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Low Velocity Impact Behaviour of Corrugated Foam Sandwich Panel

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Abstract

Composite sandwich structures, renowned for their high flexural stiffness and low weight, are widely used across industries such as aerospace, automotive, and marine. However, their durability can be compromised by impact-related damages, which affect both the core and face sheets. This study explores the performance of corrugated sandwich panels compared to conventional designs under low-velocity impacts. Using a drop weight impact testing machine, panels made from polyurethane foam cores and various fibre face sheets (Glass, Kevlar, Carbon) were tested at energies ranging from 15 to 45 Joules. Results indicated that corrugated panels exhibited significantly higher peak forces and energy absorption capacities than conventional counterparts, especially in Kevlar and carbon configurations. For instance, the corrugated Kevlar panel reached peak forces exceeding 3000 N at lower energy levels, while the conventional variant peaked at around 1000 N. Similar trends were observed in glass and carbon panels, with corrugated designs consistently outperforming in impact resistance. These findings underscore the potential for enhanced structural performance and sustainability through the adoption of corrugated core designs in composite sandwich constructions, suggesting a promising direction for future material innovation in engineering applications.

Keywords: Impact; sandwich panels; ballistic limit; glass; kevlar; carbon

INTRODUCTION

Composite sandwich structures offer numerous advantages, such as high flexural stiffness, low weight, and the flexibility to choose from a broad range of materials. Nevertheless, many of these advantages could be offset by damage to these buildings. Today, a wide range of industries, including wind turbines, building, consumer goods, automotive, marine, and aerospace, use structural sandwich composites using composite face sheets. Impact events have the potential to cause a variety of structural damages. While the core may sustain damage from shear and crushing forces, the face sheet may experience delamination and fibre breaking. Impact studies must therefore comprehend the level of deformation and the damage resulting from an impact event, which has been widely reviewed in the literature [1, 2, 3, 4] said that metal sandwich panel with a corrugated core possesses higher impact resistance compared to a monolithic solid plate of the same mass. [5] said that Corrugated sandwich panels are a new type of structure composed of two face sheets and a cell core. They are commonly used as a substitute for traditional metal components due to their lightweight nature. These panels offer numerous benefits including low construction cost, high specific strength, effective sound insulation, high energy absorption efficiency, and strong impact resistance. According to [6], the performance of sandwich panels under low-velocity

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local impact is significantly influenced by the fracture stress and fracture strain of the core material. Sandwich panels with cores made of stainless steel are the most capable of absorbing energy and supporting heavy loads. A corrugated sheet sandwiched between two thin skins is the usual construction of a corrugated-core sandwich panel, according to [7] ,with similar observations reported for foam-filled honeycomb structures [8], bending predictions [9], and morphing-aircraft applications [10].

The great strength-to-weight ratio of this kind of structure is well known. The corrugated core resists vertical forces to support the component and keeps the skin apart. Because of its tremendous shear strength, this supports the component and keeps the skins apart. Because of its tremendous shear strength, this design enables the entire structure to function as a single thick plate. Research has shown that corrugated cores offer shear strengths that are comparable with square honeycombs and significantly greater than those exhibited by diamond cores and more traditional foam cores when tested in the longitudinal direction.[11] Said that Sandwich structures are commonly made using honeycomb core and polymeric foam materials, which can trap air and humidity. Moisture retention is a major issue in aircraft sandwich construction as it can cause the weight of the construction to increase and degrade the core properties. To address this, an open channel core material such as a two-dimensional prismatic core can be used to prevent moisture accumulation. Additionally, using corrugated core as a replacement core design can make sandwich construction more sustainable

EXPERIMENTAL PROCEDURE

Specifications of Glass, Kevlar and Carbon fibre Cloths

Glass fibre cloth is primarily composed of silica (SiO2) along with other oxides, and comes in two main types: E-glass, which offers good strength and electrical insulation, and S-glass, which provides higher strength and temperature resistance. It has a density of 2.5-2.6 g/cm^3, a tensile strength ranging from 3.5 to 4.5 GPa, and a Young's modulus of 70-75 GPa. With an elongation at break of 4.8%-5%, thermal conductivity of approximately 1 W/m·K, and an operating temperature range from -73°C to +650°C, glass fibre cloth is commonly used in composites, automotive components, construction materials, and marine applications.

Kevlar fibre cloth, made from aramid fibres (aromatic polyamide), is available in several types, including Kevlar 29 for body armor, ropes, and cables; Kevlar 49 for aerospace and marine composites; and Kevlar 149, which offers higher modulus and better thermal properties. Kevlar has a density of around 1.44 g/cm^3, a tensile strength of 2.7-3.6 GPa, and a Young's modulus of 70-112 GPa. It features an elongation at break of 2.5%-4.4%, low thermal conductivity of about 0.04 W/m·K, and operates within a temperature range of -196°C to +160°C, decomposing at around 500°C. Notably, Kevlar is self-extinguishing and is used in applications like body armor, helmets, protective clothing, and in aerospace and automotive composites.

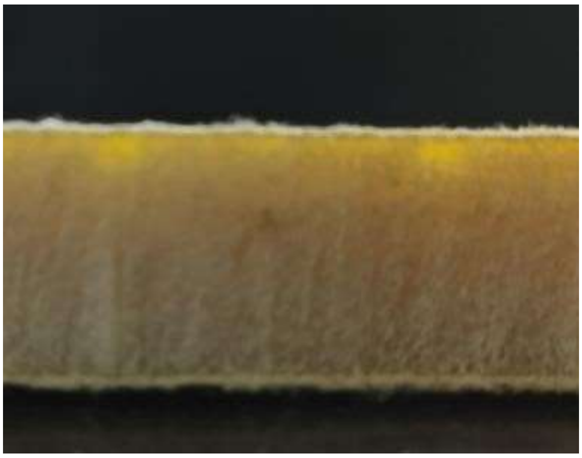
Carbon fibre cloth, produced by pyrolyzing polyacrylonitrile (PAN) or pitch, is categorized into standard modulus for industrial and recreational uses, intermediate modulus for aerospace and high-performance automotive sectors, and high modulus for precision instruments, aerospace, and space applications. Carbon fibre has a density of 1.75-1.95 g/cm^3, a tensile strength ranging from 3.5 to 7.0 GPa, and a Young's modulus between 230 and 600 GPa, with an elongation at break of 1.5%-2.0%. Its thermal conductivity varies significantly from 20 to 1000 W/m·K depending on the type and direction, and it can withstand temperatures up to 3000°C in inert environments, though it oxidizes at high temperatures in air. Carbon fibre cloth is widely used in aerospace, sports equipment, automotive components, civil engineering, and high-performance composites.

Material Selection and Specimen Fabrication

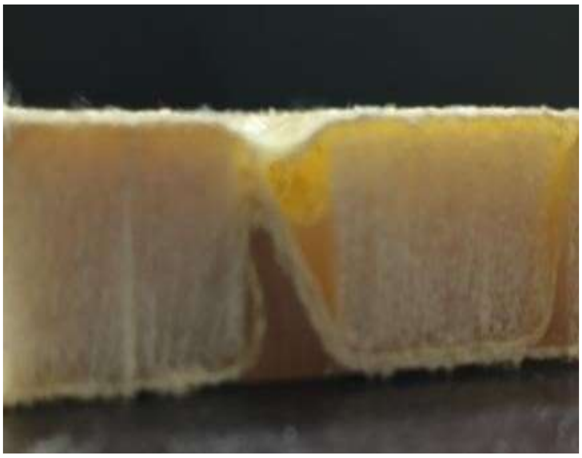
The core material Selected for this study was Polyurethane ‘H’ grade foam core (density = 80 kg/m3, thickness = 10 mm). Foams and honeycomb are among the most commonly used core materials. Foam cores are preferred for their waterproof, soundproof, and heat-insulating properties. Additionally, foam cores are the most cost-effective among core materials and offer several benefits in sandwich manufacturing. This foam core was selected for its superior fatigue and impact resistance, damage tolerance, lightweight properties, and excellent cost-effectiveness. Glass fibre, Kevlar fibre, and Carbon fibre cloths are used as face sheets.

Foam core is Sandwiched between two layers of glass fibre, Kevlar fibre, and carbon The fibre on each side. This fabrication process has used a hand stitching approach in addition to using Glass Yarn G37 1/5 3.8S for stitching, which uses a modified lock stitch method with an adjustable 10mm step in the new configuration. Figure 1 illustrates how the sandwich panels were made at the Hindustan Institute of Technology and Science in Chennai, India, utilizing the vacuum infusion method following stitching, which aligns with earlier comparative studies on infusion, bagging, and hand lay-up processes [3] and experimental/numerical validations of resin infusion in thin-walled composites [12]. The panels were made with a low-viscosity epoxy resin that was derived from bisphenol A and was altered with hardener C2693 and Araldite GY257, an aromatic glycidyl ether. The weight ratios of the hardener and resin were combined at 100:45, respectively. The producer supplied information about the characteristics of the glass yarn, foam, resin, and hardener. Following mixing, the specimens were allowed to cure for 24 hours before being removed. The cross-sectional configurations of conventional and corrugated Kevlar, carbon, and glass sandwich panels are shown in Figure 2.

