



The effect of preload on the impact behavior of laminated and sandwich composites

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Abstract

The objective of this study is to conduct a comparative analysis of the influence of preload and impact energy levels on the impact response of sandwich composites. Composite laminates were fabricated using carbon woven fibers in a stacking sequence of $[0/90]_6$ and Kevlar woven fibers in a stacking sequence of $[0/90]_4$. Sandwich composites were constructed using the stacking sequences $[(0/90)_3]/PET/[(0/90)_3]$ based carbon fiber and $[(0/90)_2]/PET/[(0/90)_2]$ based Kevlar fiber. The production of sandwich composites was conducted using a vacuum infusion system. The curing process was carried out at a temperature of 80 °C for a duration of 12 h. Subsequently, specimens measuring 150 mm × 150 mm were obtained. The specimens were placed in a specially designed test fixture capable of independent compressive loading along both axes prior to impact loading. Then, impact tests were conducted at three distinct energy levels (10, 20, and 30 J) for cases of biaxial tensile, compressive, and pure shear (tension–compression) (at 250 μ e and zero preload). Experimental measurements were taken to assess the effect of preload on parameters such as permanent deflection depth, absorbed energy, and peak impact loads. The results revealed that the presence and magnitude of preload had a notable impact on penetration/perforation depth, peak load, and absorbed energy during impact loading. It is crucial to note that preload has a beneficial effect on the impact behavior of composite laminates, whereas it has a detrimental effect on the impact behavior of sandwich laminates.

Keywords Low-velocity impact · Preload · Impact behavior · Sandwich composite · PET foam

1 Introduction

In recent years, there has been a growing utilization of sandwich composite structures in various applications of lightweight technology, such as aerospace surfaces, sports equipment, defense systems, and the automotive sector. This surge in adoption can be attributed to the unique characteristics of these structures, which feature high-strength thin face sheets and low-density thick cores. Sandwich composite structures offer numerous advantages over conventional

materials, including superior strength-to-weight ratios and controlled thermal and electrical properties. Within the realm of sandwich composites, the core component plays a pivotal role by providing exceptional bending stiffness and strength to the overall structure without incurring significant weight penalties. Specifically, these structures consist of two robust and rigid surfaces that bear the majority of in-plane and bending loads, securely bonded to a low-density core responsible for carrying transverse shear and normal loads. Despite being recognized for their vulnerability to impact damage, sandwich composites exhibit remarkable energy-absorbing capabilities [1, 2]. Research conducted by Arikan and Sayman [3] delved into the impact response of E-glass fiber-reinforced composites, highlighting the substantial impact of resin type on the repeated impact behavior of these composites. Notably, they observed that the choice of resin had a significant influence on the composites' response to repeated impacts. Moreover, the utilization of a balsa sandwich core with enhanced shear properties contributes not only to improve shear stiffness but also allows for the evaluation of shear strength [4]. Mahesh [5] conducted a

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comprehensive study to compare the low-velocity impact behavior of composites comprising metal, carbon fiber, and elastomer. Their research underscored the viability of using a combination of elastomer, metal, and carbon fiber-reinforced polymer (CFRP) to meet the demand for lightweight materials. Furthermore, Boumbimba et al. [6] conducted a study aimed at evaluating the impact resistance of glass fiber-reinforced acrylic thermoplastic resin-based tri-block copolymer composites under various impact energies and temperatures. Their findings revealed that both temperature and impact energy, as well as the concentration of all-acrylic block copolymers, had significant effects on the damage area of these composites, further illuminating the multifaceted nature of impact behavior in composite materials.

Dhakal et al. [7] conducted a study on the influence of varying impactor geometries (hemispherical, conical with 30°, and conical with 90°) and impact velocities (2.52, 2.71, 2.89, and 2.97 m/s) on the low-velocity impact damage patterns and failure mechanisms of non-woven hemp fiber/unsaturated polyester composite laminates. Arikan and Dogan [8] investigated the impact response of sandwich composites with E-glass reinforced epoxy (thermoset) and polypropylene (thermoplastic). It was observed that the bending stiffness of the thermoplastic matrix is lower than that of the thermoset matrix. García-Castillo et al. [9] conducted a comprehensive study on the effect of biaxial preload on the impact behavior of E-glass/polyester plain woven plates with a thickness of 3.19 mm under high-velocity impact loading, utilizing experimental, analytical, and numerical methods. They observed that preloading of the composite plates increased the ballistic limit. The authors validated the experimental results with analytical and numerical models, obtaining a good correlation between the three sets of results. Garcia-Gonzalez et al. [10] analyzed the impact energy absorption capability of short carbon fiber-reinforced composites based on polyether-ether-ketone over a temperature range from -75 to $+25$ °C. They found that as the temperature of the polymeric matrix approached the transition from ductile to brittle, the energy absorption capacity of the composite decreased significantly. Guillaud et al. [11] investigated the influence of preload and impact energy on the impact response of laminated carbon/epoxy composite plates with a thickness of 5 mm under uniaxial tensile preloading. Despite a decrease in the projected area and fiber breakage due to buckling, the cumulative area of delamination increased with preload. Heimbs et al. [12] examined the effect of a compressive preload on the low-velocity impact behavior of three different laminated carbon fiber/epoxy plates. They observed an increase in the absorbed energy of the preloaded composite plates. Both experimental and numerical investigations were conducted to explore the influence of two different preload levels, compression and tension, on the high-velocity impact performance of T800S/

M21 carbon/epoxy plates in a study conducted by Heimbs et al. [13]. Preloading was found to have a substantial effect on the impact response of laminated composite plates.

Herszberg and Weller [14] experimentally examined the impact resistance and tolerance of post-buckled 2-mm-thin orthotropic carbon/epoxy laminates. It was observed that the critical velocity decreased with increasing preload. Kandas and Ozdemir [15] investigated the single and repeated impact behavior of E-glass/polypropylene sandwich composite plates under tensile, compressive, and shear preloads. In the impact tests of preloaded specimens, they found that the relationship between absorbed energy and preload did not vary [15, 16]. Each impact energy and its associated absorbed energy were independent of the preload. Kursun et al. [17] examined the effects of impactor shape and biaxial preload on the impact behavior of E-glass/epoxy-laminated composite plates. Their results indicated that the rigidity of the material, absorbed energy, deflection, contact force, and time increased with increasing biaxial tension preloading. Furthermore, as biaxial tensile preload increased, the impact duration and deflection decreased [18]. Interestingly, no significant changes were observed in peak force, absorbed energy, or damage area with increasing preload. Additionally, the ballistic resistance of the specimens decreased under different preloading conditions compared to cases with no preload.

Moallemzadeh et al. [19] attempted to describe the influence of impact behaviors within a velocity range of 185–235 m/s for glass fiber-reinforced polyester composite laminates under tension/compression and hybrid preloading. Ozdemir and Kandas [20] examined the effects of thickness and temperature on the impact behavior of glass fiber-reinforced polypropylene thermoplastic composites with two different thicknesses (4 and 6 mm). They observed that the maximum contact force increased with increasing thickness of the composites but decreased with increasing temperature. The impact resistance of the thermoplastic composites was found to depend on factors such as fiber type, temperature, fiber/matrix interface strength, and laminate thickness. Ozdemir et al. [21] investigated the single and repeated impact responses of bio-sandwich structures consisting of E-glass fiber-reinforced thermoplastic face sheets and a balsa wood core. Russo et al. [22] studied the influences of plate thickness and test temperature on composite laminates based on thermoplastic polyurethane reinforced with a balanced glass fabric under low-velocity impact tests conducted at ambient and low temperatures (-25 and -50 °C). Saghafi et al. [23, 24] conducted a study on the effect of the type of curvature (convex or concave) and preloading of laminates with curved surfaces under low-velocity impact loading. In concave laminates, with or without preload, the effect of preload on the damaged area was lower than in convex laminates. Increasing curvature and stress through the thickness

significantly affected impact parameters such as maximum load and damaged area. Schueler et al. [25] discussed the influence of static preloads, including tensile and compressive loads, on the impact damage response of composite plates. A comparative study on the low-velocity impact behavior of carbon woven-ply reinforced polymer composites was presented by Vieille et al. [26]. Besides, a number of papers in the literature have mentioned the impact behavior of laminated and sandwich composite structures [27–29].

From this literature review, it becomes evident that there is a need for further exploration of the specific influence of preload on the impact response and damage behavior of various types of woven-ply laminates. Therefore, the objective of this study is to investigate the effects of preload and impact energy on sandwich composite plates composed of woven carbon and Kevlar fiber fabrics as sheet materials with a PET foam core. Impact damage is of paramount importance for sandwich structural components in operational settings. The current research is centered on conducting low-velocity impact tests at varying impact energies (10, 20, and 30 J). This investigation is crucial for assessing the low-velocity impact behavior of sandwich composite structures utilizing carbon and Kevlar fiber fabrics as well as a PET foam core material. The analysis will focus on energy absorption and damage behavior, providing valuable insights into the performance of these materials and structures under impact conditions.

