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Original Paper

An experimental study on the low energy impact behavior of different number of layer e-glass/epoxy composites

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ABSTRACT

Composite materials are increasingly used in structural applications due to the high strength-to-weight ratio, corrosion resistance, and design flexibility they offer; however, susceptibility to impact damage remains a critical concern, particularly in layered configurations. In the present research, low-velocity impact experiments were performed on 8-layer and 16-layer unidirectional E-glass/epoxy composite plates with $[+45/-45/90/0]_s$ and $[+45/-45/90/0]_{2s}$ stacking sequences, which were manufactured using the vacuum-assisted hand lay-up method, at impact energy levels of 10, 20, and 30 J. Findings indicated that a rise in impact energy resulted in an increase in maximum contact force and energy absorption for both 8-layer and 16-layer composite plates, with no noticeable change in bending rigidity. At the same energy level, an increase in the number of layers enhanced the maximum contact force and bending rigidity of the composite plates, whereas displacement and the amount of energy absorbed by the material decreased. For all energy levels, the damage observed in the 8-layer composite plates spread over a wider area compared to the damage in the 16-layer plates.

I. INTRODUCTION

Composite materials offer significant advantages over traditional materials in both structural and functional components owing to their superior strength-to-weight ratio, design flexibility, and excellent corrosion resistance. The aligned fiber arrangements in fiber-reinforced composites enable the optimization of mechanical properties in specific loading directions, making these materials more attractive for engineering applications. These features provide substantial benefits in industries such as aerospace, automotive, marine, and construction, particularly in terms of weight reduction, energy efficiency, and durability [1-3].

To fully leverage the superior properties of composite materials, understanding their behavior under impact loads is of great importance. Impact loads are generally classified into different categories depending on the application conditions and impact velocity. These categories include low-velocity impacts, high-velocity impacts, and ballistic impacts [4]. Among these, low-velocity impacts represent a type of loading commonly encountered in scenarios such as accidental collisions, drops, or minor impacts during service. Although such impacts may not result in visible surface damage, they can cause microstructural damage within the material, such as delamination, matrix cracking, or fiber-matrix interfacial weakening [5]. These damages can significantly weaken the material's load-bearing capacity and structural integrity over time, adversely affecting its long-term performance.

Understanding low-velocity impact resistance is critical not only for safety considerations but also for optimizing design processes. For instance, improvements in parameters such as material selection, layer configuration, fiber

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orientation, and hybridization to enhance impact resistance can contribute to the development of more durable and long-lasting composite structures. This knowledge is essential both for the development of new materials and for evaluating the applicability of existing materials under varying conditions.

Various studies in the literature have investigated the impact behavior of composite materials. Öndürücü and Karacan [6] experimentally examined the impact behavior of 8- and 12-layer glass fiber/epoxy composite plates with different configurations at energy levels of 10, 20, and 30 J. They observed that increasing the impact energy led to higher maximum contact forces, displacements, and damage areas. Additionally, they reported that the impact resistance of 12-layer composite plates was higher than that of 8-layer plates. Esendemir and Caner [7] investigated the impact behavior of 8- and 16-layer E-glass fiber/epoxy composite plates at energy levels of 20 and 60 J. They concluded that increasing the number of layers improved impact resistance and noted that higher energy levels caused perforation damage in the composite plates. Uyaner et al. [8] experimentally examined the effect of plate dimensions (180 mm × 50 mm, 180 mm × 100 mm, 180 × 150 mm) on the damage of E-glass/epoxy laminated composites subjected to low-velocity impacts. They found that increasing sample width decreased displacement while increasing the maximum contact force. Esendemir and Erbil [9] investigated the effects of plate thickness, impactor tip geometry, impact energy level, and seawater environment on the impact behavior of glass fiber/epoxy composite plates. They observed that higher impact energy, thinner samples, and smaller impactor tip diameters resulted in decreased impact resistance and the occurrence of perforation damage. Karakuzu et al. [10] experimentally and numerically investigated the effects of impact energy, impact mass, and impact velocity on the impact resistance and damage evolution of glass fiber/epoxy composite plates. Yapıcı and Yapıcı [11] analyzed the low-velocity impact behavior of 16-layer E-glass/epoxy composite plates using the finite element method. Kara and Uyaner [12] experimentally investigated the effect of impactor geometry on the low-velocity impact response of 10-layer E-glass fiber epoxy composite tubes. Reddy et al. [13] examined the low-velocity impact behavior of E-glass/epoxy composites with varying thicknesses under different temperatures. While temperature had minimal effect on energy absorption, it significantly influenced displacement and damage behavior. The peak force increased with thickness but dropped by 25% as temperature rose from −20 °C to 100 °C. Russo et al. [14] investigated the low-velocity impact behavior of glass/polyurethane laminates at sub-zero and ambient temperatures, finding that decreasing temperature increased both stiffness and damage extent. Saylık and Temiz [15] examined the low-velocity impact behavior of glass, carbon, and hybrid glass/carbon fiber epoxy composites at energy levels of 10–40 J. They found that increasing impact energy raised the peak force and damage. Glass fiber composites showed the highest impact resistance, while hybrid composites performed better than carbon but worse than glass fiber composites. Yalkın et al. [16] investigated the low-velocity impact behavior of E-glass/epoxy laminates both experimentally and numerically. They found that contact force, deflection, and contact time increased with impact energy up to the penetration threshold. Beyond this point, these parameters remained mostly unchanged except for a notable decrease in contact time. Numerical and experimental results showed strong agreement, particularly in delamination area predictions. Ayten and Haque [17] experimentally and numerically investigated the low-velocity impact behavior of 8-harness satin weave S2 glass fiber/epoxy composites. The comprehensive mechanical properties of the composite plates were experimentally determined to be used in the numerical model. The material properties were calibrated through numerical simulations. Binbin Liao et al. [18] investigated how the z-pinning method influences delamination behavior in carbon fiber/epoxy laminates of varying thicknesses (2.1 mm, 4.5 mm, and 6.9 mm) subjected to low-velocity impact. Their findings indicated that z-pinning became particularly effective once the impact energy exceeded the delamination threshold, leading to a 15% reduction in internal delamination area in the thicker laminates. Reddy et al. [19] investigated the effect of laminate thickness on the low-velocity impact behavior of E-glass/epoxy composites. Their results showed that the peak force increased proportionally with laminate thickness at all impact energy levels. Evci [20] investigated the low-velocity impact behavior of woven and unidirectional E-glass/epoxy composite laminates with thicknesses ranging from 2 mm to 8 mm under varying impact energy levels. The study concluded that the penetration thresholds of the composite laminates increased in a non-linear manner with thickness. In recent studies, various investigations have focused on the low-velocity impact behavior of hybrid composites formed by combining glass fibers with different types of fibers. Rezasefat et al. [21] examined the effects of hybridization, laminate configuration, and impact energy levels on the low-velocity impact behavior of aramid/S2-glass fiber epoxy hybrid composite laminates. The study concluded that hybridization had a significant influence on damage morphology, and at higher impact energies, laminate configuration played a critical role. Subadra et al. [22] investigated the low-velocity impact response of carbon/glass fiber epoxy hybrid composite laminates. The results indicated that the hybrid effect became more prominent when the weight fraction of carbon fabrics was lower compared to glass fabrics, and this behavior could be predicted through both experimental and theoretical analyses.