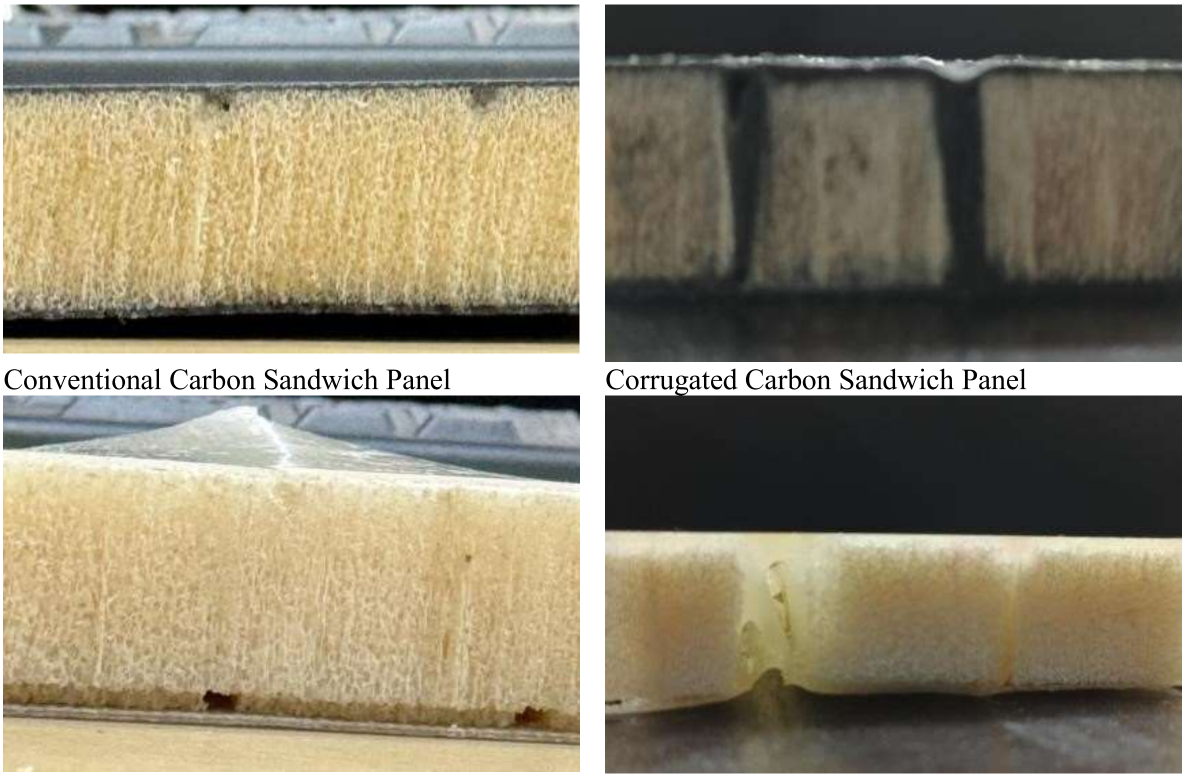
Figure 1. Vacuum Infusion Process.



Conventional Kevlar Sandwich Panel



Corrugated Kevlar Sandwich Panel



Conventional Carbon Sandwich Panel | Corrugated Carbon Sandwich Panel

Conventional Glass sandwich panel | Corrugated Glass Sandwich Panel

Figure 2. Cross-sectional view of sandwich panels.

Water Jet Cutting

Waterjet cutting systems typically operate at pressures between 50,000 to 60,000 PSI, with high-performance options capable of reaching up to 90,000 PSI for thicker or more challenging materials. Garnet is the most commonly used abrasive, with mesh sizes ranging from 80 to 120, selected based on the required precision and cutting speed. Nozzle diameters usually fall between 0.010 and 0.015 inches, where smaller nozzles produce finer cuts at slower speeds, while larger nozzles enable faster cutting with a wider kerf. Cutting speeds vary depending on material thickness, typically ranging from 10 to 500 inches per minute. The kerf width is usually between 0.04 to 0.06 inches, with tolerances as tight as ±0.005 inches. Water flow rates generally range from 0.5 to 1.5 gallons per minute, adjusted according to nozzle size and pressure, with higher flow rates used for cutting thicker or harder materials to maintain efficiency. These systems can cut materials up to 12 inches thick, though thicker materials may require multiple passes or reduced speeds.

Cutting composite materials with conventional tools can be challenging due to their rigidity and difficulty in machining. Waterjet cutting has gained popularity for composites because of its superior performance. This high-precision technology uses a high-pressure water jet, often enhanced with a fine abrasive, to efficiently cut through composite materials. The water jet is precisely directed at the material, with adjustable pressure and diameter tailored to specific requirements. CNC-controlled cutting systems provide high accuracy and repeatability, ensuring precision and quality, particularly in cutting plastics. Modern waterjet systems from STM offer extensive fine-tuning options, making them ideal for processing a wide range of materials, including metals, alloys, stone, wood, glass, composites, ceramics, and more. Waterjet cutters can handle composite blocks up to 12 inches thick, with no minimum thickness requirement for sheets. This versatility and precision make waterjet cutting a preferred method for slicing composites, especially where other techniques are limited to thicker materials. For cutting harder materials, abrasives are added to the water, transitioning the process to abrasive waterjet cutting, which erodes material at supersonic speeds with extreme precision.

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Low Velocity Impact Tests

The impact test was carried out using a Fractovis Plus Drop Weight Impact Testing Machine that was equipped with a data gathering system and a pneumatic clamping fixture (according to ASTM D 5628 FD standards). For all testing, a steel hemispherical impactor weighing 3.926 kg and measuring 12.7 mm in diameter was used. Samples measuring 60 mm by 60 mm were positioned in between the pneumatic clamps, as illustrated in Figure 3.

Circular clamping heights that were modified in accordance with the intended impact energy levels depicted in Figure 3 were made possible by the specimen support fixture at the base of the drop tower. Drop heights of 390, 519, 649, 779, 909, 1039, and 1169 mm were correlated with impact energy of 15, 20, 25, 30, 35, 40, and 45 J, respectively. In addition, force-time graphs were recorded for every sample. The samples' damage trend was indicated by peak load, energy absorbed, total duration, and load declines in the plot.

Figure 3. Impact test Facilities (a) Outer view of the Low velocity impact test facility, (b) Inner view of the Low velocity impact test facility and (c) Specimen on the steel hemispherical impactor.

RESULTS AND DISCUSSION

The Load vs time graph at 15J of conventional and corrugated Kevlar sandwich panel is shown in Figure 4, the line depicting conventional Kevlar sandwich shows a sharp peak early on, reaching just above 1000 N, then it drops quickly and fluctuates around a lower force value before gradually tapering off towards the end of the graph. The Corrugated Kevlar exhibits a much higher peak force, reaching over 3000 N. After this peak, the force drops sharply and then shows a smaller secondary peak before gradually decreasing over time.

The Load vs time graph of 20J of conventional and corrugated Kevlar sandwich panel is shown in Figure 5, the Conventional Kevlar line shows a peak early on, reaching just above 1000 N, then it drops and exhibits a series of fluctuations before gradually tapering off towards the end of the graph. The Corrugated Kevlar line starts with a higher peak load, reaching approximately 2500 N. After this peak, the force drops and then shows a series of fluctuations, with a notable secondary peak before gradually decreasing over time.

The Load vs time graph of 25J of conventional and corrugated Kevlar sandwich panel is shown in Figure 6, Both lines start at 0 ms with a force close to 0 N. As time progresses, both lines show an increase in force, with the Corrugated Kevlar line reaching a higher peak force than the Conventional Kevlar. The peak force for Corrugated Kevlar appears to be just above 3000 N, occurring at approximately 4 ms. The Conventional Kevlar reaches its peak force slightly later and at a lower value, around 2000 N. After reaching their respective peaks, both lines show a decrease in force. The Corrugated Kevlar line decreases sharply and then fluctuates before gradually declining, while the Conventional Kevlar line shows a more gradual and steady decline.

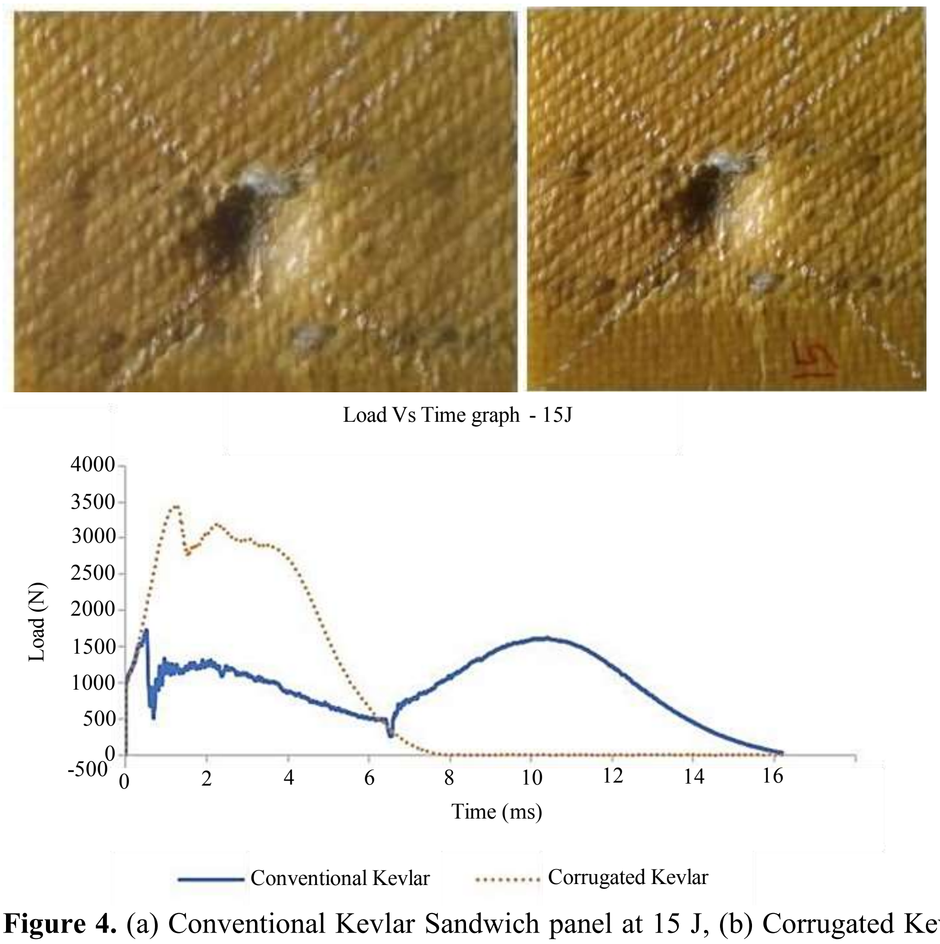

Figure 4. (a) Conventional Kevlar Sandwich panel at 15 J, (b) Corrugated Kevlar sandwich panel at 15J and (c) Load Vs time graph at 15 J of conventional and corrugated Kevlar Sandwich panel.