2 Materials and method

2.1 Materials

The sandwich composite plates used in this study were fabricated using reinforced woven carbon and Kevlar fibers

based on epoxy (a mixture of F 11564 resin and F 13486 hardener) as the matrix material, which is a thermoset. These materials were employed as the face sheet materials. PET (polyethylene terephthalate) foam was selected as the core material. The individual thickness of a single carbon ply is 0.2 mm, a Kevlar ply is 0.3 mm, and the PET foam core measures 4 mm, resulting in a total thickness of 6.4 mm for the sandwich composite laminates. To account for the varying permeability of the woven fabrics, the number of layers was adjusted to maintain the final thickness of the laminates while keeping the total fiber content as constant as possible. The stacking sequence for both the top and bottom face sheets was chosen as [0/90]. The nominal thickness of the top and bottom face sheets, consisting of carbon fiber and Kevlar fiber, was 1.2 mm (equivalent to 6 plies) and 1.2 mm (equivalent to 4 plies), respectively, with a stacking sequence of [0/90]. The configuration of the sandwich composite plates tested in this study is designated as [(0/90)₃/PET/(0/90)₃] for woven carbon sheet/foam PET core and [(0/90)₂/PET/(0/90)₂] for woven Kevlar sheet/foam PET core. The production of sandwich composites was carried out using a vacuum infusion system. The curing process was carried out at a temperature of 80 °C for a duration of 12 h. Following that, 150 × 150 mm specimens were acquired from these plates utilizing a water-cooled cutting device.

2.2 Method

The low-velocity impact testing of the developed sandwich composite laminates was conducted in accordance with the ASTM D7136 standard. For the low-velocity impact tests conducted at energy levels of 10, 20, and 30 J, a CEAST 9350 brand Fractovis Plus impact test machine was employed (as shown in Fig. 1a). The impact tests were carried out using a hemispherical steel impactor with a diameter

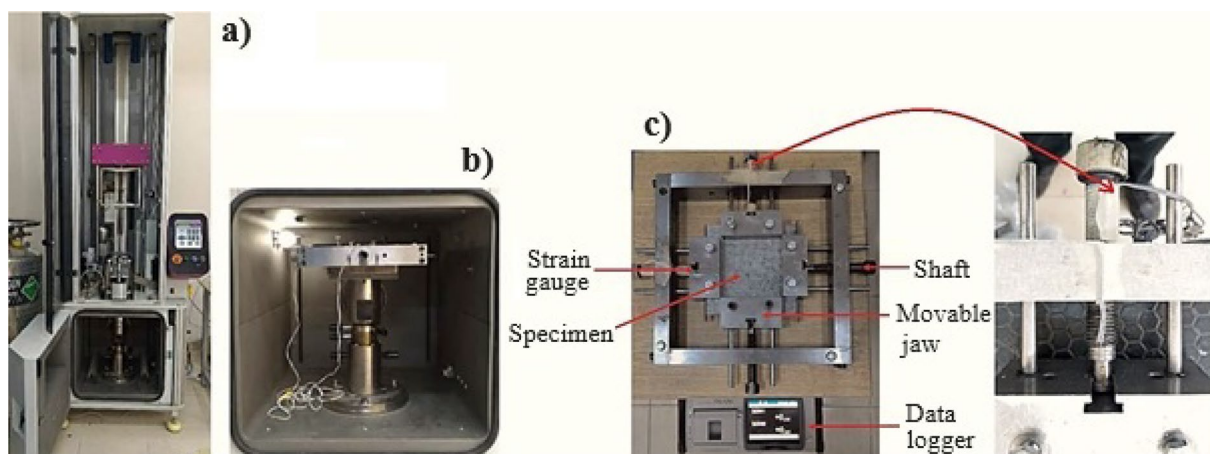


Fig. 1 a CEAST 9350 Fractovis Plus impact test machine, b preload specimen and fixture inside the test cabin, and c preload specimen and fixture

of 12.7 mm and a total mass of 5.02 kg. The test specimen had dimensions of 150 mm × 150 mm × 6.4 mm. To perform impact tests on preloaded and un-preloaded specimens, a specialized experimental fixture was designed and manufactured (Fig. 1b). This fixture was suitable for conducting impact tests on specimens subjected to tensile, compressive, and tension–compression (shear) preload conditions. Impact tests were conducted on both sandwich and non-sandwich specimens under biaxial preload conditions.

To prepare the specimens for the impact tests within the preloading fixture, composite plates measuring 1500 mm × 1200 mm were used to create specimens with dimensions of 150 mm × 150 mm. For this purpose, a specialized test fixture capable of applying a biaxial 100-kN preloading was designed and produced. This fixture made it possible to apply biaxial in-plane preloads, including tension/tension, compression/compression, and compression/tension (shear), by adjusting the position of the pulling–pressing jaws located on both axes of the specimen in the desired direction (Fig. 1c). In the literature studies, the preload is defined either by a strain [18, 30–33] or by a percentage of the tensile strength [9, 19, 34]. The pre-strain was chosen for this study. Referring to the study by Moallemzadeh et al. [19], the loading condition was precisely controlled and measured using strain gauges placed on the 9.8-mm diameter shaft. Strain gauges were employed on the preloaded specimens to accurately determine the level of pre-strain. For each impact energy level, at least three tests were conducted, and the results of these tests were represented graphically using load–impactor displacement and energy–time curves. These graphs were generated to assess the impact behavior of the specimens under three different preload conditions.

3 Results and discussion

Composite structures are subjected to various preloads and impacts during their lifecycle, making preload and impact events crucial considerations. In this study, low-velocity impact tests were conducted on both preloaded and un-preloaded non-sandwich composites and sandwich composites consisting of PET core material and woven carbon and Kevlar fiber fabrics. The thickness of the specimen for non-sandwich composites and sandwich composites was kept constant, and the results are graphically presented for comparison. To ensure data reliability, each parameter was tested three times. Initially, low-velocity impact tests were performed on laminated carbon/epoxy and Kevlar/epoxy composites without using PET core material (non-sandwich composites). Subsequent impact tests were conducted based on the insights gained from these initial tests.

During impact testing, the typical load versus impactor displacement and absorbed energy versus time curves offer valuable insights into the impact test and the specimen's behavior. In impact tests, perforation was the main damage mode in non-sandwich composites, while for sandwich composites, there were three damage modes: rebounding, penetration, and perforation. A closed contact load versus impactor displacement curve indicates that the impact test resulted in rebounding, while an open curve signifies that the impact test resulted in penetration or perforation conditions. Additionally, the absorbed energy can be calculated from the area under the load and impactor displacement curve that is obtained after the test. For materials such as plastic, the collected data are usually fitted with a smooth curve to determine the effective maximum impact load and absorbed energy. However, for composites, the oscillations in the impact load usually reflect the actual state of force on the specimen and should not be eliminated by fitting a curve.

3.1 Impact behavior of un-preloaded specimens

The load–impactor displacement and energy–time curves obtained from impact tests yield valuable information for evaluating the damage processes of specimens. Initially, impact tests were conducted on the carbon/epoxy and Kevlar/epoxy composite specimens without any preloading at 10, 20, and 30 J impact energy levels. Figures 2 and 3 present the load versus impactor displacement and energy versus time curves for these energy levels, respectively. The load–impactor displacement curves show an initial pseudo-linear phase characterized by a steady increase in load. At a certain load value (dependent on factors such as impact energy level and fiber fabric type), small oscillations appear, indicating the initial decrease in the stiffness of the specimen due to the onset of damage, typically through matrix cracking. Subsequently, the maximum load is reached, and a significant drop in load occurs due to the propagation of damage in the specimen, including fiber failures. The final section corresponds to the dry friction between the impactor and the specimen during impactor perforation and the strength of the specimen. These curves were obtained for three different impact energies (10, 20, and 30 J), as shown in Fig. 2. Figure 2 shows that when examining the descending regions of the curves for the carbon and Kevlar layer fabric specimens, the specimens were perforated at all energy levels, with the maximum load being 1485 and 2488 N, respectively. Due to its lower toughness, the maximum load of the carbon layer fabric (C-L) is lower than that of the Kevlar layer fabric (K-L). In the region marked by the green oval in Fig. 2b, some small load drops or oscillations occur. Such load–displacement diagram behavior can be associated with the emergence of a transverse matrix crack or localized indentation of the specimen, as described by

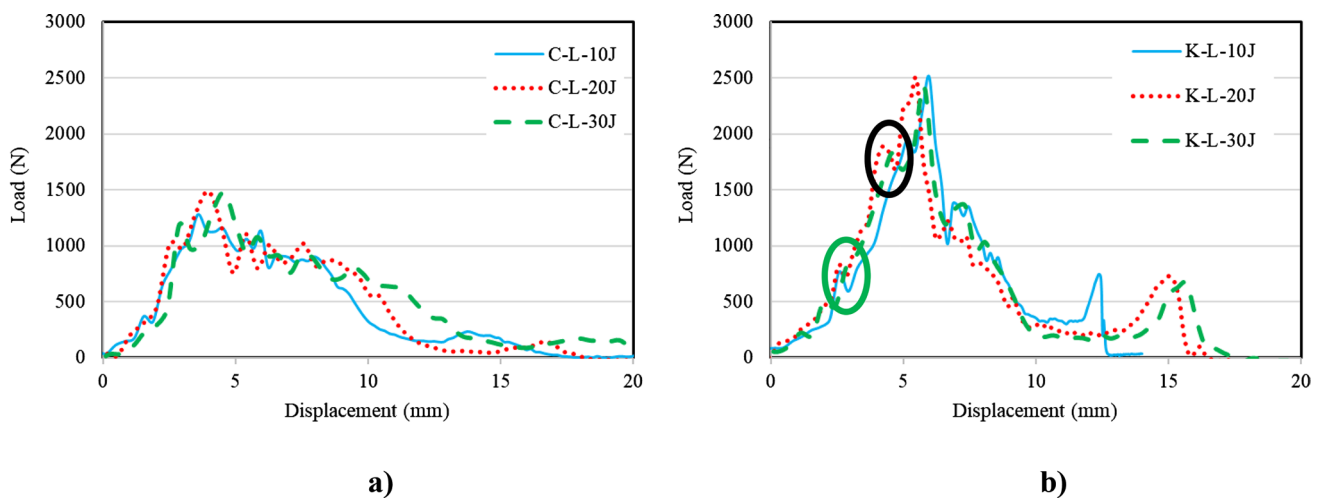


Fig. 2 Typical load versus impactor displacement curves for the different energy levels: **a** carbon/epoxy composite lamina and **b** Kevlar/epoxy composite lamina