Although various studies have been conducted on the low-velocity impact behavior of composite materials, further research is still needed to investigate the effects of parameters such as different numbers of layers, impact energy levels, and boundary conditions. In this study, E-glass fiber-reinforced epoxy composite plates with $[+45/-45/90/0]_s$ and $[+45/-45/90/0]_{2s}$ stacking sequences were manufactured in 8- and 16-layer configurations, and low-velocity impact tests were carried out at 10, 20, and 30 J energy levels. The stacking sequence was deliberately kept constant to isolate the effect of laminate thickness and eliminate the influence of fiber orientation and layer arrangement. This approach allows for a more direct and controlled comparison of the mechanical response between thinner and thicker laminates under identical loading conditions. Moreover, instead of fully clamping all edges—a common boundary condition in experimental studies—the specimens in this research were clamped only along two opposite edges, while the remaining edges were left free. This partial constraint better simulates actual support conditions found in many structural applications, such as aircraft fuselage panels, automotive components, or marine structures, where full edge constraint is rarely present. The two-edge clamping also allows greater flexibility and energy dissipation, offering more realistic insight into deformation behavior and damage propagation. In this regard, the present study contributes to literature by examining the influence of the number of layers under a constant stacking configuration and incorporating a more application-relevant boundary condition to better reflect the actual behavior of composite components under impact loading.

II. EXPERIMENTAL METHOD

2.1 Materials and Preparation Techniques

In present research, unidirectional E-glass fiber epoxy composite plates were fabricated using the vacuum-assisted hand lay-up method, schematically illustrated in Figure 1. The composite plates were produced with 8 and 16 layers, corresponding to an average thickness of 1.6 mm and 3.2 mm, respectively. The stacking sequences of the 8-layer and 16-layer plates were configured as $[+45/-45/90/0]_s$ and $[+45/-45/90/0]_{2s}$, respectively. For the fabrication of the composite plates, Vetrotex 1200 tex E-glass fabric with a fiber diameter of 17 μm and a density of 2.6 g·cm^{-3} was used as reinforcement. The epoxy matrix system consisted of Ciba Geigy Bisphenol-A based CY-225 epoxy resin combined with 25 wt.% of Ciba Geigy Anhydride HY-225 hardener. The fiber volume fraction was carefully controlled and maintained at approximately 0.65 for all specimens to ensure consistent material properties.