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The Load vs time graph of 30J of conventional and corrugated Kevlar sandwich panel is shown in Figure 7, Both lines start at 0 ms with a force close to 0 N. As time progresses, both lines show an increase in force, with the Corrugated Kevlar line reaching a higher peak force than the Conventional Kevlar. The peak force for Corrugated Kevlar appears to be just above 3000 N, occurring at approximately 4 ms. The Conventional Kevlar reaches its peak force slightly later and at a lower value, around 2000 N.After reaching their respective peaks, both lines show a decrease in force. The Corrugated Kevlar line decreases sharply and then fluctuates before gradually declining, while the Conventional Kevlar line shows a more gradual and steady decline.

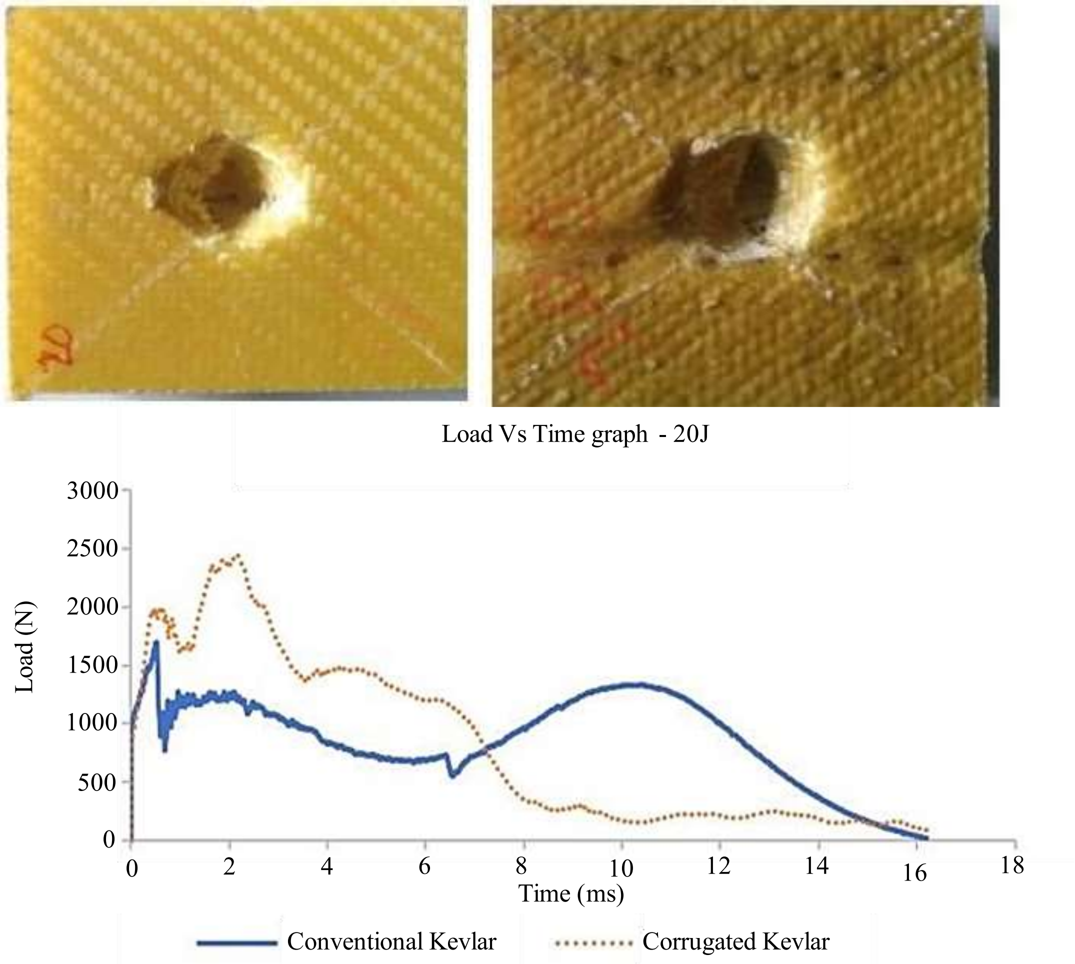
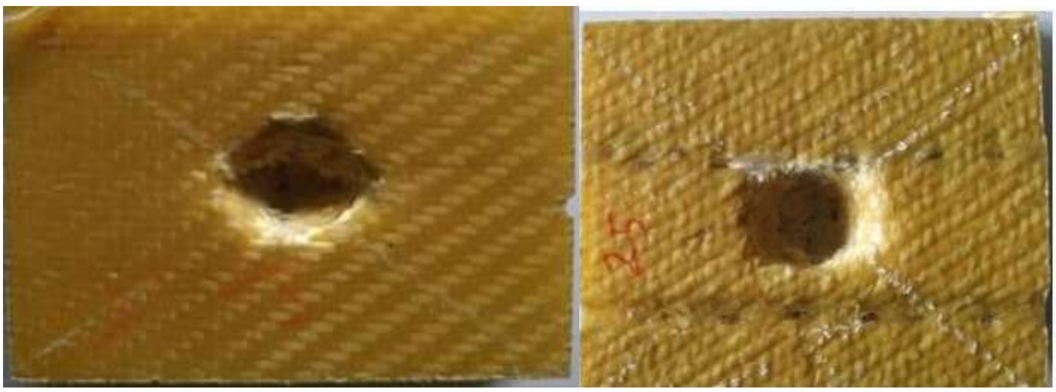


Figure 5. (a) Conventional Kevlar Sandwich panel at 20J, (b) Corrugated Kevlar sandwich panel at 20J and (c) Load Vs time graph at 20 J of conventional and corrugated Kevlar sandwich panel**.**



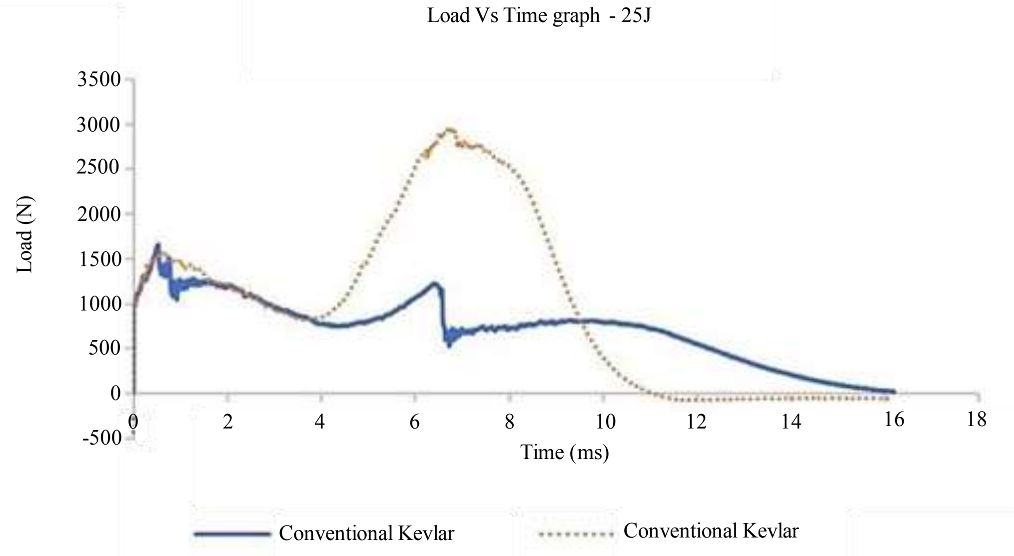


Figure 6. (a) Conventional Kevlar Sandwich panel at 25J, (b) Corrugated Kevlar sandwich panel at 25J and (c) Load Vs time graph at 25 J of conventional and corrugated Kevlar sandwich panel**.**

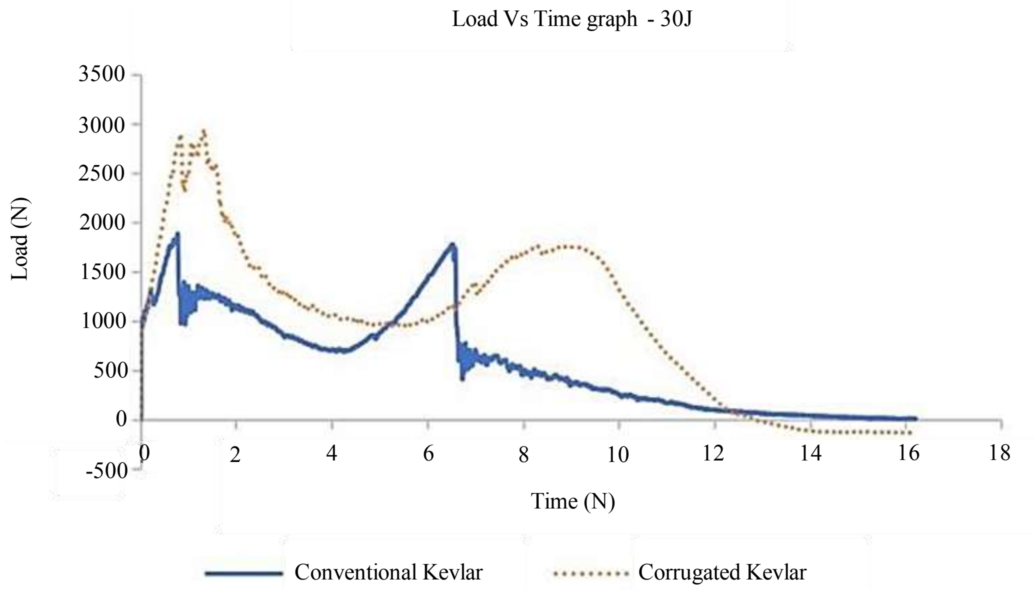


Figure 7. (a) Conventional Kevlar Sandwich panel at 30J, (b) Corrugated Kevlar sandwich panel at 30J and (c) Load Vs time graph at 30 J of conventional and corrugated Kevlar sandwich panel