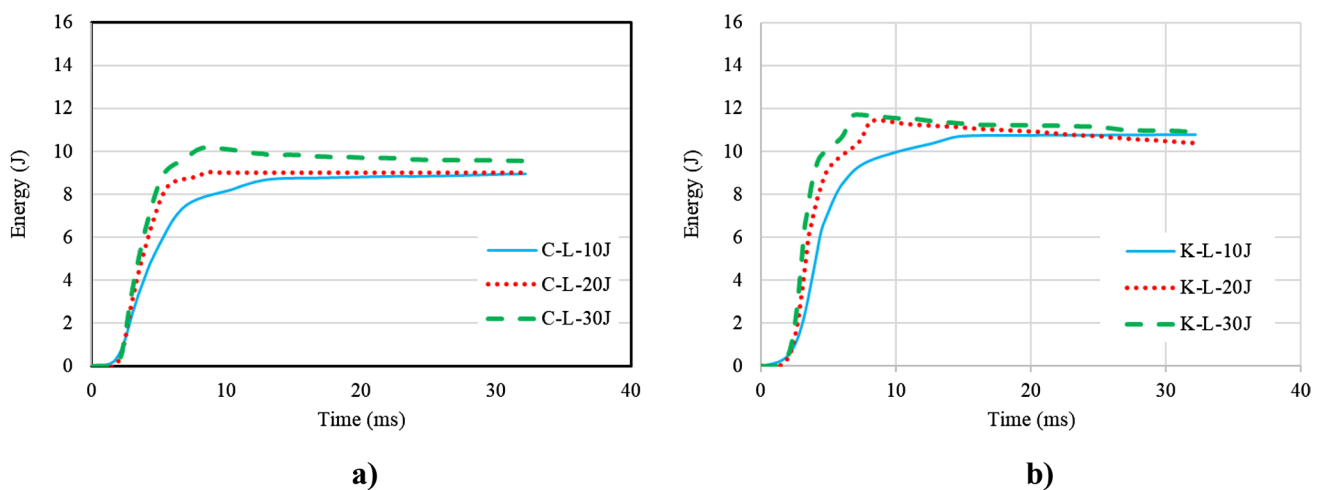


Fig. 3 Energy–time histories for the different energy levels: **a** carbon/epoxy composite lamina and **b** Kevlar/epoxy composite lamina

Abrate [1], Vaidya [35], Schoepner and Abrate [36], and Song et al. [37]. The matrix cracks in the upper laminae initiate at the contact edges of the impactor. The location of the delamination threshold load on the curves is determined by a black oval. As shown, delamination starts almost at the same time in all curves, but at different load values. Delamination occurs as a result of bending stiffness mismatches between adjacent layers, i.e., different orientations between layers. As shown in Fig. 2, Kevlar/epoxy composite specimens exhibit the largest maximum contact loads but the smallest maximum displacement, indicating that their higher bending stiffness, resulting from their higher modulus and thicker structure, can absorb the same amount of energy with less out-of-plane displacement. Besides, for the Kevlar/epoxy composite specimens, the contact load decreases sharply after exceeding the maximum contact load, which

indicates that the Kevlar/epoxy composite specimens may be seriously damaged. The curves of all specimens exhibit a similar trend.

The impactor possesses potential energy (PE) when it is at a certain height, and when it is released, the PE converts into kinetic energy (KE). When the impactor starts to come into contact with the specimen, it starts to transfer its KE to the specimen, with part of it being deposited in the form of elastic deformation and the rest being released mainly as damage develops, with a small amount of energy lost through friction, sound, and heat. When the impactor completely transfers its KE to the specimen, the full KE of the impactor is converted into elastic strain energy and stored in the specimen. Figure 3 displays the energy–time curves for both the carbon and Kevlar layer fabrics. The curves exhibit three distinct sub-curves. The initial linear phase

extends to the maximum energy value. The second phase starts at the maximum energy value and ends at a constant energy value, that is, at the point where the impact energy is not absorbed further. The third phase is characterized by a constant energy value. Since the specimens experienced perforation at all energy levels, only two sub-curves were observed. Additionally, it is evident that the absorbed energy increases with increasing impact energy for both specimen types. The maximum energy absorption values of carbon/epoxy and Kevlar/epoxy composites are recorded to be 10.1 and 11.6 J, respectively. Kevlar/epoxy composite specimens absorbed 14.85% higher energy than carbon/epoxy composite specimens. Since Kevlar layer fabric is more elastic in nature, it can absorb more strain energy, as shown in Fig. 3b. This is the reason Kevlar/epoxy composites absorb more energy than carbon/epoxy composites.

3.2 Impact behavior of specimens under tensile preload

In the existing literature, preload is often determined based on factors such as strain rate [18, 30–33] or a specific ratio of tensile strength [9, 19, 34]. However, in our study, we opted for pre-strain as the determining factor. A tensile pre-strain of 250 $\mu\epsilon$ was applied to the test specimens to assess the influence of tensile preloading on the low-velocity impact behavior of carbon/epoxy and Kevlar/epoxy composite laminates. Preloaded specimens were subsequently subjected to impact loads at the same energy levels as non-preloaded specimens. Figure 4 illustrates the load versus impactor displacement curves. During the impact test, the maximum impactor displacement of the specimens is determined based on the current position of the impactor. It is noteworthy that the rigidity of the composite structure increases significantly

due to the effect of preloading [17]. As observed in Fig. 4, the impactor displacement and contact load exhibit a decrease as a result of the preload, regardless of the impact energy level. For instance, the carbon/epoxy specimen experienced a contact load of 1179 N, while the Kevlar/epoxy specimen had a contact load of 1970 N. This reduction in impactor displacement and contact load can be attributed to the extra strain induced in the specimens by the preload, rendering the composite structure more sensitive to the impact. Also, it was observed that the impact energy level did not have an important effect on determining the maximum load.

The results indicate that tensile preloading decreased the absorbed energy for both carbon/epoxy and Kevlar/epoxy composite specimens when compared to their non-preloaded counterparts (as observed in Figs. 3 and 5). Furthermore, the Kevlar/epoxy specimens exhibited higher absorbed energy values compared to the carbon/epoxy specimens. Specifically, the maximum absorbed energy reached 9.7 J for carbon/epoxy composite specimens and 11.1 J for Kevlar/epoxy composite specimens. Notably, Fig. 5 illustrates that the preloaded specimens exhibited more extensive damage than the non-preloaded specimens.

3.3 Impact behavior of specimens under compressive preload

The specimens underwent biaxial compressive loading and were subsequently impacted by a hemispherical steel impactor with a diameter of 12.7 mm and a total mass of 5.02 kg at impact energy levels of 10, 20, and 30 J. The compressive preload that could be applied to the specimens without buckling was determined to be 250 $\mu\epsilon$. The load–impactor displacement histories for the biaxial compression preloading on both composite plates are depicted in Fig. 6.

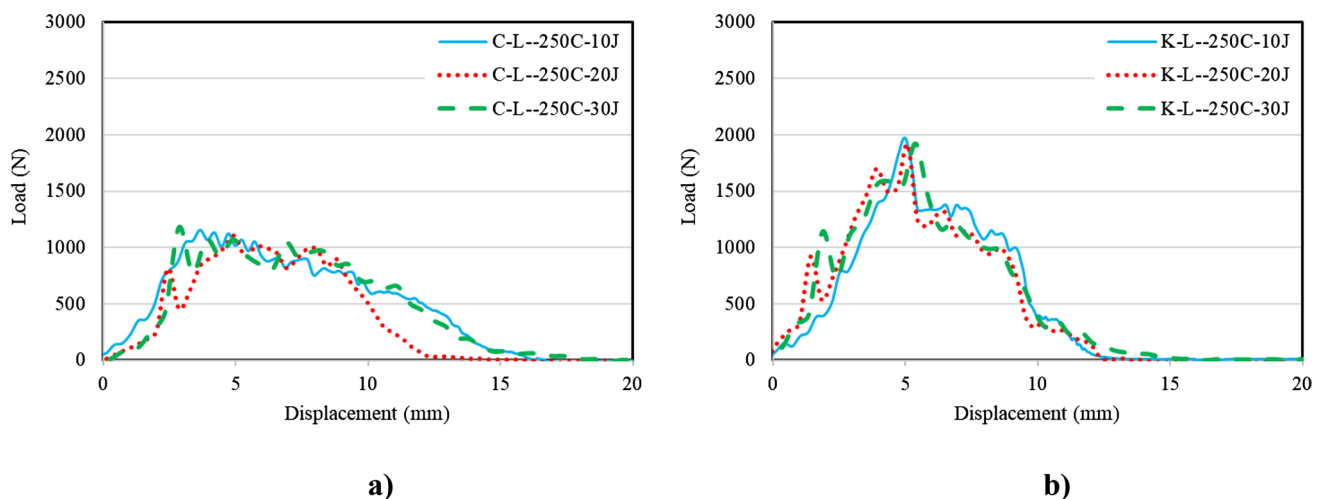


Fig. 4 Typical load versus impactor displacement curves for the different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under tensile preload