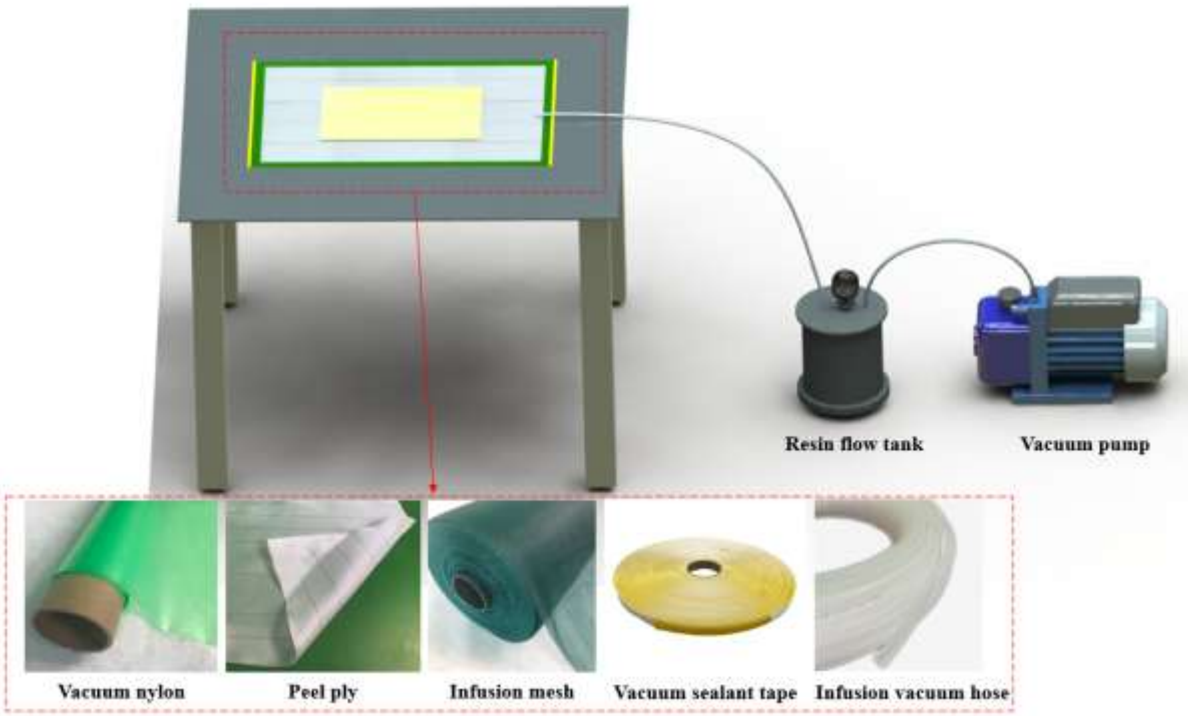


Figure 1. Schematic representation of composite plate production

2.2 Low-Velocity Impact Test

Low-velocity impact tests on unidirectional E-glass/epoxy composite plates were performed using a low-velocity impact test device designed based on the ASTM D7136/D7136M-15 standard [23]. The test setup is illustrated in Figure 2.

Composite plates with dimensions of 140 mm × 140 mm × 1.6 mm and 140 mm × 140 mm × 3.2 mm were prepared, with two opposing edges fixed and the remaining two edges left free. The steel impactor used in the device had a weight of 6.35 kg and a hemispherical tip with a radius of 24 mm. Impact experiments at low velocities were carried out at three energy magnitudes—10, 20, and 30 J—with each energy level tested three times under ambient laboratory conditions. These energy magnitudes correspond to impact scenarios relevant to real-world applications—particularly in the automotive and aerospace sectors—where composite structures may be subjected to accidental tool drops, low-velocity debris strikes, or minor collision events during service or maintenance.

Each specimen was impacted at its center using the hemispherical-tipped steel impactor. Following the initial impact, the impactor mass was held to prevent repeated impacts. During the tests, a sensor with a measurement capacity of 22.6 kN was used to capture the applied force. A computer software program was utilized to generate force-time curves, and custom-developed codes were used for kinematic analyses to determine displacement, absorbed energy, and other related parameters [25].

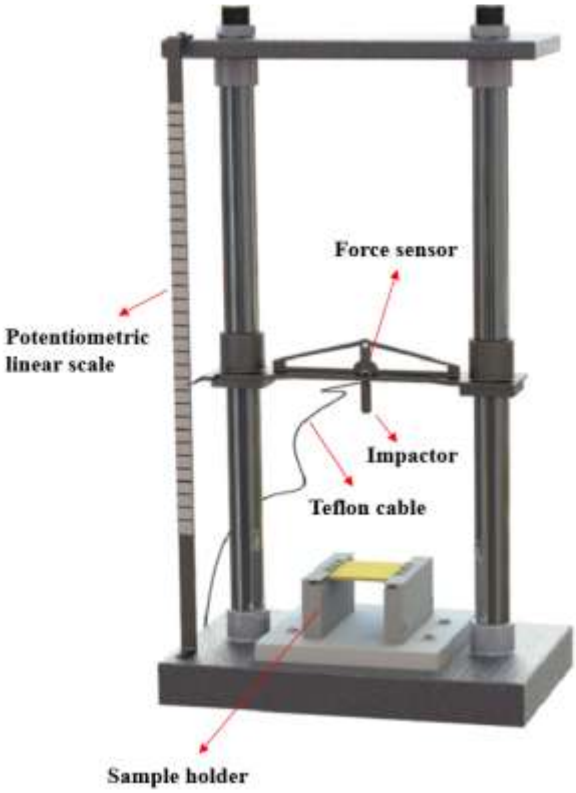


Figure 2. Low-velocity impact test device [24]

Force-displacement curves for the low-velocity impact tests were obtained using Equations 1–6. The acceleration at the moment of impact was calculated using Equation 1.

$$a_i = \frac{F_t}{m} \tag{1}$$

Here a_i, represents the acceleration at time t_i (m·s^{-2}); F_t represents the force at time t_i (N) and m denotes the impactor's mass (kg).

Assuming that the change in acceleration with respect to time is linear over very small-time intervals, the acceleration function can be calculated using Equation 2.

$$a(t) = kt + c \tag{2}$$

In this equation, $a(t)$ is the acceleration function (m·s^{-2}), k represents the slope of the line (m·s^{-3}), t is time (s), and c is a constant value (m·s^{-2}). The slope k and constant c are calculated using Equation 3 and Equation 4, respectively.

$$k = \frac{a_i + a_{i-1}}{t_i + t_{i-1}} \tag{3}$$

$$c = \frac{t_i \cdot a_{i-1} + \ t_{i-1} \cdot a_i}{t_i - t_{i-1}} \tag{4}$$

Here, t_i represents the time at the "i" moment (s). The velocity at any given point and the displacement during any two-time intervals are calculated using Equation 5 and Equation 6, respectively.