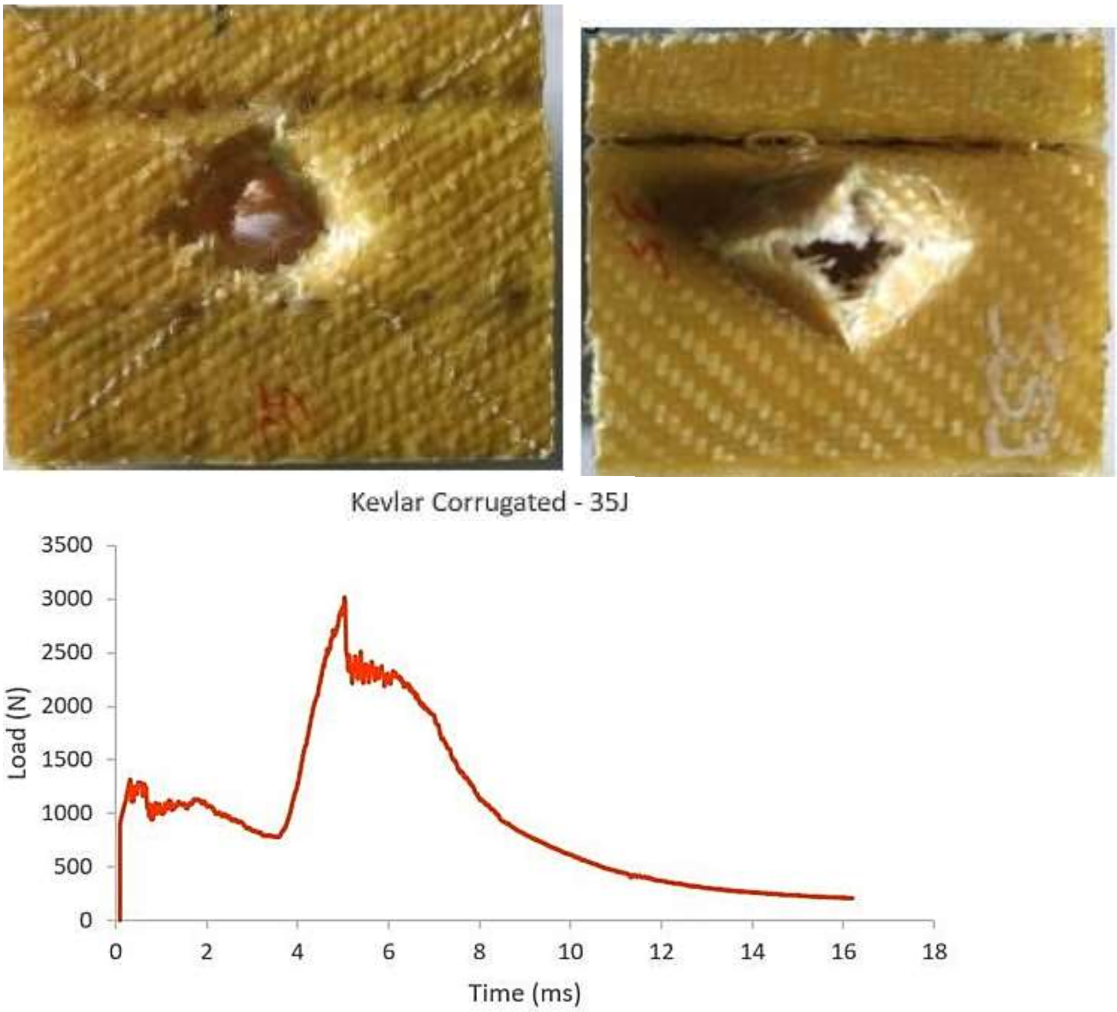


Figure 8. (a) Corrugated Kevlar Sandwich panel at 35J, (b) Back view of Corrugated Kevlar sandwich panel at 35J and (c) Load Vs time graph at 35 J of corrugated Kevlar sandwich panel.

The Load vs time graph of corrugated sandwich is shown in Figure 8, Initially, there is a sharp increase in force, which quickly peaks and then drops. This is followed by a series of smaller fluctuations, with one significant peak that stands out before the force gradually decreases over time. The initial peak and sub-sequent fluctuations represent the dynamic response of the material to the impact, including the absorption and dissipation of energy.

The Load vs time graph of 15J of conventional and corrugated Glass sandwich panel is shown in Figure 9, Corrugated Glass shows a rapid increase in force, peaking at just under 2000 N before sharply dropping to below 0 N (indicating a negative force or pullback), and then it stabilizes around 500 N after some fluctuations. Conventional Glass also shows an increase in force, but it peaks at a lower value of around 1500 N. After the peak, the force drops and then exhibits a smaller secondary peak before gradually declining and stabilizing at a level slightly above 0 N.

The Load vs time graph of 20J of conventional and corrugated Glass sandwich panel is shown in Figure 10, Corrugated Glass shows a rapid increase in force, peaking at around 2000 N before sharply dropping to below 0 N (indicating a negative force or pullback), and then it exhibits a series of fluctuations before gradually declining and approaching a stable level. Conventional Glass also shows an increase in force, peaking at a slightly lower value than the Corrugated Glass, around 1300N.

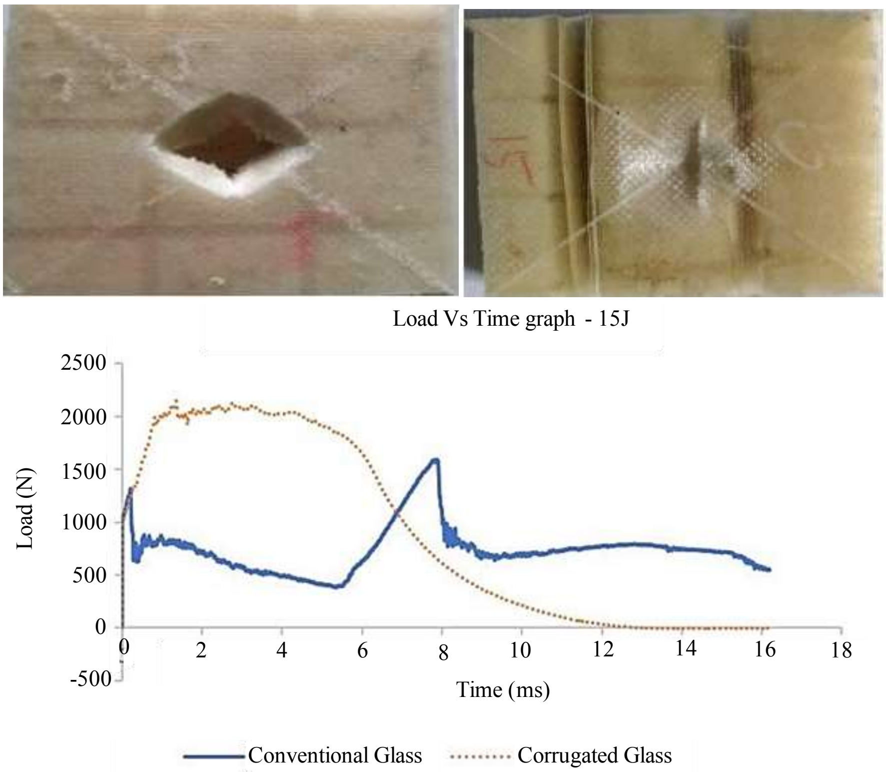


Figure 9. (a) Conventional Glass Sandwich panel at 15J, (b) Corrugated Glass sandwich panel at 15J and (c) Load Vs time graph at 15 J of conventional and corrugated Glass sandwich panel.

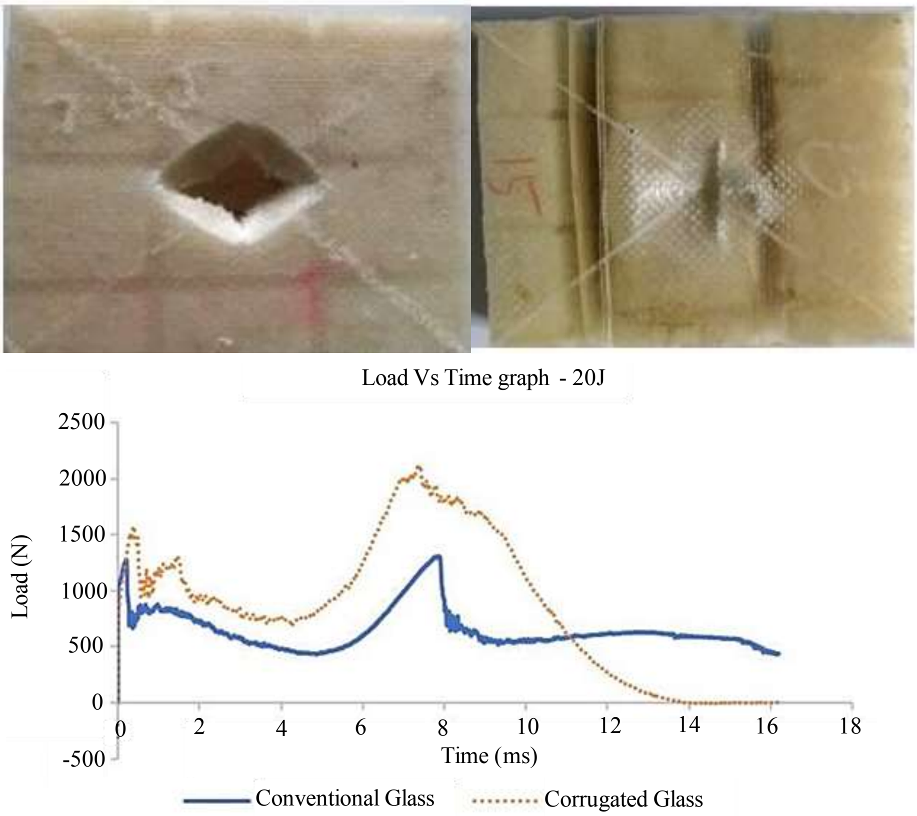


Figure 10. (a) Conventional Glass Sandwich panel at 20J, (b) Corrugated Glass sandwich panel at 20J and (c) Load Vs time graph at 20 J of conventional and corrugated Glass sandwich panel**.**

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The Load vs time graph at 25J of corrugated Glass sandwich panel is shown in Figure 11, The force sharply increases at the beginning, reaching a peak of over 2000 N very quickly (in less than 2 ms), indicating a sudden and strong impact. After the initial peak, the force decreases in a series of smaller peaks and valleys, suggesting oscillations or vibrations in the material as it absorbs the impact. The force then gradually decreases over time, stabilizing around 1000 N before slowly tapering off further as time progresses, ending below 1000 N at around 18 ms.