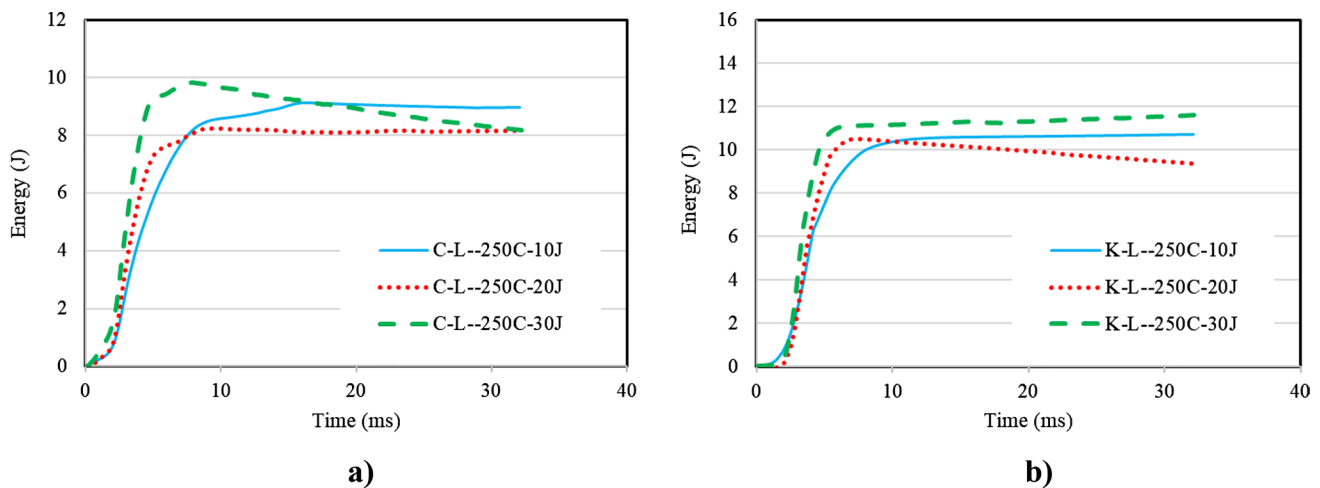


Fig. 5 Energy–time histories for the tensile preloading and different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under tensile preload

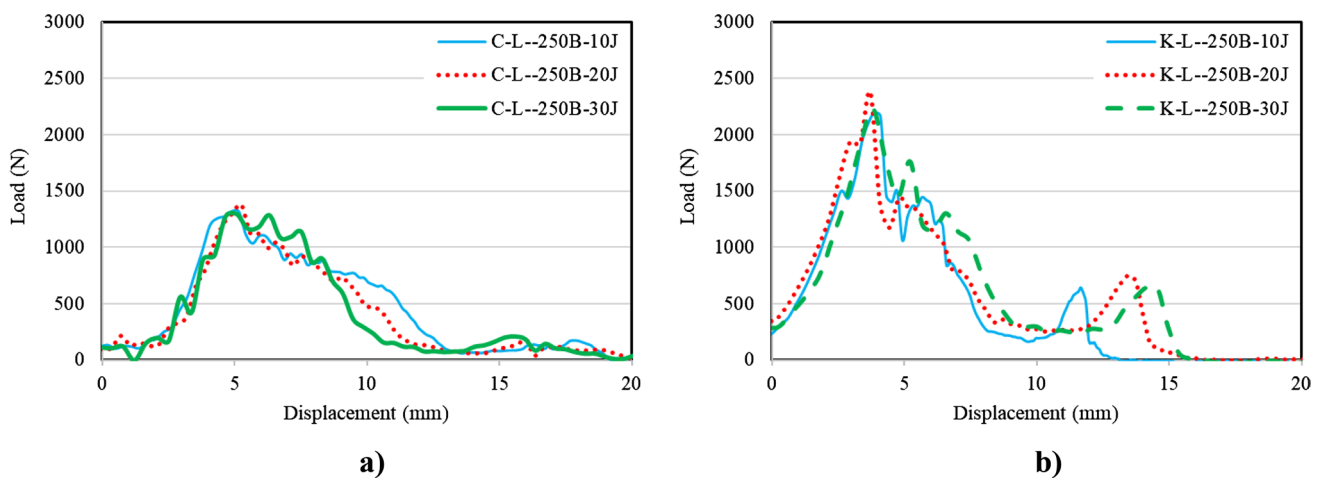


Fig. 6 Typical load versus impactor displacement curves for the different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under compressive preload

When examining the descending regions of the curves for both types of specimens, it was observed that the specimens were perforated at three energy levels, with maximum loads determined as 1377 and 2375 N, respectively. When considering Figs. 2, 4, and 6 together, it can be concluded that tensile and compressive preloading have an important effect on the impact behavior of the specimens.

The maximum absorbed energy was 9.1 J for carbon/epoxy specimens and 13.0 J for Kevlar/epoxy specimens. When analyzing the energy versus time curves shown in Fig. 7, it can be observed that with the compressive preload, the absorbed energy decreased for carbon/epoxy composite specimens, while it increased for Kevlar/epoxy composite specimens. This difference in behavior may be attributed to the fact that carbon fiber is brittle while Kevlar fiber is tough. Generally,

the absorbed energy cannot be higher than the impact energy. However, in the examined specimens, a penetration case has occurred. Consequently, friction between the impactor and the specimen has occurred. Additionally, in low-velocity impact tests, there is a collapse in the contact area of the specimen. Due to friction and collapse, the value of absorbed energy can be higher than the impact energy, albeit to a very small extent. This phenomenon can also be observed from the force–deformation curve. Similar results can also be seen in some studies reported in the literature.

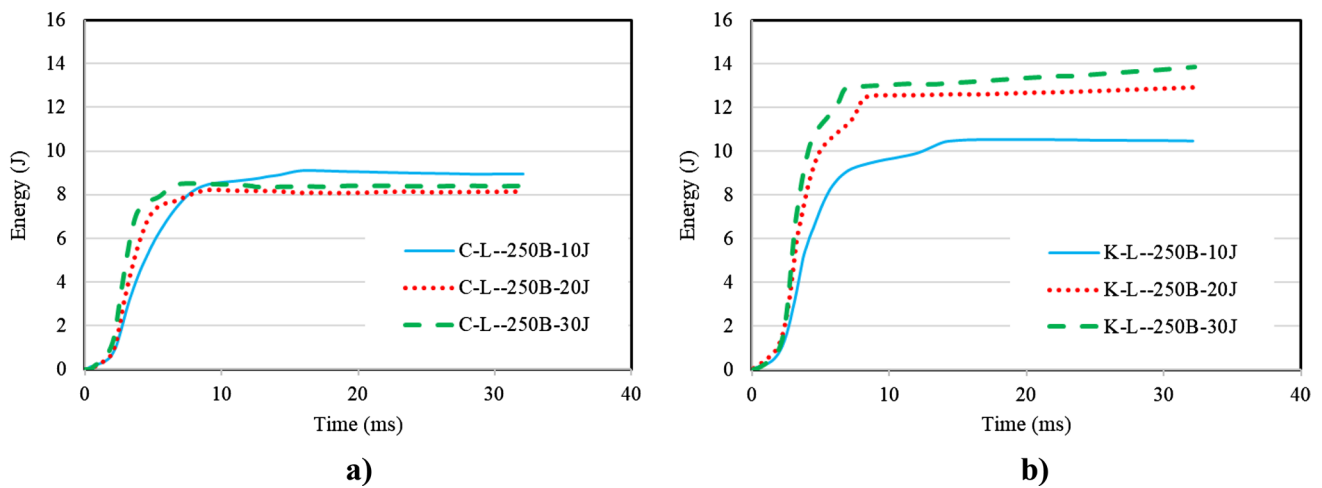


Fig. 7 Energy–time histories for the different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under compressive preload

3.4 Impact behavior of specimens under tension–compression (shear) preloading

The pre-strain of 250 $\mu\epsilon$ was applied to the test specimens to evaluate the effect of tension–compression preloading on the low-velocity impact behavior of the carbon/epoxy and Kevlar/epoxy composite specimens. This applied preload can also be considered as a shear loading. The results are compared via maximum load–impactor displacement, absorbed energy–time curves. In Fig. 8, when examining the descending regions of the curves for both types of specimens, it was observed that the specimens were perforated at all energy levels. The maximum loads were obtained as 1270 and 2145 N for carbon/epoxy and Kevlar/epoxy composite specimens, respectively. The results show that preloading

has an important effect on the impact response of carbon/epoxy and Kevlar/epoxy composite specimens.

Energy versus time curves of the specimens under the shear preloads are shown in Fig. 9. The maximum absorbed energies are 8.7 and 12.3 J for carbon/epoxy and Kevlar/epoxy composite specimens, respectively.