$$v_i = v_{i-1} + \frac{1}{2} \cdot k_i \cdot \left(t_i{}^2 - t_{i-1}^2\right) + c_i \cdot (t_i - t_{i-1}) \tag{5}$$

$$s_i = s_{i-1} + \frac{1}{6} \cdot k_i \cdot \left(t_i{}^3 - t_{i-1}^3\right) + \frac{1}{2} \cdot c_i \cdot \left(t_i{}^2 - t_{i-1}^2\right) - (v_{i-1} + c_i \cdot t_{i-1} + \frac{1}{2} \cdot k_i \cdot t_{i-1}^2) \cdot (t_i - t_{i-1}) \tag{6}$$

In these equations, v_i is the velocity at time t_i (m/s), and s_i represents the displacement during the time interval $t_i - t_{i-1}$ (m). The energy retained by the composite specimen during the impact test is determined by calculating the area under the force-displacement curve. This area is obtained using Equation 7.

$$E_{abs} = \int_0^s F \cdot ds \tag{7}$$

Here, E_{abs} represents the absorbed energy (J), F is the applied force during the impact (N), and s is the displacement (m).

2.3 Damage Analysis

Damage in E-glass/epoxy composite materials can be identified by shining light from the back of the specimen. The size and shape of the delamination, as well as the presence of matrix cracks, can be visually detected [26].

To visualize the macro damage caused by low-velocity impact experiments on composite plates, light was projected from the back surface of the specimen, and high-resolution photographs were captured.

In addition to the macro-scale observations, scanning electron microscopy (SEM) analyses were conducted on cross-sectional areas of the impacted specimens to evaluate the internal damage mechanisms such as matrix cracking, fiber–matrix debonding, and delamination at the microstructural level.

III. RESULTS AND DISCUSSIONS

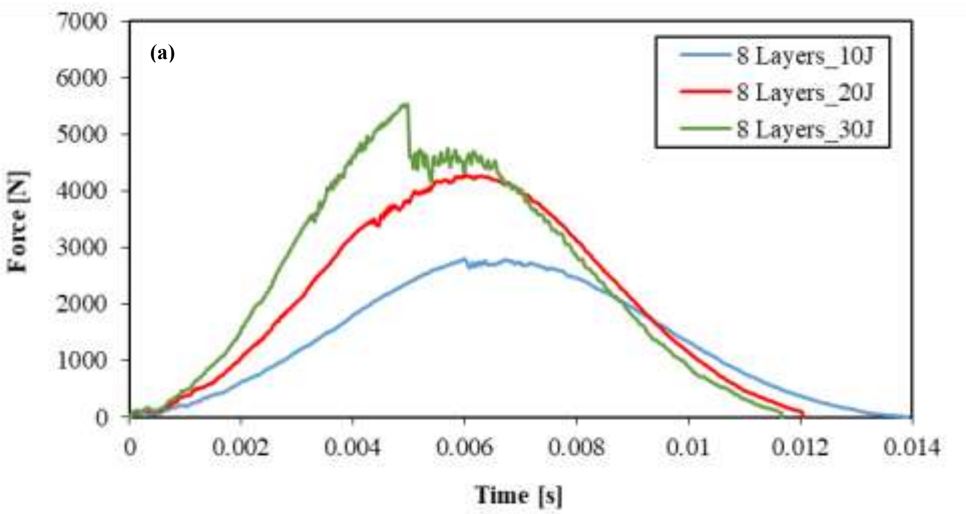
Low-velocity impact tests were conducted on 8- and 16-layer composite plates at energy levels of 10, 20, and 30 J. To evaluate the impact response of the composite plates, graphs of force versus time, force versus displacement curves, and energy versus time graphs were plotted. These curves and graph are presented in detail below, and the variations are explained.

3.1 Force-Time Curves

Figure 3 presents the force–time variations for 8- and 16-layer E-glass/epoxy composite plates subjected to impact energies of 10, 20, and 30 J.

Figure 3 demonstrates that, for all energy levels and both composite types, the force rapidly increases upon contact between the impactor and the specimen surface, reaches its peak value, and then drops to zero. The force-time variations exhibit a characteristic bell-shaped curve. It is clearly observed in the graphs that with increasing impact energy, the peak contact force rises as well. Conversely, while the contact force increases, the contact duration decreases. Additionally, the graphs indicate that a rise in layer number results in higher peak contact force, whereas the contact duration decreases. This observation is in agreement with previous findings in the literature; for instance, it was reported that increasing the number of E-glass/epoxy composite plate layers from 6 to 18 led to a 2.39-fold increase in peak force, further validating the results of the current study [27]. This supports the conclusion that a higher number of layers enhances the stiffness of the composite plates.

Furthermore, when the curves in Figure 3 are examined, it is observed that, at the 30 J energy level, the 8-layer composite plate exhibits more pronounced oscillations compared to both the 16-layer plate at the same energy level and all specimens subjected to lower energy levels. These oscillations indicate the occurrence of different damage mechanisms in the composite plates [28].