The load-time curve for glass corrugated under 30J impact is shown in Figure 12. The load increases rapidly to a peak of about 3200N in about 2ms, and then decreases gradually to about 1000N over the next 15ms.

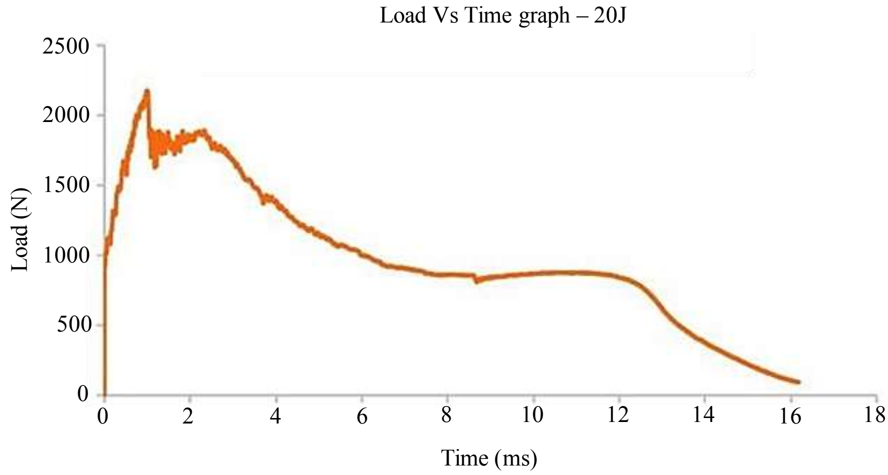


Figure 11. (a) Glass corrugated Sandwich panel at 25 J and (b) Load Vs time graph at 25 J of corrugated Glass sandwich panel**.**

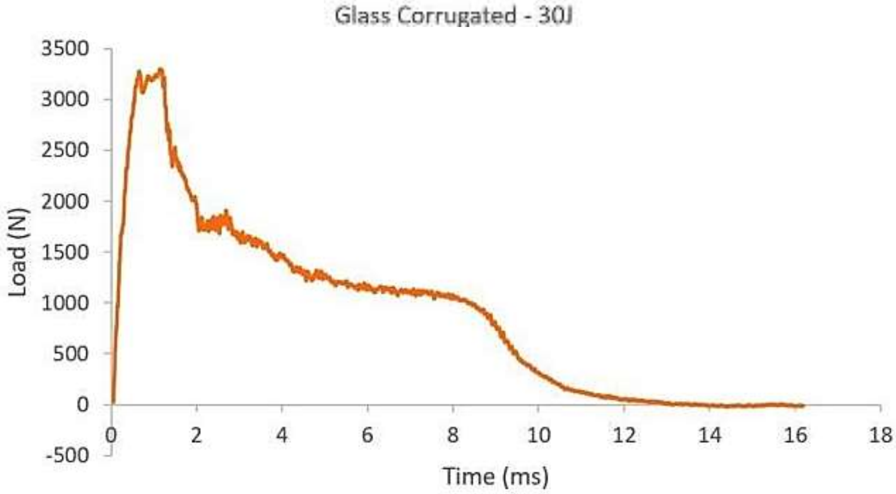


Figure 12. (a) Glass corrugated sandwich panel at 30 J, (b) Back view of the glass corrugated sandwich panel at 30 J and (c) Load Vs time graph of corrugated glass sandwich panel at 30 J.

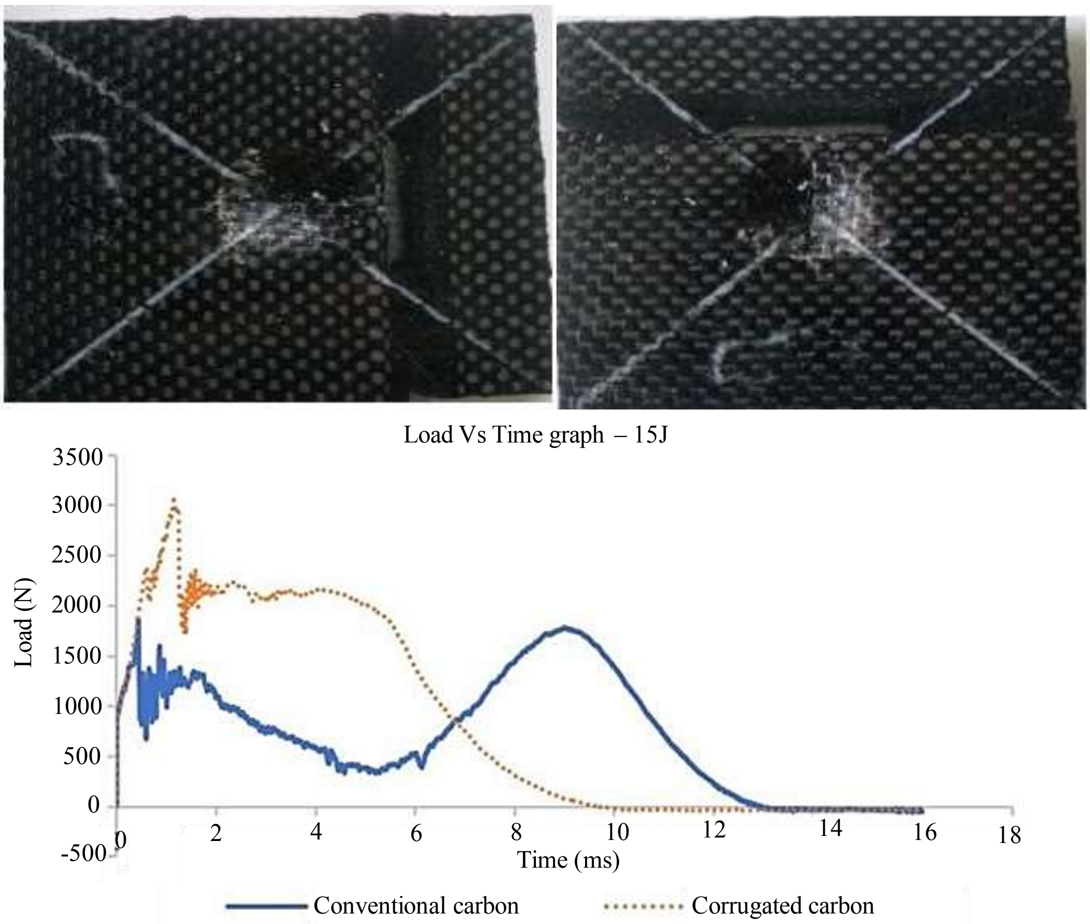


Figure 13. (a) Conventional carbon sandwich panel at 15 J, (b) Corrugated carbon sandwich panel at 15J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 15 J.

The Load vs time graph at 15J of conventional and corrugated carbon sandwich panels is shown in Figure 13, the Conventional Carbon exhibits a sharp peak in force early on, reaching just over 1000 N within the first 2 ms. After this peak, the force quickly drops and then shows a smaller secondary peak before gradually declining and approaching zero force as time approaches 18 ms. The Corrugated

Carbon reaches a higher peak force of over 3000 N very quickly, also within the first 2 ms. After this initial peak, the force decreases but with more pronounced oscillations compared to the conventional carbon. The force then gradually reduces, with the line trending downward and approaching zero force by the end of the graph. The corrugated carbon appears to absorb more energy initially (as indicated by the higher peak force) and exhibits more significant oscillations, which may suggest different damping properties compared to the conventional carbon.

The Load vs time graph at 20J of conventional and corrugated carbon sandwich panels is shown in Figure 14, Conventional Carbon, starts at around 0 N, quickly peaks to just over 1000 N within the first millisecond, and then fluctuates rapidly before gradually rising to a peak of around 1500 N at approximately 8 ms. Corrugated Carbon begins similarly but quickly rises to a much higher peak of nearly 1500 N before 2 ms. After this initial peak, the force decreases sharply, then rises again to a smaller peak of about 2000 N around 8 ms. Following this second peak, the force decreases gradually, approaching 0 N by around 11 ms.

The Load vs time graph at 25J of conventional and corrugated carbon sandwich panels is shown in Figure 15, Conventional Carbon starts at around 0 N, quickly peaks to just over 1500 N within the first millisecond, and then exhibits a series of fluctuations and another peak near 1500N gradually descending to approach 0 N by around 16 ms. Corrugated Carbon starts at around 0 N and shows a sharp peak reaching nearly 3000 N before 8 ms. Following this, the force gradually decreases, as it approaches 0 N by around 11 ms.