Three different impact energy levels, namely, 10, 20, and 30 J, were systematically employed to investigate the impact response of both preloaded and un-preloaded specimens. The resulting data regarding the maximum load and absorbed energy for carbon/epoxy and Kevlar/epoxy composite specimens, subjected to various pre-strain configurations, are summarized in Table 1. It is worth highlighting that, interestingly, the maximum load exhibited a smaller magnitude in cases where tension preloading was applied, in

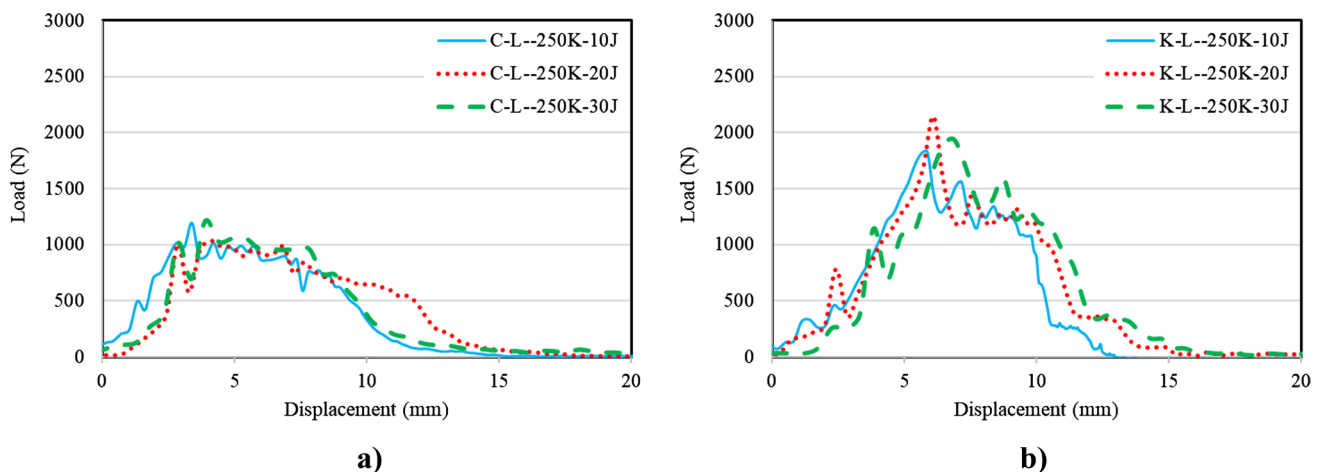


Fig. 8 Typical load versus impactor displacement curves for the different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under tension–compression (shear) preloading

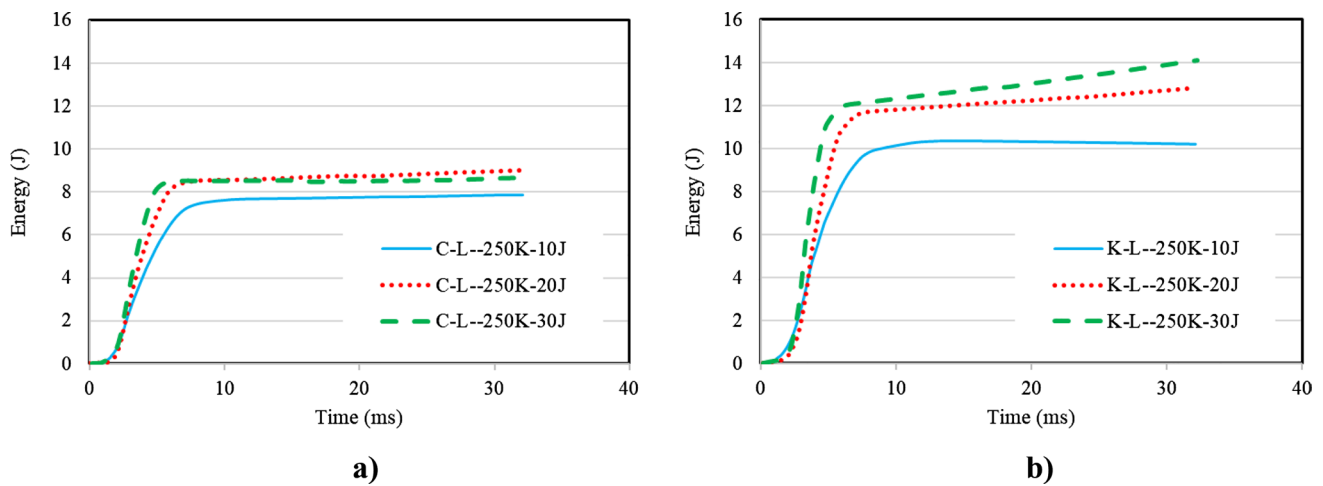


Fig. 9 Energy versus time curves for the different energy levels: **a** carbon/epoxy composite specimens and **b** Kevlar/epoxy composite specimens under tension–compression (shear) preload

Table 1 Maximum contact load and absorbed energy versus pre-strain loading for carbon/epoxy and Kevlar/epoxy composite specimens

Preload type	Microstrain ($\mu\epsilon$)	Maximum load (N)	Absorbed energy (J)
Carbon/epoxy composite specimens			
Zero (un-preload)	250	1485 ± 52	10.1 ± 0.2
Tensile		1179 ± 29	9.7 ± 0.2
Compressive		1377 ± 35	9.1 ± 0.1
Tension–compression (shear)		1270 ± 52	8.7 ± 0.3
Kevlar/epoxy composite specimens			
Zero (un-preload)	250	2488 ± 71	11.6 ± 0.3
Tensile		1970 ± 82	11.1 ± 0.3
Compressive		2375 ± 101	13.0 ± 0.4
Tension–compression (shear)		2145 ± 105	± 0.3

contrast with other preload configurations. Notably, the lowest absorbed energy was observed in specimens subjected to compressive preload for carbon/epoxy composites and tensile preload for Kevlar/epoxy composites. The previous studies, as cited [18, 27], have indicated a rise in the maximum contact force with tension preload scenarios, while a decrease is observed in cases involving compressive and shear preload conditions. This phenomenon was attributed to the stiffening effect induced by tension preloading on the specimens, resulting in a higher maximum load. However, our present study revealed a contrary trend, with the maximum load decreasing across all preload conditions. This variation in contact load and absorbed energy during the impact event among the different preload scenarios has been demonstrated to significantly influence the impact behavior of the composite specimens. It is crucial to note that perforation was consistently observed in all cases during the impact tests. Since the chosen energy levels were determined for sandwich composite specimens, non-sandwich composite

specimens were perforated at these impact energies. Therefore, perforation damage occurred in the specimens at energies lower than the impact energy levels.

It is relevant to note that in impact tests where the impactor is embedded within the specimen, the absorbed energy corresponds to the impact energy, serving as a crucial indicator of the damage threshold. Perforation during these impact tests has been observed to result in heightened fiber breakage, along with a significant increase in back surface splitting and delamination of the composite material. Due to the tensile preload, the composite specimens are stiffer than other preloaded composite specimens. So, the maximum load is lower in tensile-preloaded specimens.

3.5 Impact behavior of un-preloaded sandwich specimens

In addition to their use in laminated forms, composite structures are employed as sandwiches in various applications to

enhance the load-bearing capacity. To further investigate the impact behavior, low-velocity impact tests were conducted on sandwich composite specimens at the same energy levels previously examined. Typical load–impactor displacement curves, presented in Fig. 10, illustrate the influence of different energy levels on the impact response of sandwich composite specimens. In the case of the 10 J impact test, rebounding behavior was observed (Fig. 10a and b). The load increased rapidly during the 20 J impact but then peaked and sharply decreased to approximately 75% of its peak value. For both 20 and 30 J impact tests, perforation occurred. It is noteworthy that the Kevlar/epoxy sandwich specimens consistently exhibited higher load and displacement compared to carbon/epoxy sandwich specimens across all impact energies. An intriguing observation from Fig. 10a is that the maximum load for the 30 J impact energy was

lower than that for the 20 J impact energy. When Fig. 10 was scrutinized for both types of specimens, it was noted that the maximum load registered as 3826 and 3696 N, respectively. In both non-preloaded sandwich specimens, contact load increased until reaching the perforation limit for both material types and then subsequently decreased. For Kevlar/epoxy sandwich composite specimens, the maximum contact load increased with higher impact energy levels (Fig. 10b).

In Fig. 11, an analysis of the absorbed energy versus time curves reveals that the absorbed energy increases as the impact energy levels increase. Specifically, the maximum absorbed energy is 26.3 J for carbon/epoxy sandwich specimens and 25.4 J for Kevlar/epoxy sandwich specimens.

