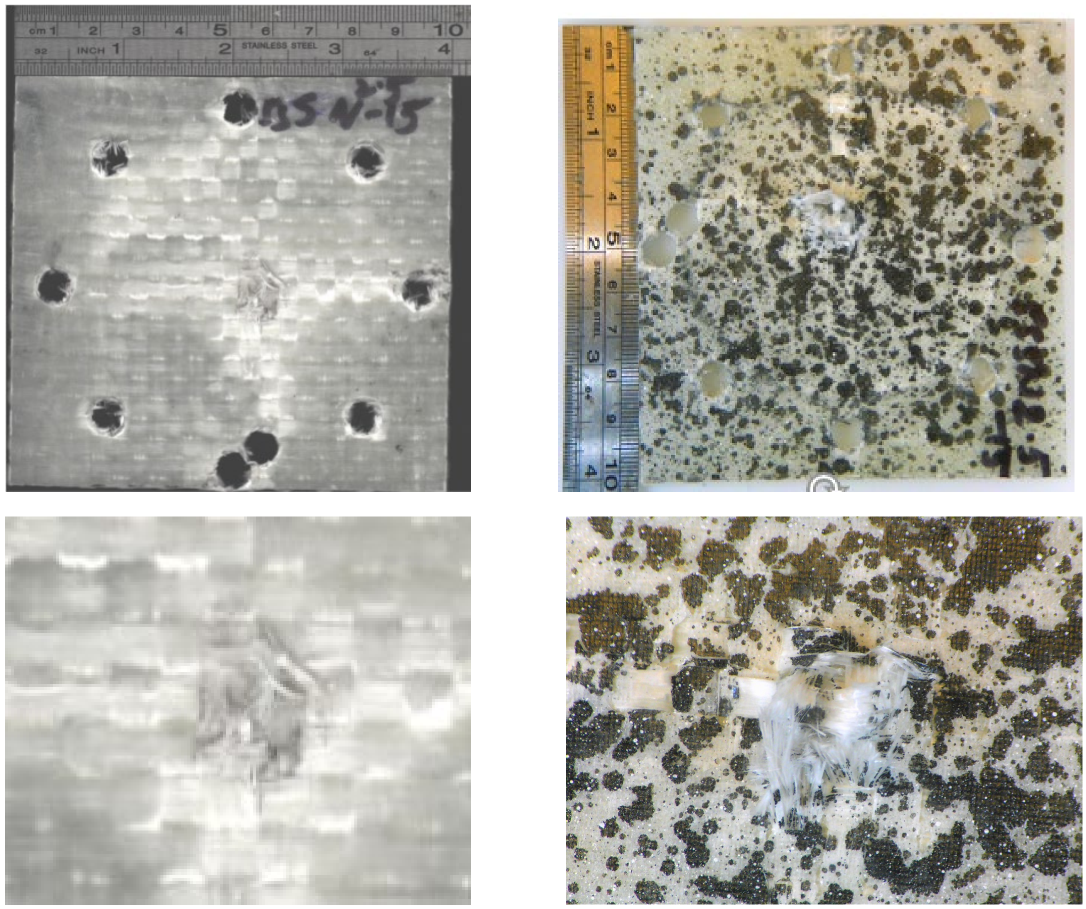


Figure 11. Shield Strand S®/epoxy based 2.5 mm thick specimen impacted at velocity of 114.4 m/s with sharp nose projectile.

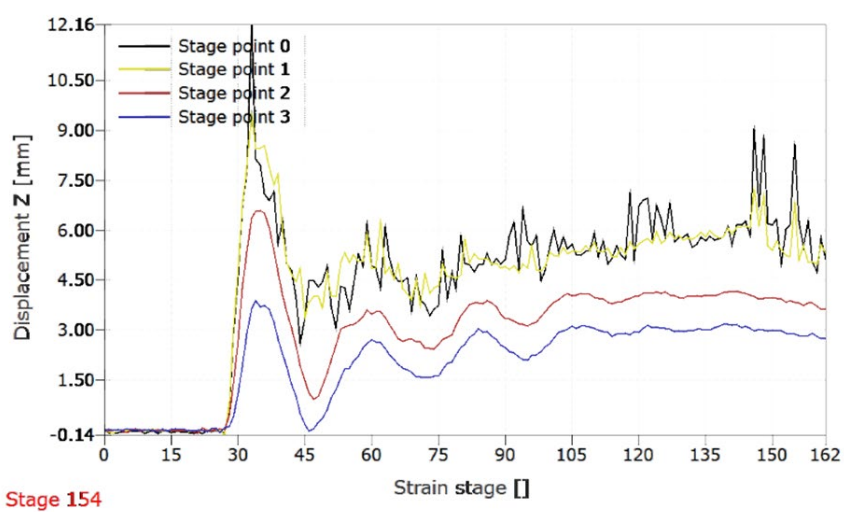


Figure 12. Displacement vs. stage plot for Shield Strand S®/epoxy based 2.5 mm thick specimen at velocity of 114.4m/s with sharp nose projectile.