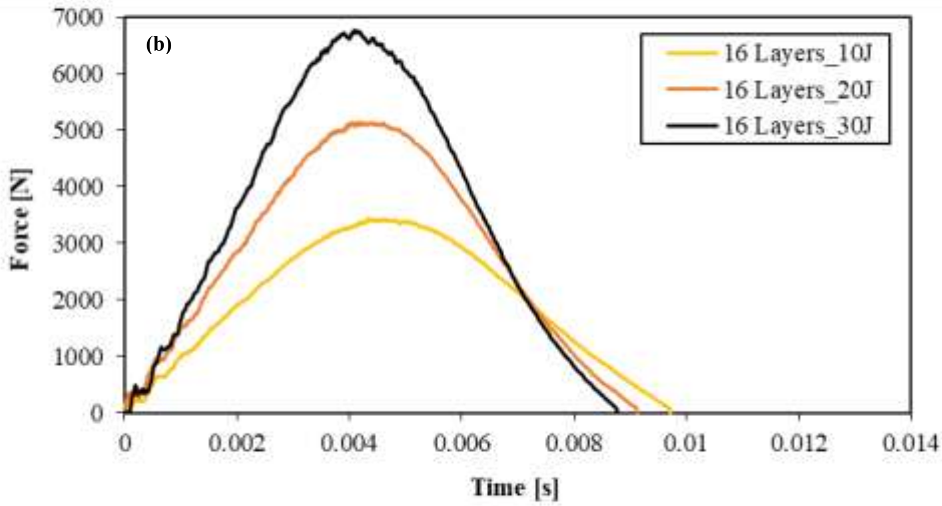


Figure 3. Force-time variation of **(a)** 8-layer and **(b)** 16-layer composite plates under varying impact energy conditions

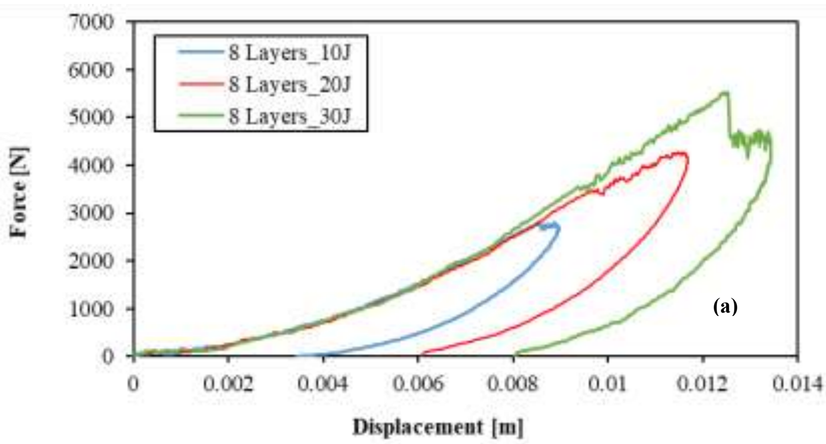
3.2 Force-Displacement Curves

Another key graph used to examine the impact response of composite materials exposed to low-velocity impacts is the force-displacement curve. The variations in force-displacement for 8- and 16-layer composite plates exposed to low-velocity impacts at 10, 20, and 30 J are presented in Figure 4.

As shown in Figure 4, displacement begins immediately upon impactor contact with the composite specimen, persisting until the force attains its peak value. The graphs distinctly reveal that both peak contact force and displacement rise with increasing impact energy. Moreover, increasing the number of layers leads to a noticeable reduction in maximum displacement. This finding aligns with the literature, where doubling the number of layers was reported to reduce maximum displacement by approximately 50% [19].

The gradient of the rising segment of the force-displacement graph is termed bending rigidity, as it represents the specimen's resistance to impact loading [29]. The graphs show that adding more layers improves the bending rigidity, while increasing the impact energy level does not significantly affect bending rigidity.

The region beneath the force-displacement graph corresponds to the energy absorbed by the composite plate. Figure 4 illustrates that, for all specimens, the region beneath the force-displacement graph expands with increasing impact energy, signifying greater energy absorption by the composite structure.



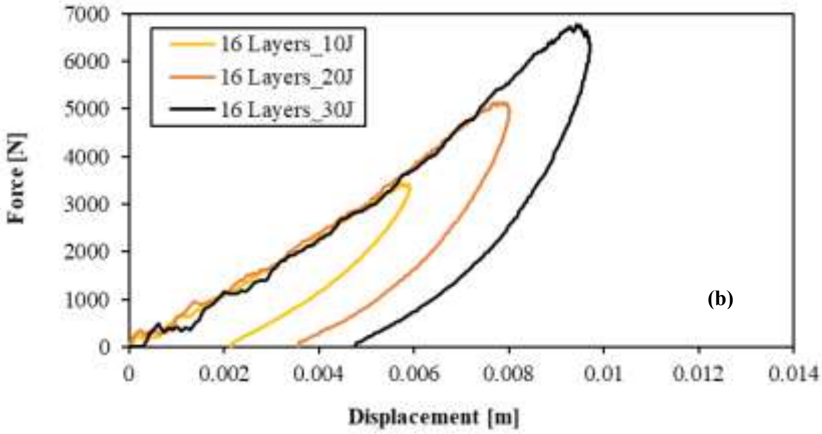


Figure 4. Force-displacement variation of **(a)** 8-layer and **(b)** 16-layer composite plates under varying impact energy conditions

3.3 Energy Distribution Graphs

In low-velocity impact events, the initial energy of the impactor before free fall (impact energy) is distributed through multiple pathways, including rebound energy, energy consumed by the force sensor, energy dissipated in the impactor, elastic energy stored in the support system, shear energy at the clamping points, and energy transferred to the composite material (absorbed elastic energy and damage energy) [30]. However, as the losses related to many of these mechanisms are relatively minor, they were disregarded in this study. The total energy was analyzed in two parts: the portion retained by the material and the rebound energy.

The variations in absorbed energy for 8- and 16-layer composite plates exposed to low-velocity impacts at energy levels of 10, 20, and 30 J are presented in Figure 5.