It is evident from Fig. 11 that a rebound occurred at the 10 J energy level, as indicated by the curve returning on the energy versus time graph. The moment when the peak

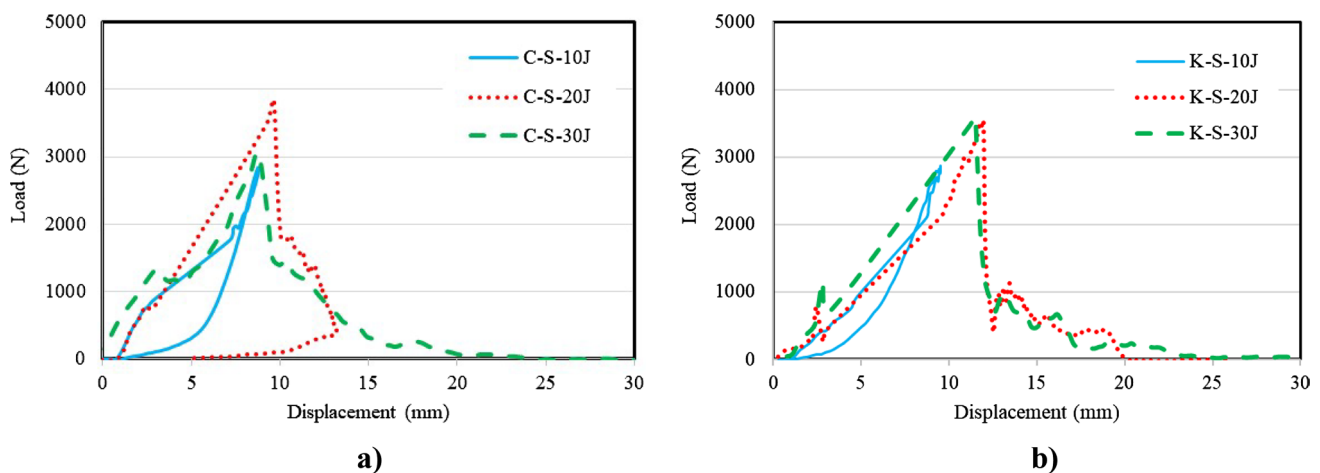


Fig. 10 Typical load versus impactor displacement curves for different energy levels: **a** carbon/epoxy sandwich specimens and **b** Kevlar/epoxy sandwich specimens

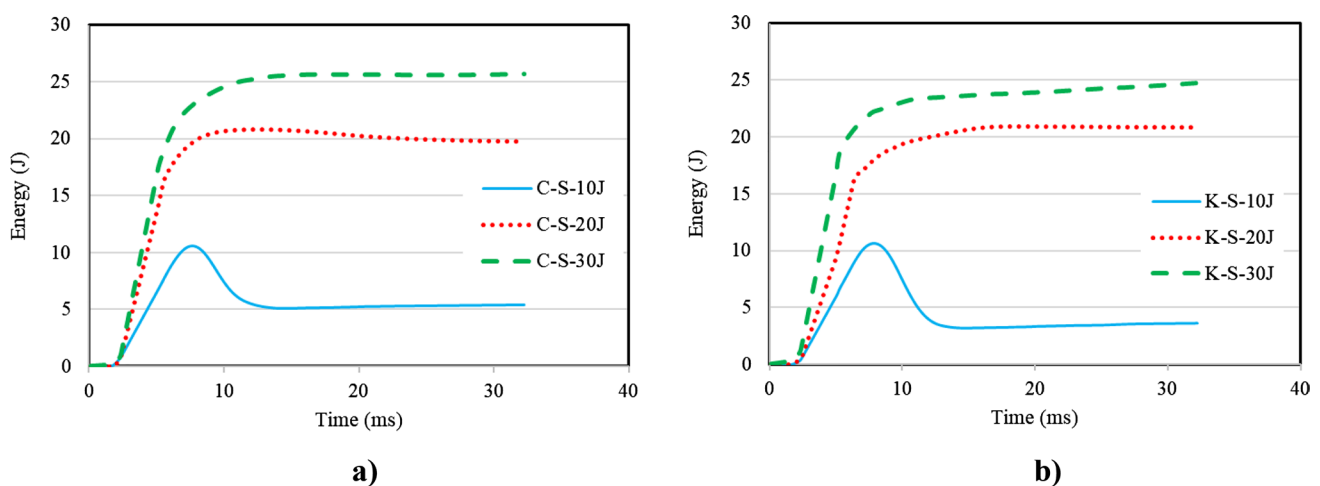


Fig. 11 Energy versus time curves for different energy levels: **a** carbon/epoxy sandwich composite and **b** Kevlar/epoxy sandwich specimens

occurs on the graph represents the point of impact. Furthermore, at the 20 J energy level, it is clear that the specimen reached the exact limit for penetration.

3.6 Impact behavior of tensile-preloaded sandwich specimens

The maximum tensile pre-strain that could be applied to the specimens without causing damage was determined to be $250 \mu\epsilon$. The contact load–displacement curves obtained from impact tests of tensile-preloaded sandwich specimens are presented in Fig. 12. As evident in all impact energy levels, Kevlar/epoxy sandwich composite specimens exhibited higher maximum contact loads and maximum displacements compared to carbon/epoxy sandwich composite specimens. This observation suggests that Kevlar/epoxy sandwich specimens generally possess greater stiffness than carbon/epoxy sandwich specimens. The tensile preload had an important effect on the impact response of the sandwich composite specimens. When a foreign object impacts the composites, various damage modes, including delamination, splitting, matrix cracking, and fiber cracking, can occur depending on factors such as the impact energy, composite shape, laminate type, and boundary conditions [24]. As depicted in the figures, the nature of the impact tests' parameters allowed for the observation of specific damage modes in all impacted specimens, including delamination, splitting, fiber cracking, and matrix cracking. Among these observed modes, delamination and matrix cracking were the predominant modes. Upon examining the descending regions of the graphs for both types of specimens, it was evident that the specimens perforated at energy levels of 20 and 30 J, with maximum contact loads recorded as 3211 and 4756 N, respectively.

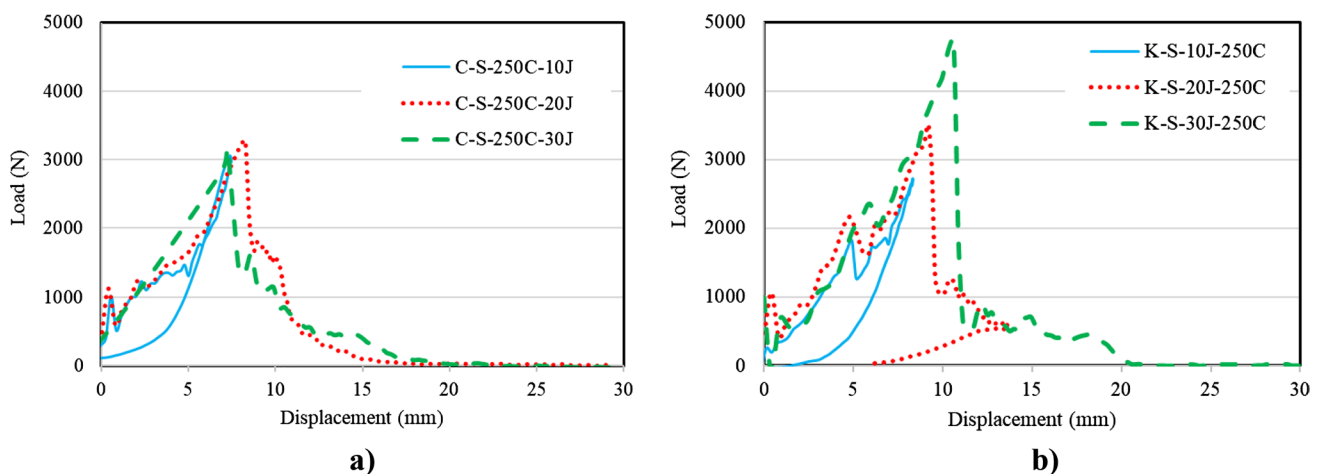


Fig. 12 Typical load versus impactor displacement curves for different energy levels: a) carbon/epoxy sandwich specimens and b) Kevlar/epoxy sandwich specimens under tensile preload

Figure 13 illustrates absorbed energy versus time curves for carbon/epoxy and Kevlar/epoxy sandwich specimens with tensile preload. The maximum absorbed energy is 23.9 and 27.2 J for carbon/epoxy and Kevlar/epoxy sandwich specimens, respectively. An analysis of these energy versus time curves (Fig. 13) reveals that preloading leads to a decrease in the perforation energy of both carbon/epoxy and Kevlar/epoxy sandwich specimens.

One intriguing phenomenon is that as the level of preloading increased in the laminates, the occurrence of matrix cracking also increased. This suggests that preloaded specimens exhibit a higher degree of matrix cracking. This phenomenon can be explained as follows: Preloading induces tensile and compressive stresses on the top and bottom surfaces of the laminate, respectively. It is important to note that at lower impact energies, such as 10 J, the curve exhibits rebounding behavior, while at higher impact energies, such as 20 and 30 J, it takes on the mode of perforation. These results clearly indicate that preloading has an important effect on the impact response of the sandwich specimens. Composites have various mechanisms for absorbing impact energy, including indentation (indicative of local matrix cracking and local fiber fracture), delamination (inter-yarn fracture), splitting (intra-yarn fracture), or fiber stripping [26].