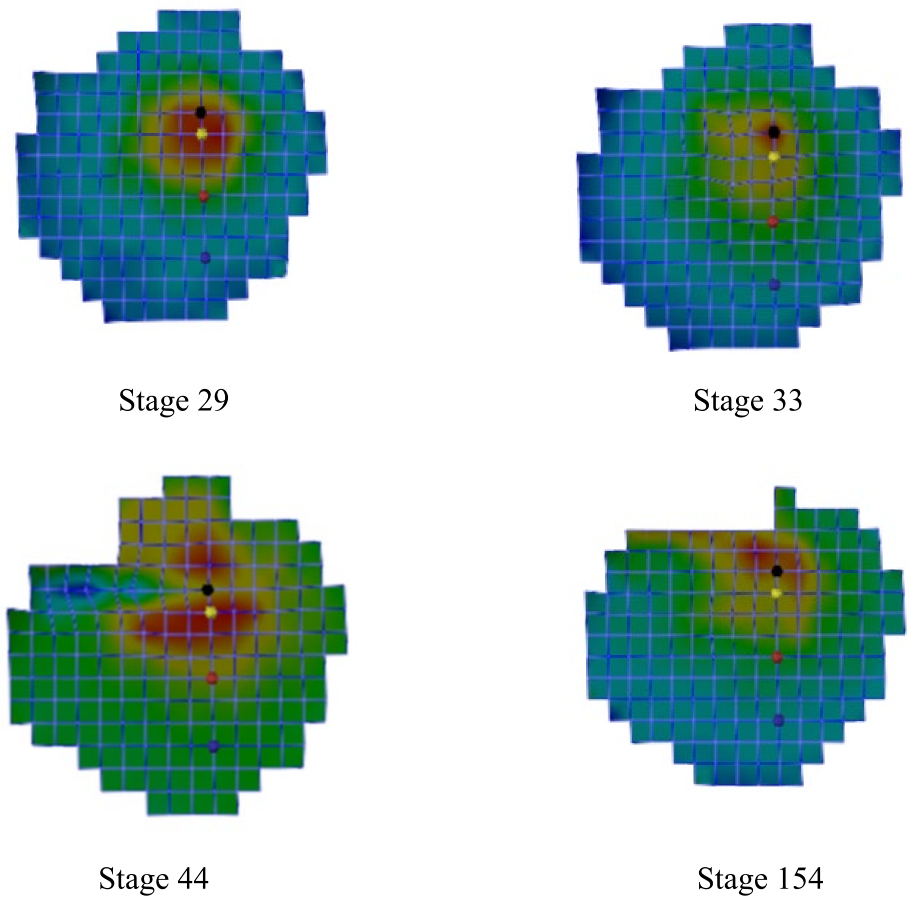


Figure 13. 3D deformation data of Shield Strad S®/epoxy based 2.5 mm thick specimen impacted at velocity of 114.4 m/s with sharp nose projectile.

Finally, the ballistic limit of the composite materials was predicted by using the Reid and Wen model was used [11]. Table 1 shows the comparison between the theoretical prediction offered by this model and the experimental ballistic limit velocities for the thermosetting and thermoplastic-based composites. Looking at the results for 2.5 mm thick specimens, the theoretical results were in close agreement with the experimental results for both the projectiles. For the Twintex® based 4.5 mm thick specimens, the experimental ballistic limit velocity was lower compared with the theoretical ballistic limit velocity for both the projectiles whereas for Shield Strand S®/epoxy 4.5 mm thick specimens the results are closer for both the projectiles suggesting the presence of different energy absorbing and failure mechanisms.

Table 1. The comparison between the experimental and predicted ballistic limit velocities (using Reid and Wen model) for Shield Strand S®/Epoxy and E Glass fiber/Polypropylene Composites

Composite and Projectile	Experimental Ballistic limit Velocity (m/s)	Theoritical Ballistic limit Velocity (m/s)
Twintex 2.5 mm Thickness with Spherical head projectile	93.8	96.348
Twintex 4.5 mm Thickness with Spherical head projectile	111.23	131.84
Twintex 2.5 mm Thickness with Sharp nose projectile	92.1	97.696
Twintex 4.5 mm Thickness with Sharp nose projectile	99.35	134.284
Shield Strand S/ Epoxy 2.5 mm Thickness with Spherical head projectile	118.5	120.858
Shield Strand S/ Epoxy 4.5 mm Thickness with Spherical head projectile	164.5	170.252
Shield Strand S/ Epoxy 2.5 mm Thickness with Sharp nose projectile	125.1	125.107
Shield Strand S/ Epoxy 4.5 mm Thickness with Sharp nose projectile	173.4	168.047

4. CONCLUSIONS

In this paper, the high velocity impact properties of polypropylene and epoxy based fiber reinforced composites were investigated using a single stage gas-gun system with spherical head and sharp nose projectiles. The composite materials were tested at different impact velocities until the ballistic limit was achieved. High speed cameras were used to determine the 3D displacements and maximum transient out-of-plane displacements. Experimental results revealed that the thermoset-based composites possess more impact resistance compared to the thermoplastic composites. Furthermore, the strain evolution and localization was revealed by the DIC system used. Finally, a numerical model was successfully used to predict the ballistic limit of the woven composites studied in this project.

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