The 8-layer composite plates absorbed approximately 57%, 63%, and 76% of the impact energy at 10, 20, and 30 J, respectively. The 16-layer composite plates absorbed approximately 51%, 61%, and 66% of the impact energy at 10, 20, and 30 J, respectively. At all impact energy levels, the 8-layer composite plates absorbed more energy than the 16-layer plates. This indicates that the 16-layer composite plates are more rigid than the 8-layer ones. The absorbed energy amount rose as the impact energy increased. Notably, at the 30 J energy level, the absorbed energy for the 8-layer composite plate showed a significant increase compared to lower energy levels. As also supported by Figure 3 and Figure 4, this increase is primarily attributed to the fact that a substantial portion of the energy absorbed by the specimen was expended on damage [31].

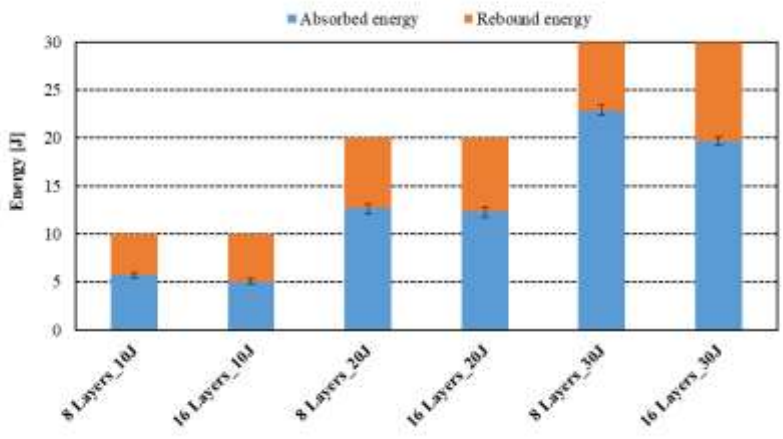


Figure 5. Energy variation of 8-layer and 16-layer composite plates under varying impact energy conditions

3.4 Damage Analysis

The energy absorbed by the material during low-velocity impact tests is expended on deformation and damage.

Figure 6 displays daylight photographs of the front and back surfaces of 8- and 16-layer composite specimens impacted at energy levels of 10, 20, and 30 J.

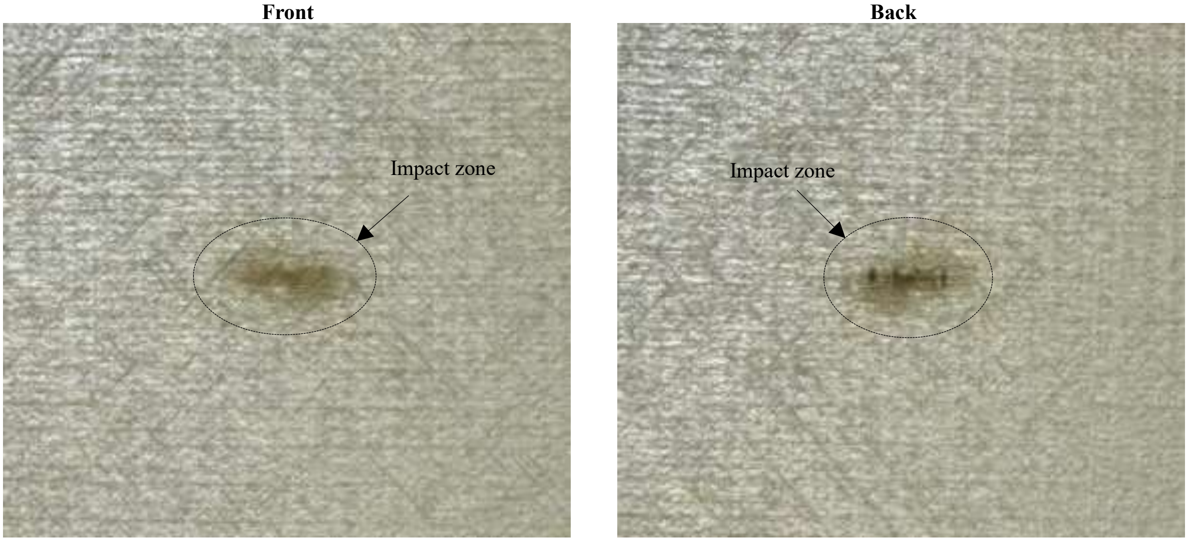
It was observed that, in all impacted composite specimens, the damage on the front surface subjected to impact was less severe than that on the back surface. While the front surface exhibited compression-induced damage, the back surface showed damage due to tensile forces. The damage caused by tension was more extensive than that caused by compression. As seen in Figure 6, matrix cracks and delamination damage were observed in both 8- and 16-layer composite plates at all energy levels. Additionally, the damage in 8-layer composite plates spread over a wider area compared to 16-layer plates at all energy levels. Furthermore, for the 30 J impact energy level, fiber/matrix debonding was observed in the lower layers of the 8-layer composite plates. As discussed in Section 3.3, at the 30 J energy level, 8-layer composite plates expended a significant portion of the absorbed energy on damage.

Figure 7 presents SEM images taken from cross-sections of damaged regions in 8-layer and 16-layer composite specimens subjected to impact energies of 10, 20, and 30 J. Examination of these images reveals that the extent of damage increases noticeably with rising impact energy in both types of specimens. The primary damage mechanisms observed in the composite materials include matrix cracking, fiber/matrix debonding, and delamination.