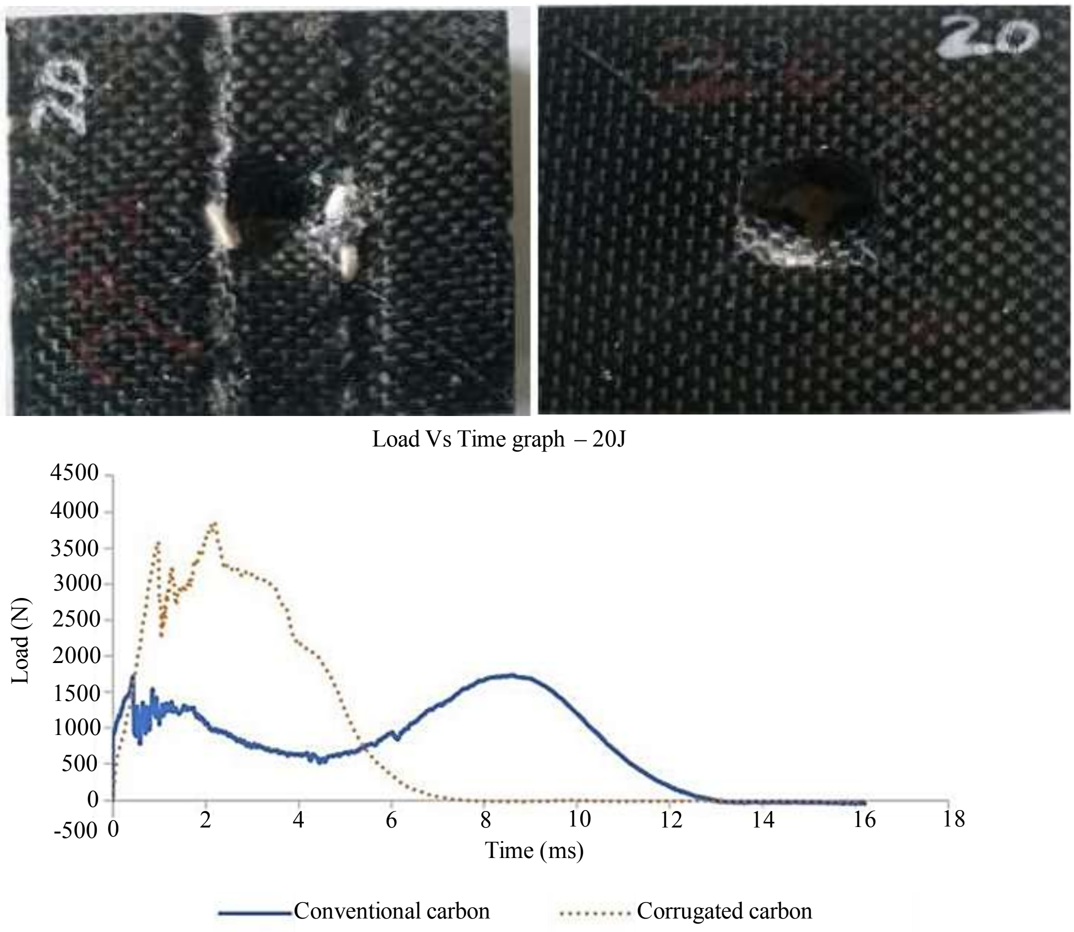


Figure 14. (a) Conventional carbon sandwich panel at 20 J, (b) Corrugated carbon sandwich panel at 20J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 20 J.

The Load vs time graph at 30J of conventional and corrugated sandwich panels is shown in Figure 16, Conventional Carbon starts at around 0 N, quickly peaks to just over 1500 N within the first millisecond, and then exhibits a series of fluctuations. The line peaks again at around 3000 N near 8 ms before gradually descending to approach 0 N by around 11 ms. Corrugated carbon also starts at around 0 N and shows a sharp peak reaching nearly 3000 N before 2 ms. After this peak, the force drops and then exhibits around 2000 N near 4 ms. Following this, the force gradually decreases, aligning closely with the Conventional carbon as it approaches 0 N by around 12 ms.

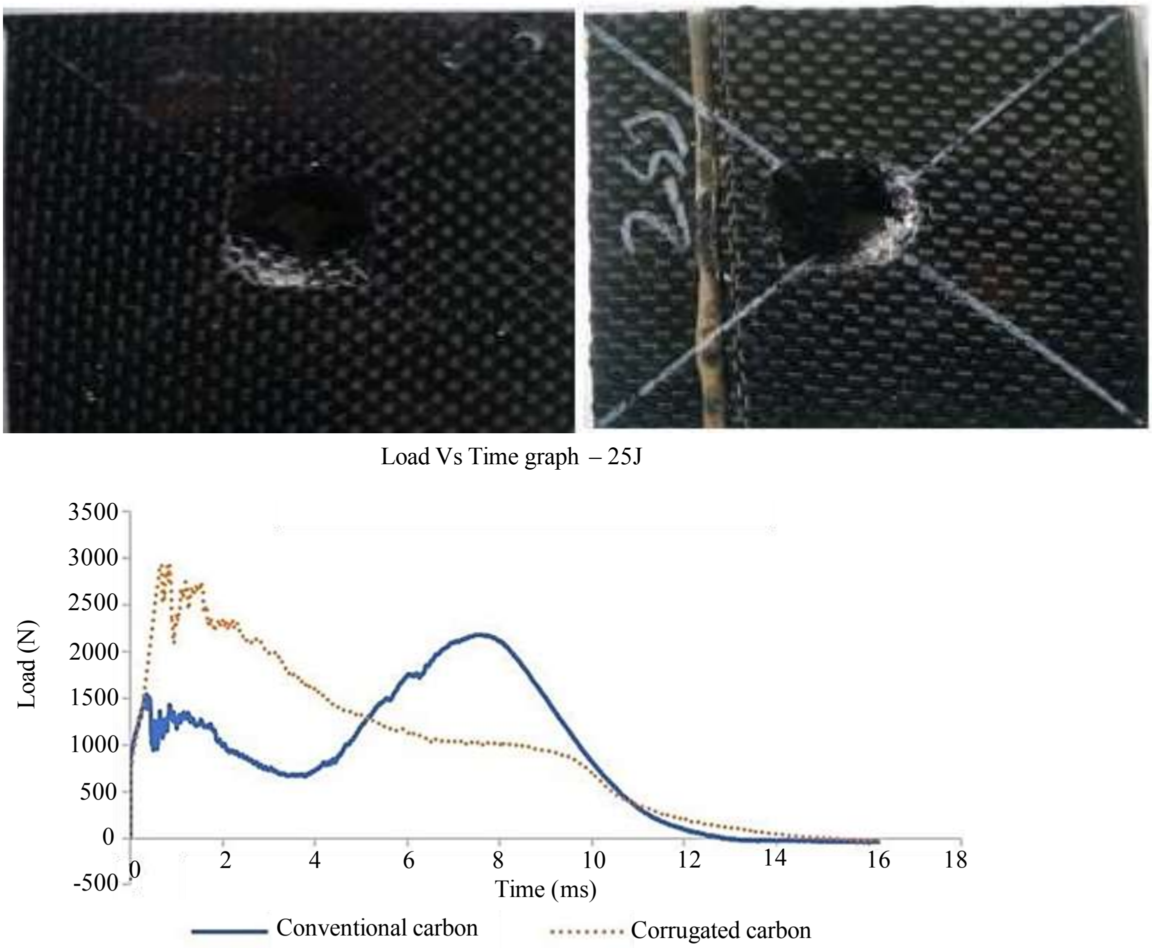
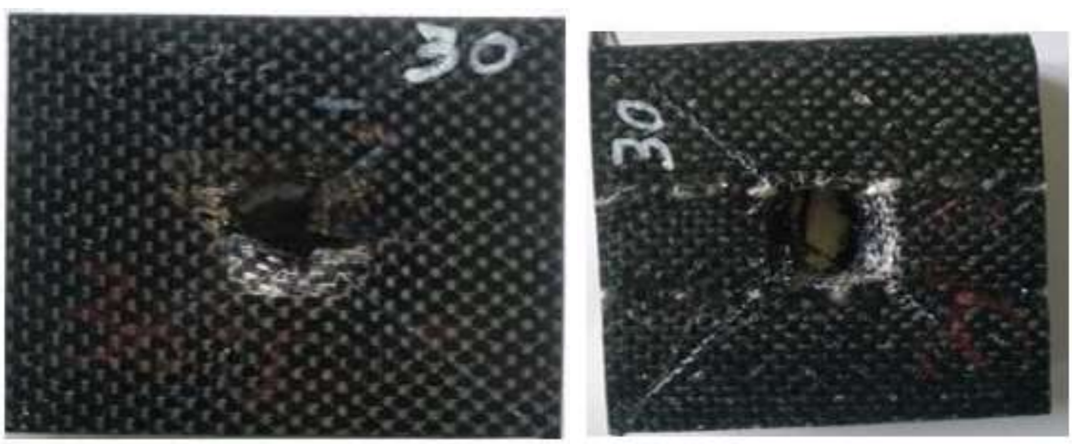


Figure 15. (a) Conventional carbon sandwich panel at 25J, (b) Corrugated carbon sandwich panel at 25J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 25 J.



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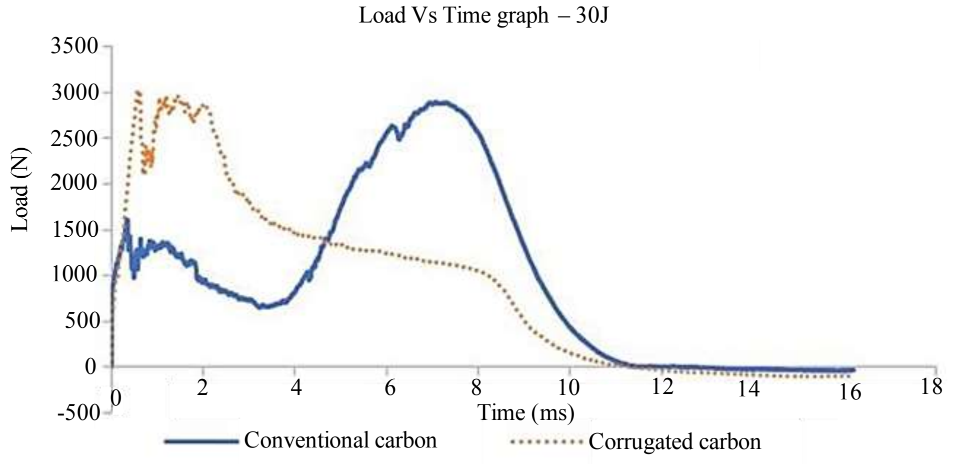

Figure 16. (a) Conventional carbon sandwich panel at 30 J, (b) Corrugated carbon sandwich panel at 30J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 30 J.