3.7 Impact behavior of compressive preloaded sandwich specimens

Figure 14 depicts the load and impactor displacement curves for two different types of specimens subjected to varying impact energy levels under compressive preload. It is evident that the maximum displacement of the impactor increases with increasing impact energy. When transitioning from low

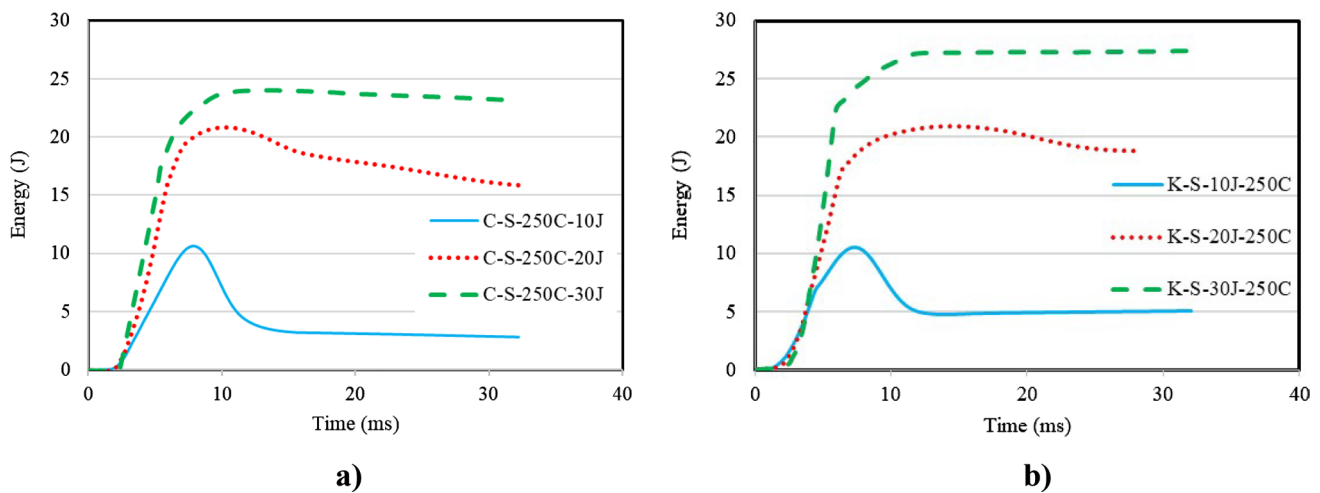


Fig. 13 Energy versus time curves for different energy levels: **a** carbon/epoxy sandwich composite and **b** Kevlar/epoxy sandwich specimens under tensile preload

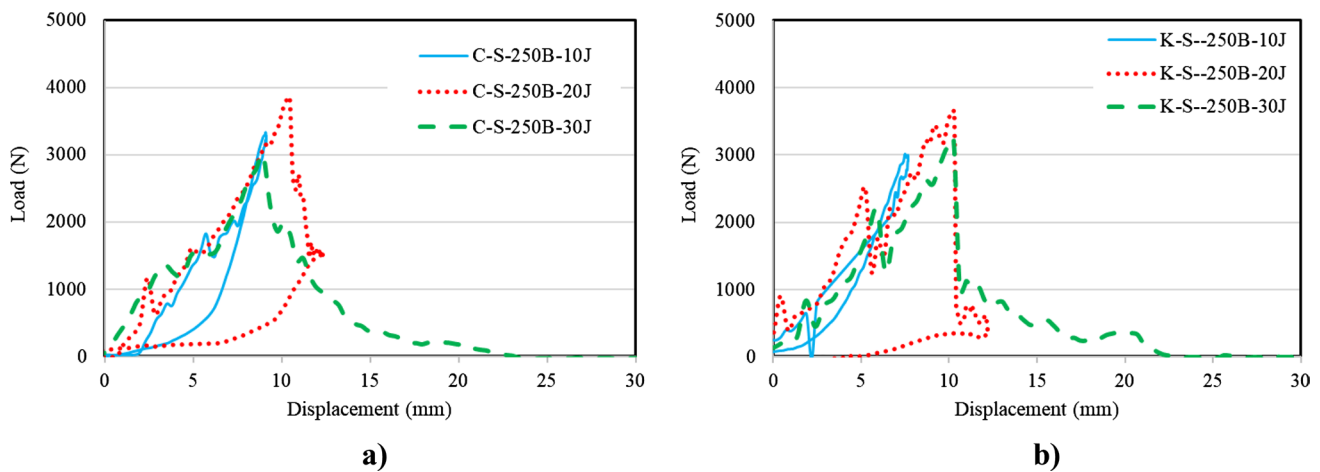


Fig. 14 Typical load versus impactor displacement curves for different energy levels: **a** carbon/epoxy sandwich specimens and **b** Kevlar/epoxy sandwich specimens under compressive preload

impact energy to high impact energies (from 10 to 30 J), the loading and rebound processes shift toward perforation. Specifically, perforation is observed in the case of 30 J impact (Fig. 14), while rebounding occurs at 10 and 20 J impact energies for both specimen types. While the rebound process affects the front and back face sheets of impacted specimens, the perforation process extends throughout the thickness of the specimen. Notably, the maximum contact load for carbon/epoxy and Kevlar/epoxy sandwich specimens is 3809 N and 3653 N, respectively.

The absorbed energy versus contact time curves for both impacted sandwich specimen types under compressive preloading are given in Fig. 15. The maximum absorbed energy by the impacted carbon/epoxy and Kevlar/epoxy sandwich specimens is found to be 25.2 and 25.7 J, respectively. It

is important to note that the difference between the impact energy and absorbed energy represents the excessive energy retained in the impactor, which is then used to rebound the impactor from the specimen during the impact event [38].

3.8 Impact behavior of tension–compression (shear) preloaded sandwich specimens

Figure 16 presents the contact load–displacement curves for the tension–compression (shear) preloaded sandwich specimens. It is evident from the figure that the permanent deflection of the sandwich specimens increases with increasing impact energy for both specimen types. The contact load–displacement curves help distinguish between rebounding, penetration, and perforation scenarios for the

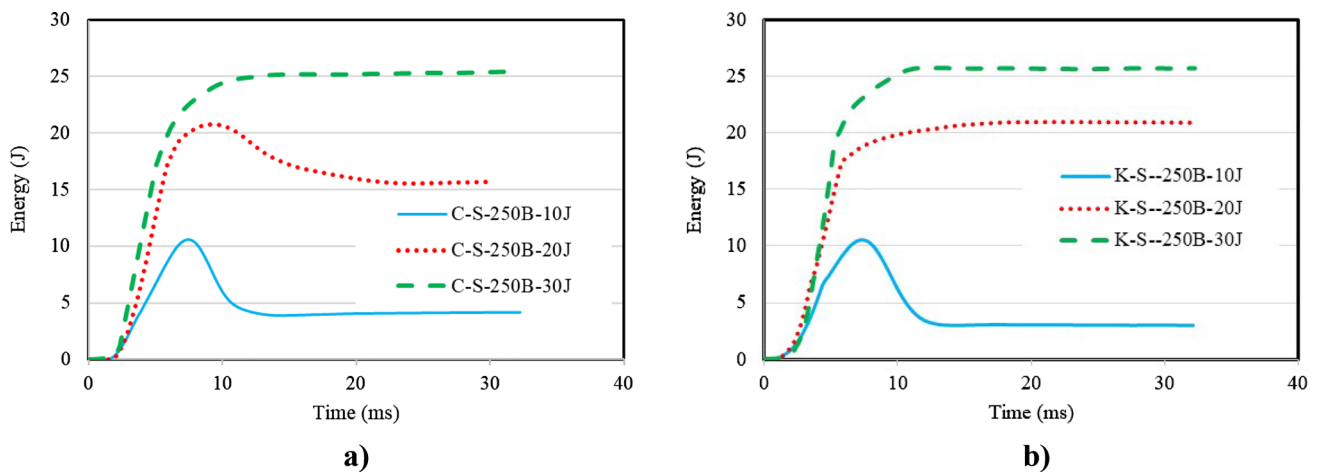


Fig. 15 Energy versus time curves for different energy levels: **a** carbon/epoxy sandwich specimens and **b** Kevlar/epoxy sandwich specimens under compressive preload

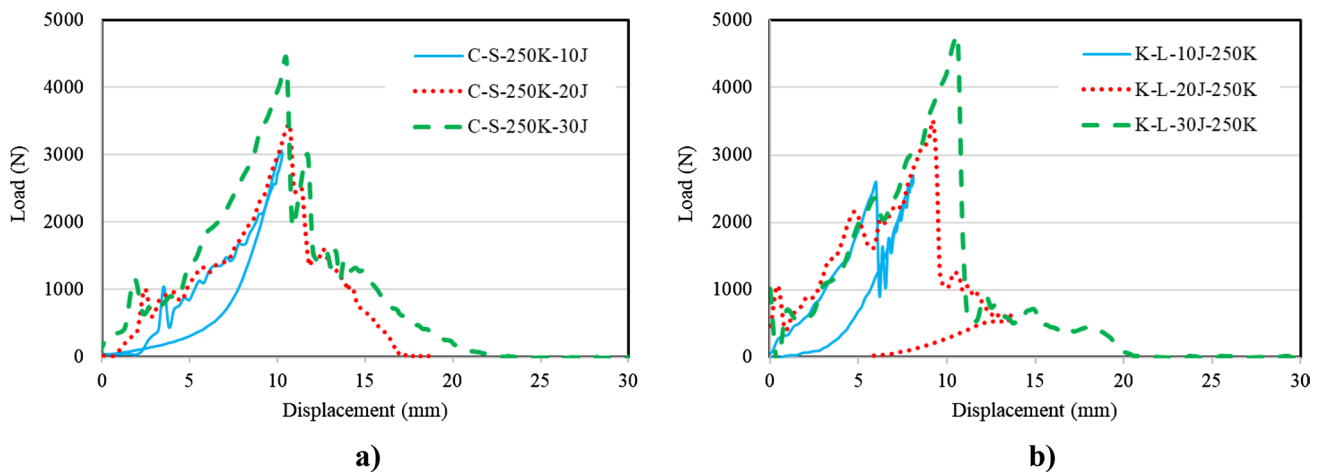


Fig. 16 Typical load versus impactor displacement (F-D) curves for different energy levels: **a** carbon/epoxy sandwich specimens and **b** Kevlar/epoxy sandwich specimens under tension–compression (shear) preload

impacted sandwich specimens. For carbon/epoxy specimens, rebounding occurs at 10 J, while for Kevlar/epoxy specimens, it occurs at 10 and 20 J. Moreover, perforation is observed at 20 and 30 J for carbon/epoxy specimens and at 30 J for Kevlar/epoxy specimens. The maximum contact load was determined to be 4410 N for carbon/epoxy sandwich specimens and 4760 N for Kevlar/epoxy sandwich specimens.