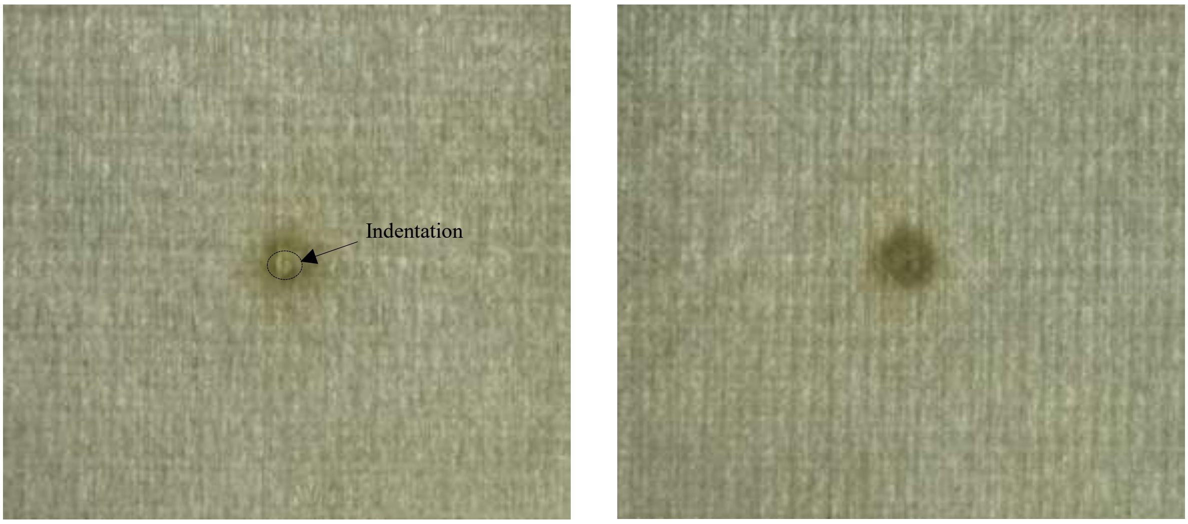
At all energy levels, it is evident that the 8-layer composite specimens exhibit a greater extent of damage compared to the 16-layer specimens. This can be attributed to the lower energy-dissipation capacity of thinner laminates. In contrast, the damage in 16-layer specimens tends to be more localized, suggesting that the increased number of layers helps distribute the impact energy more effectively, thereby maintaining structural integrity.

These microstructural findings are consistent with the macroscopic observations presented in Figure 6 and the absorbed energy data discussed in Section 3.3, reinforcing the conclusion that the number of layers plays a crucial role in determining the impact resistance and damage behavior of E-glass/epoxy composites.