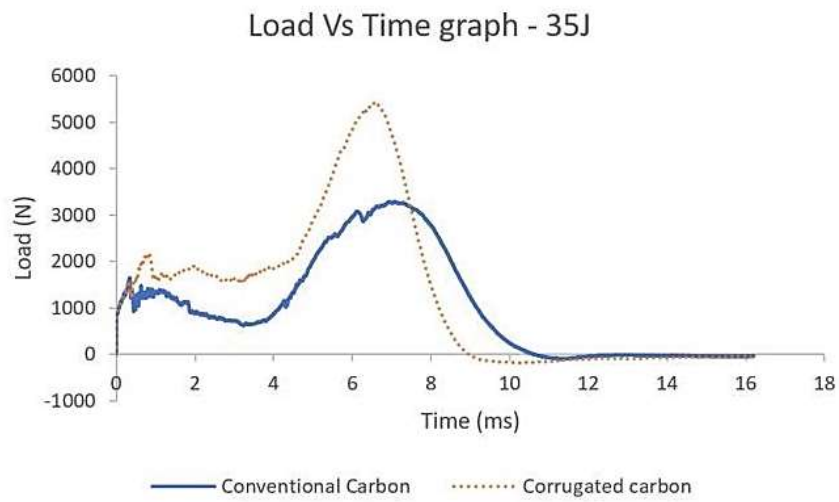

Figure 17. (a) Conventional carbon sandwich panel at 35 J, (b) Corrugated carbon sandwich panel at 35J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 35 J.

The Load vs time graph at 35J of conventional and corrugated carbon sandwich panels is shown in Figure 17, Both lines show a similar pattern with some fluctuations at the beginning, a sharp peak, and then a de-cline back to near zero. The peak for the Corrugated Carbon is slightly higher than that of the Conventional Carbon, indicating that at its maximum, the corrugated carbon withstood a higher force.

The peak force for the Corrugated Carbon appears to be just over 5000 N, while for the Conventional Car-bon it is slightly below 3000 N. The time at which the peak force occurs is around 8 ms for both materials. After reaching the peak, the force rapidly decreases for both materials, returning close to zero by approximately 12 ms.

The Load vs time graph at 40J of corrugated carbon sandwich panel is shown in Figure 18, the force initially spikes sharply, reaching a peak of just over 3000 N very quickly, within approximately 1 ms. After this initial peak, the force drops significantly and then exhibits a series of smaller fluctuations or oscillations, with the force values going up and down but generally decreasing over time. These fluctuations gradually diminish in magnitude as the force stabilizes around 1000 N by approximately 6 ms. From this point, the force continues to decrease more smoothly and steadily, reaching close to 500 N by around 16 ms.

The load-time curve of a carbon corrugated sample is shown in Figure 19. The sample was loaded to 45J. The load increased rapidly at first, then reached a peak, and finally decreased. The sample failed at 18 ms. The contact force can alternatively be described as the responsive force exerted by the specimen onto the impactor As previously mentioned, data acquisition systems were utilized to obtain the Force-time (F-t) curves.

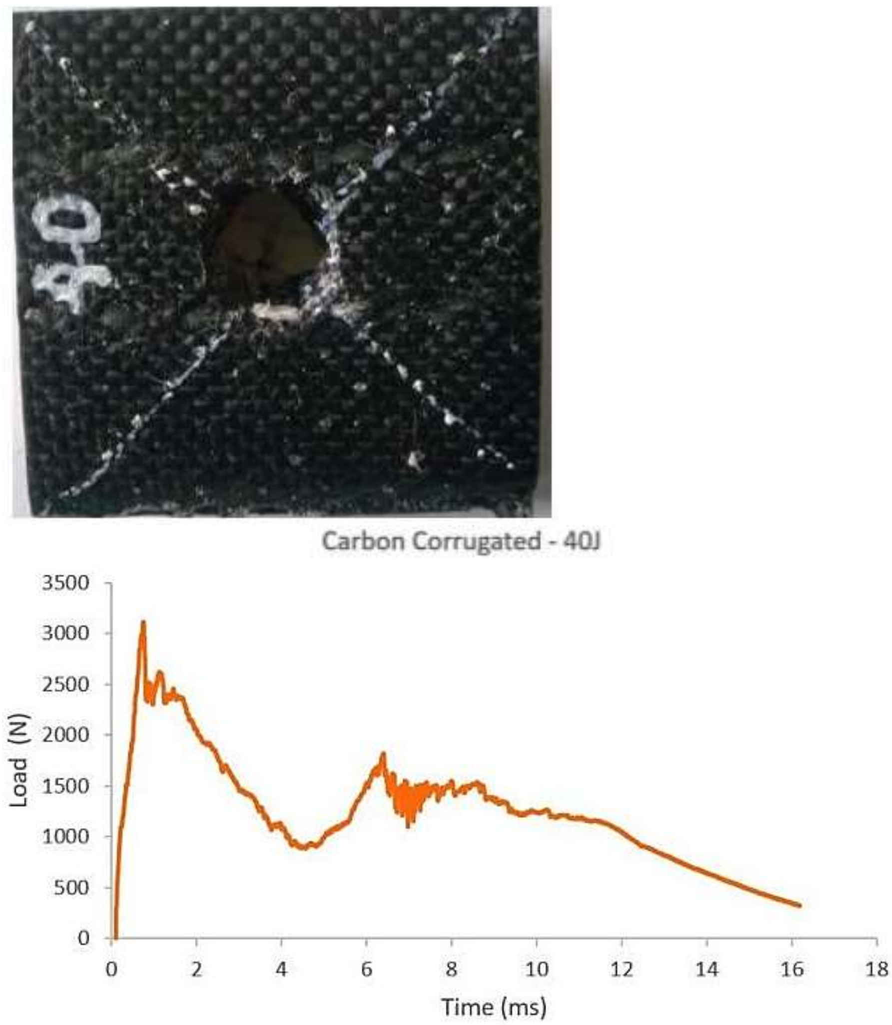

Figure 18. (a) Corrugated carbon sandwich panel at 40J and (b) Load Vs time graph of corrugated carbon sandwich panel at 40 J.

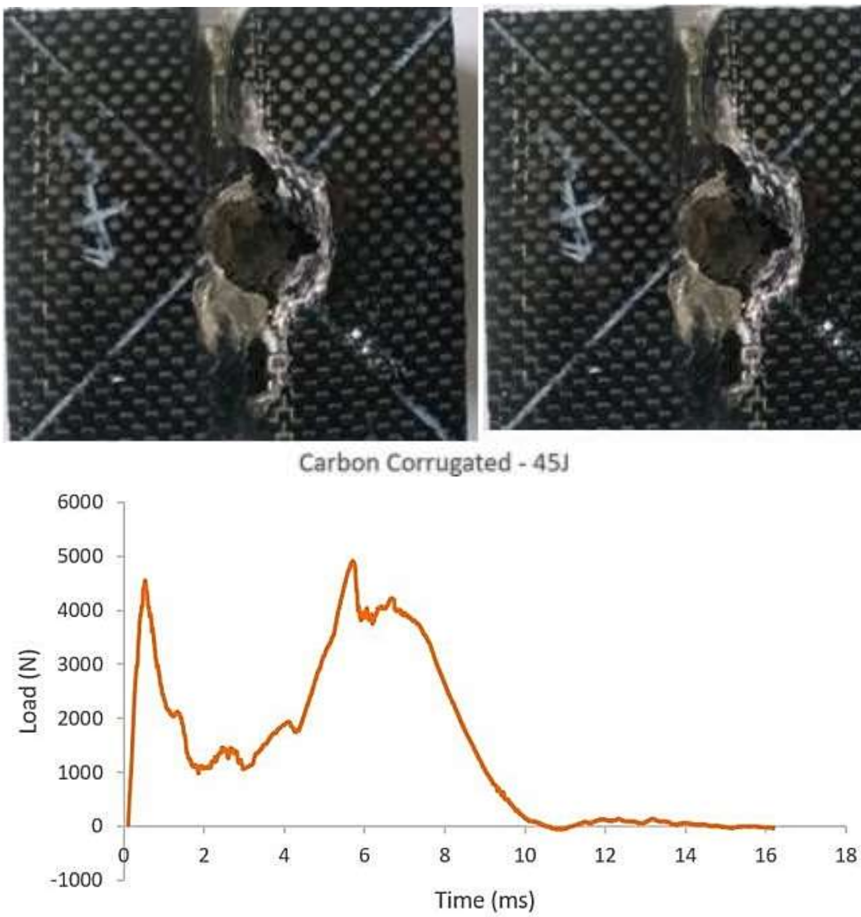

Figure 19. (a) Corrugated carbon sandwich panel at 45J, (b) Back side view of corrugated sandwich panel at 45J and (c) Load Vs time graph of conventional and corrugated carbon sandwich panel at 45 J.

Figures 4 to 19 show the force-time plot and the picture of the impact surface of Conventional Sandwich Panels and Corrugated Sandwich Panels at different impact energies (15 ~ 45J) The corresponding ballistic limits and peak load capacities are summarised in Table 1, where corrugated designs consistently exhibit higher resistance across all face sheet materials.

Three separate regions can be identified and interpreted from the sandwich panel's typical contact load-time (L-t) graph: a primary peak, followed by a plateau zone, and a secondary peak. The load-time (L-t) graph's primary apex depicts the perforation of the impacted side face sheet, while the secondary peak shows the perforation of the secondary face sheet, which leads to the sandwich panels' complete perforation. The plateau region with the gradual force increase corresponds to the core crushing process. For the higher energy impacts, a visual assessment was conducted; these zones were less distinct for the lower energy impacts.