Figure 17 shows the energy–time curves for the tension–compression (shear) preloaded sandwich specimens. The absorbed energy increases by increasing the impact energy for both sandwich specimen types under shear preloading. The maximum absorbed energy is obtained as 29.8 and 27.3 J for carbon/epoxy and Kevlar/epoxy specimens, respectively. In the rebounding case, the absorbed energy is

lower than the impact energy. So, specimens cannot absorb the entire impactor energy.

In an effort to ease the assessment of results, maximum contact load and absorbed energy values for sandwich composites under various preloads at three different impact energy levels have been evaluated and are tabulated in Table 2. It provides more insight into the influence of the preloading type. A noteworthy observation in Table 2 is that the maximum contact load and absorbed energy of carbon/epoxy sandwich specimens with tensile preload are lower than those of other preload and un-loaded specimens. Conversely, for Kevlar/epoxy sandwich specimens, the maximum contact load and absorbed energy with compressive preload are lower than those of other preloading and un-preloading specimens. When both types

of sandwich specimens are considered together in Table 2, it is evident that tensile and compressive preloads have a significant influence on the impact behavior of the sandwich specimens. In the case of compressive preload, the impactor faces greater resistance, making it harder for the impactor to penetrate the specimen. Thus, a slight increase is observed in the contact load and absorbed energy values of impacted carbon/epoxy sandwich specimens under

compressive preloading, in contrast with the tensile preload case.

Digital images of the front, rear, and detailed views of the damaged surface of carbon and Kevlar sandwich specimens subjected to a specific impact energy level, i.e., 30 J, under tension–compression (shear) preload are provided in Figs. 18 and 19. Upon examination of the images, it is observed that perforation case occurred in both carbon and

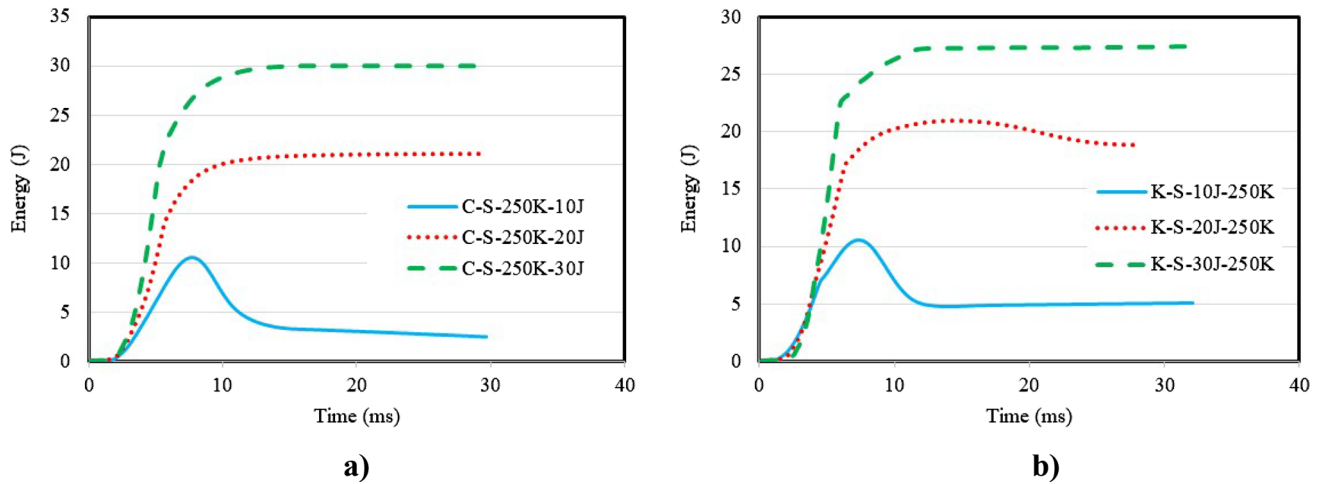


Fig. 17 Energy versus time curves for different energy levels: **a** carbon/epoxy sandwich specimens and **b** Kevlar/epoxy sandwich specimens under tension–compression (shear) preload

Table 2 Maximum contact load and absorbed energy versus pre-strain loading for carbon/epoxy and Kevlar/epoxy sandwich specimens

Preload type	Microstrain ($\mu\epsilon$)	Maximum load (N)	Absorbed energy (J)
Carbon/epoxy sandwich composite specimens			
Zero (un-preload)	250	3826 ± 120	26.3 ± 0.7
Tensile		3211 ± 94	23.9 ± 0.5
Compressive		3809 ± 87	25.2 ± 0.5
Tension–compression (shear)		4410 ± 162	29.8 ± 0.8
Kevlar/epoxy sandwich composite specimens			
Zero (un-preload)	250	3696 ± 113	25.4 ± 0.4
Tensile		4756 ± 126	27.2 ± 0.2
Compressive		3653 ± 187	25.7 ± 0.3
Tension–compression (shear)		4760 ± 152	27.3 ± 0.6

Fig. 18 Top, rear, and detailed views of the damaged surface images of the carbon sandwich composites under tension–compression (shear) preload (at 30 J)

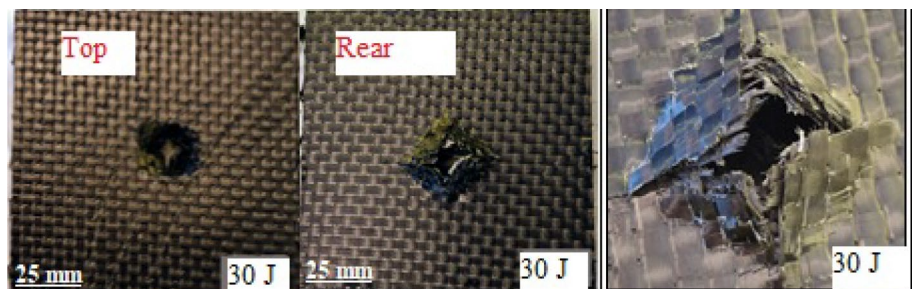
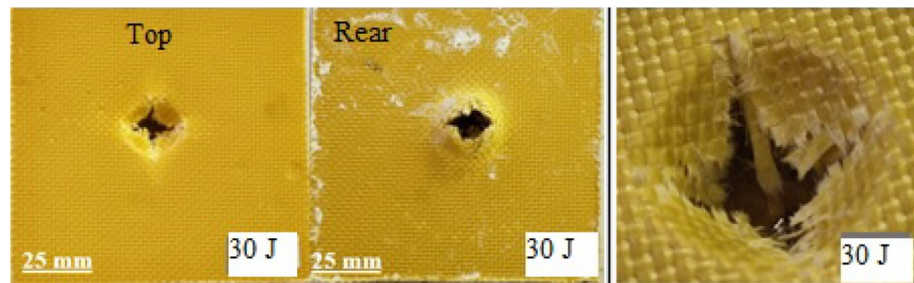


Fig. 19 Top, rear, and detailed views of the damaged surface images of Kevlar sandwich composites under tension–compression (shear) preload (at 30 J)



Kevlar specimens. Delamination, matrix cracks, and fiber damage are visible on the front surfaces of both samples. Moreover, there was a roughly circular-shaped damaged area at the top and rear surfaces. It has been observed that the damage area in carbon epoxy specimens is larger than that in Kevlar epoxy specimens.

This study shows that the preload is a very important parameter for the impact behavior of the carbon fiber/epoxy and Kevlar fiber/epoxy composites. Also, it has been shown that sandwich composites based on carbon fiber/epoxy and Kevlar fiber/epoxy with PET foam core material have better impact behavior under different preloads than non-sandwich composites due to their lower density, good bending strength, and better energy absorption ability. The results obtained in this study showed that sandwich composites may provide better results in some applications.

4 Conclusions

In this experimental study, low-velocity impact tests were conducted on non-sandwich composites and sandwich composites composed of carbon fiber/epoxy and Kevlar fiber/epoxy with a PET foam core material. These tests considered various preload cases, including tensile, compressive, and tension–compression (shear) preloading, as well as unpreloaded cases. The resulting explanations can be summarized as follows:

- The presence and type of preload have an important effect on the impact resistance of carbon/epoxy and Kevlar/epoxy non-sandwich and sandwich composites.
- While perforation failure occurred in non-sandwich composite specimens at whole impact energies, rebounding at low-energy levels and perforation at high-energy levels occurred in sandwich composite specimens.
- The results showed that carbon fiber is brittle and Kevlar is tough. Therefore, Kevlar/epoxy composites have better impact behavior than carbon/epoxy composites.
- While preloading decreased the impact behavior of non-sandwich composites, it improved the impact behavior of sandwich composites.

- When preload was introduced, the impact behavior of Kevlar/epoxy with compressive preload and carbon/epoxy sandwich composites with tensile preload was weaker than in other preloaded and non-preloaded cases.

Declarations

Conflict of interest The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

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