Conventional Vs Corrugated Kevlar Sandwich panels

The load–time responses of Kevlar sandwich panels under different impact energies are presented in Figures 4–7. At 15 J (Figure 4), the corrugated Kevlar panel shows a much higher peak force (over 3000 N) compared to the conventional panel (just above 1000 N) and also exhibits a smaller secondary peak. At 20 J (Figure 5), a similar trend is observed, with the corrugated Kevlar panel reaching approximately 2500 N, while the conventional panel peaks at just above 1000 N; both exhibit fluctuations after the peak. At 25 J (Figure 6), both configurations show a force increase from 0 N, but the corrugated Kevlar reaches a higher peak (just above 3000 N) compared to the conventional Kevlar (~2000 N). After their respective peaks, the corrugated panel decreases sharply with fluctuations, while the conventional panel declines more gradually. At 30 J (Figure 7), the corrugated Kevlar again reaches a peak slightly above 3000 N, whereas the conventional panel peaks around 2000 N, with the latter showing a steadier decline after peak. The response at 35 J is shown in Figure 8, where the corrugated Kevlar panel displays an initial sharp increase, followed by smaller fluctuations and a significant peak, before gradually decreasing over time, representing the material's dynamic response to impact and energy absorption. A summary of the Kevlar results is provided in Table 2, which highlights the sharper fluctuations and higher force absorption of the corrugated configuration From this we can say that Corrugated Kevlar withstands higher peak forces but exhibits more variability after the peak compared to Conventional Kevlar, consistent with previous work on corrugated and stitched sandwich configurations [7, 13, 14]. The ballistic limit is reached at a higher energy level (35J) for corrugated Kevlar sandwich panels compared to conventional ones (30J).

Table 1. Ballistic Limit of Sandwich Panels.

Peak Load Carrying Capacity of Panels						
Energy Level (J)	**Glass Conventional (N)**	**Glass Corrugated (N)**	**Kevlar Conventional (N)**	**Kevlar Corrugated (N)**	**Carbon Conventional (N)**	**Carbon Corrugated (N)**
15	1266.612	2100.812	1659.825	3019.534	1863.475	2937.462
20	**1307.035**	2147.36	1696.574	2436.452	1736.998	3057.508
	(Ballistic limit)					
25	**-**	2175.534	1727.198	2963.186	2179.822	3040.359
30	**-**	**3300.051 (Ballistic limit)**	**1887.668 (Ballistic limit)**	2948.486	2897.038	3115.081
35	**-**	**-**	**-**	**3466.646 (Ballistic limit)**	**3291.782 (Ballistic limit)**	4921.902
40	**-**	**-**	**-**	**-**	**-**	3115.081
45	**-**	**-**	**-**	**-**	**-**	**5408.2132 (Ballistic limit)**

Table 2. Summary table for load washes time graph for conventional and Corrugated Kevlar sandwich panels.

Energy Level (J)	**Material Type**	**Peak Force (N)**	**Force Behavior After Peak**	**Additional Observations**
15J	Conventional Kevlar	~1000	Gradual decline	
	Corrugated Kevlar	>3000	Smaller secondary peak, sharper fluctuations	Higher peak force
20J	Conventional Kevlar	~1000	Fluctuations after peak	
	Corrugated Kevlar	~2500	Fluctuations after peak, sharper decline	Higher peak force
25J	Conventional Kevlar	~2000	Gradual decline	
	Corrugated Kevlar	>3000	Sharper decline, fluctuations	Higher peak force
30J	Conventional Kevlar	~2000	Gradual decline	
	Corrugated Kevlar	>3000	Sharper decline, fluctuations	Higher peak force
35J	Corrugated Kevlar	Significant Peak	Gradual decline	Only corrugated Kevlar data available, ballistic limit reached
Ballistic Limit				Corrugated Kevlar: 35J, Conventional Kevlar: 30J

Conventional Vs Corrugated Glass Sandwich panels

The load–time responses of glass sandwich panels under different impact energies are shown in Figures 9–12. At 15 J (Figure 9), the corrugated glass panel exhibits a rapid force increase, peaking just under 2000 N before sharply dropping below 0 N and stabilizing around 500 N after fluctuations. By contrast, the conventional glass panel peaks at around 1500 N, followed by a smaller secondary peak and a gradual decline that stabilises slightly above 0 N. At 20 J (Figure 10), a similar trend is observed, with the corrugated glass panel peaking near 2000 N and then dropping below 0 N before exhibiting fluctuations and stabilising, while the conventional panel peaks slightly lower at ~1300 N. At 25 J (Figure 11), the corrugated glass panel shows a rapid force rise exceeding 2000 N in less than 2 ms, followed by oscillations and valleys before gradually stabilising around 1000 N. At 30 J (Figure 12), the corrugated configuration reaches its highest resistance, with a peak of about 3200 N, before gradually decreasing to ~1000 N over the next 15 ms. As detailed in Table 3, the ballistic limit for corrugated glass is 30 J, compared to 20 J for the conventional design, indicating the improved energy absorption capability of corrugated cores.

From these results, it can be concluded that corrugated glass panels demonstrate greater peak force resistance but also higher post-peak variability, whereas conventional panels show steadier force decline. The ballistic limit is achieved at a higher energy level (30 J) for corrugated glass sandwich panels compared to 20 J for conventional panels, highlighting the superior energy absorption capacity of corrugated designs.

Conventional Vs Corrugated Carbon Sandwich panels

The load–time responses of carbon sandwich panels at different impact energies are presented in Figures 13–17. At 15 J (Figure 13), the corrugated carbon panel exhibits a rapid increase in force, reaching over 3000 N within the first 2 ms, while the conventional panel peaks at just above 1000 N in the same timeframe. At 20 J (Figure 14), both materials show rapid force increases, but the corrugated carbon panel attains a higher peak of ~1500 N and displays more pronounced oscillations than the conventional panel. At 25 J (Figure 15), the corrugated carbon panel demonstrates a peak of nearly 3000 N before 8 ms, whereas the conventional panel peaks lower at just above 1500 N within the first millisecond. At 30 J (Figure 16), both configurations exhibit sharp peaks; however, the corrugated carbon panel reaches nearly 3000 N before 2 ms, while the conventional variant peaks at ~1500 N in the same period. At 35 J (Figure 17), both materials show similar load–time patterns, though the corrugated carbon panel withstands a much higher peak force (~5000 N) compared to the conventional panel (~3000 N).

Table 3. Summary table for load washes time graph for conventional and Corrugated Glass sandwich panels.

Energy Level (J)	Material Type	Peak Force (N)	Force Behavior After Peak	Additional Observations
15J	Conventional Glass	~1500	Gradual decline, stabilizes slightly above 0 N	Smaller secondary peak, more stable post-peak behavior
	Corrugated Glass	Just under 2000	Sharp drop below 0 N, fluctuations, stabilizes around 500 N	Higher peak force, significant post-peak variability
20J	Conventional Glass	~1300	Gradual decline	Lower peak force, more stable post-peak behavior
	Corrugated Glass	~2000	Sharp drop below 0 N, fluctuations before declining	Higher peak force, significant post-peak variability
25J	Corrugated Glass	>2000	Decreases in smaller peaks and valleys, stabilizes around 1000 N	Quick initial rise (under 2 ms), more pronounced post-peak fluctuations
Ballistic Limit				Corrugated Glass: 30J, Conventional Glass: 20J

Table 4. Summary table for load washes time graph for conventional and Corrugated Carbon sandwich panels.

Energy Level (J)	Material Type	Peak Force (N)	Force Behavior After Peak	Additional Observations
15J	Conventional Carbon	~1000	Rapid increase, stabilizes after initial peak	Lower peak force compared to corrugated
	Corrugated Carbon	>3000	Rapid increase within 2 ms, followed by gradual stabilization	Higher peak force, more pronounced response
20J	Conventional Carbon	~1500	Rapid increase, minor oscillations	Lower peak force, relatively stable post-peak behavior
	Corrugated Carbon	~1500	Rapid increase, more pronounced oscillations	Higher peak force, significant post-peak variability
25J	Conventional Carbon	~1500	Peaks within the first millisecond, followed by gradual decline	Lower peak force, early stabilization
	Corrugated Carbon	~3000	Peaks before 8 ms, followed by fluctuations	Higher peak force, more complex post-peak behavior
30J	Conventional Carbon	~1500	Sharp peak within the first millisecond	Lower peak force, rapid stabilization
	Corrugated Carbon	~3000	Sharp peak before 2 ms, followed by gradual decline	Higher peak force, more pronounced post-peak variability
35J	Conventional Carbon	~3000	Similar pattern, stabilizes after initial peak	Lower peak force compared to corrugated
	Corrugated Carbon	~5000	Higher peak force, followed by gradual decline	Significant post-peak variability, higher peak force
40J	Corrugated Carbon	~3000	Initial spike, followed by gradual decrease, stabilizes around 1000 N by 6 ms	Peak force within first millisecond, followed by stabilization
45J	Corrugated Carbon	>4000	Peaks above 4000 N initially, another peak near 5000 N within 6 ms, then gradual decrease	Higher ballistic limit, significant force spikes observed
Ballistic Limit				Corrugated Carbon: 45J, Conventional Carbon: 35J

The higher-energy impacts are shown in Figures 18 and 19. At 40 J (Figure 18), the corrugated carbon panel initially spikes above 3000 N within ~1 ms, then gradually decreases and stabilises around 1000 N by ~6 ms. At 45 J (Figure 19), the corrugated carbon panel peaks above 4000 N in the first millisecond, followed by another peak near 5000 N at ~6 ms, before gradually decreasing to zero between 10–16 ms.

Overall, corrugated carbon panels consistently withstand higher peak forces across all energy levels when compared to conventional designs. The ballistic limit is reached at 45 J for corrugated carbon sandwich panels, significantly higher than the 35 J limit observed for conventional panels, confirming the superior impact resistance of the corrugated configuration. The ballistic limits, presented in Table 4, show that corrugated carbon panels resist up to 45 J, compared with 35 J for conventional carbon panels, confirming their superior impact resistance.

CONCLUSIONS

With the increase in impact energy, the following characteristics were obtained from the Load vs time graph of conventional and corrugated sandwich panels. The load time graph shows no peak load then first sharp peak load, which usually gives the highest load carrying capacity. Then a low loading plateau which corresponds to the crushing of the core material, then non remarkable peak load and the second sharp peak load which corresponds to the breaking of the bottom facing sheets. The sharp loads on the plots indicate the penetrations. The Corrugated sandwich panels considerably improves the impact properties and load carrying capacities. The Corrugated sandwich panels have more load carrying capacity than the conventional sandwich panels. Corrugated Carbon sandwich panel has the highest load carrying capacity among the other panels. The results show that the ballistic limit of corrugated sandwich panels are 1.5 times or more than the conventional sandwich panels**.**

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