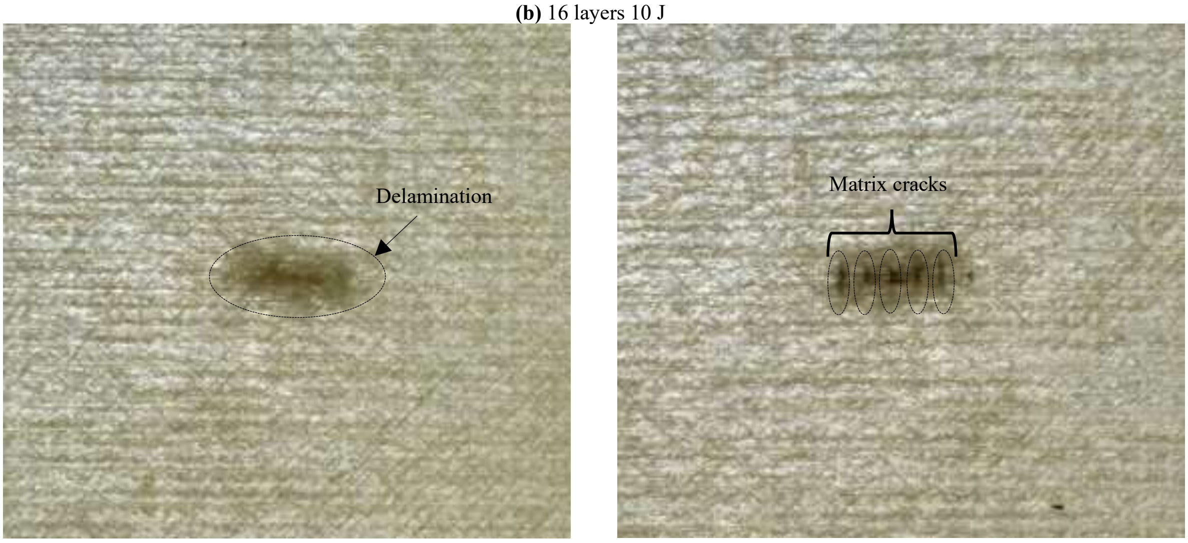
Front **Back**



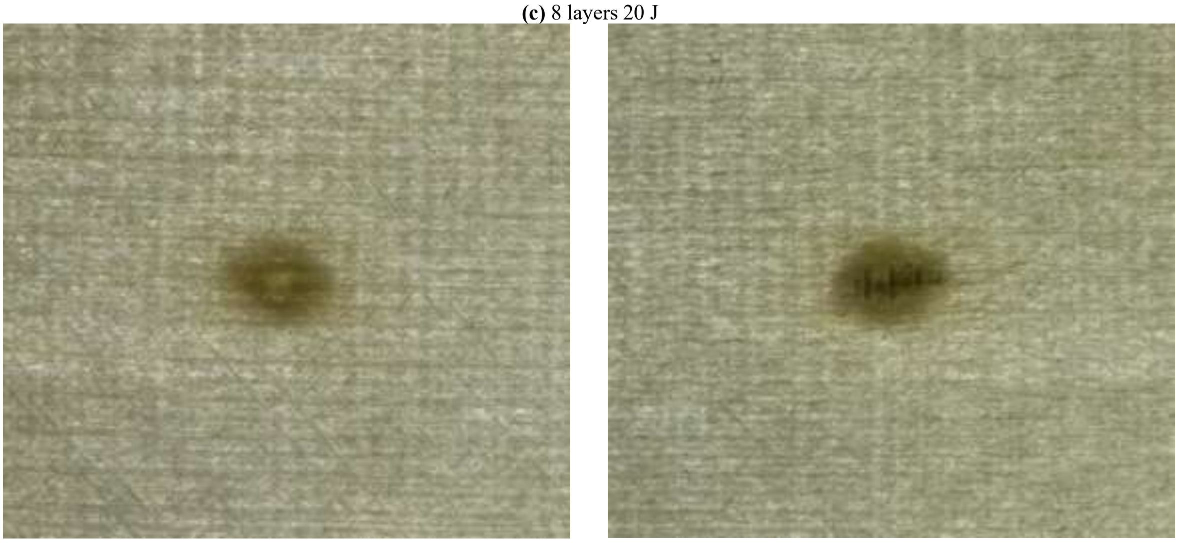
(a) 8 layers 10 J



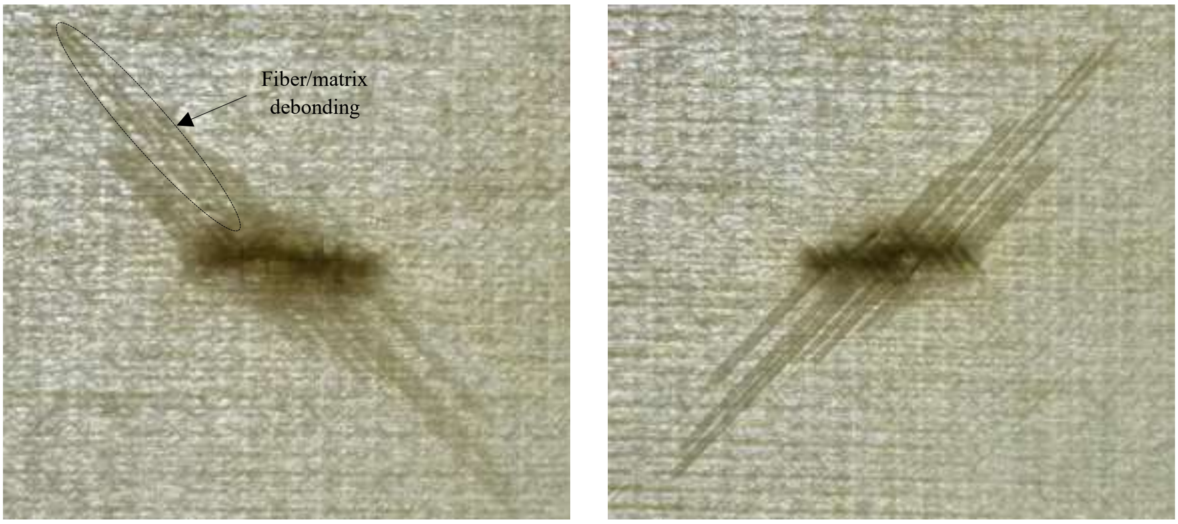
(b) 16 layers 10 J



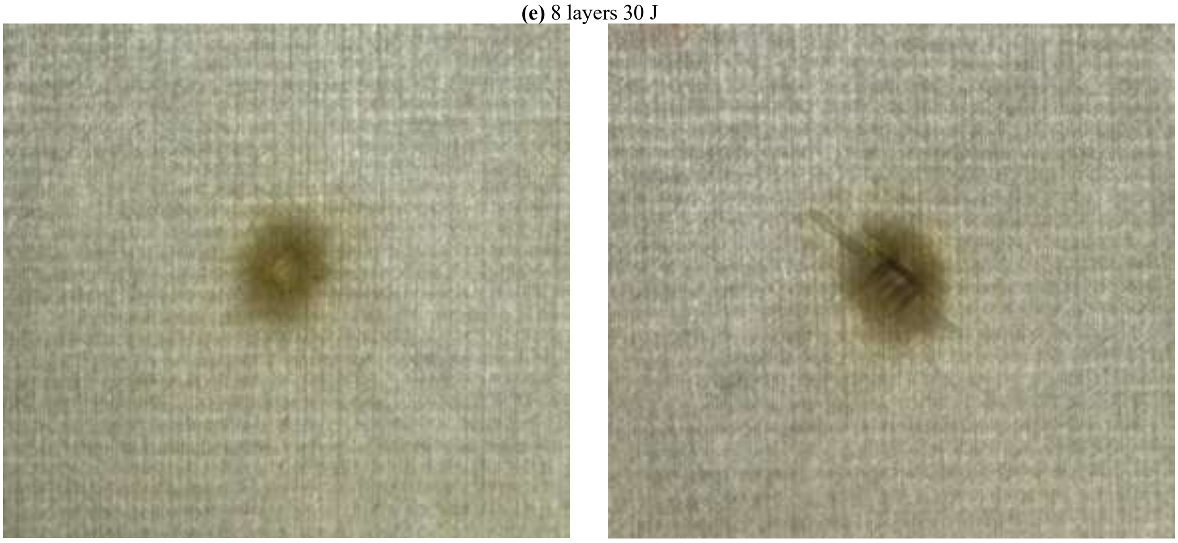
(c) 8 layers 20 J



(d) 16 layers 20 J

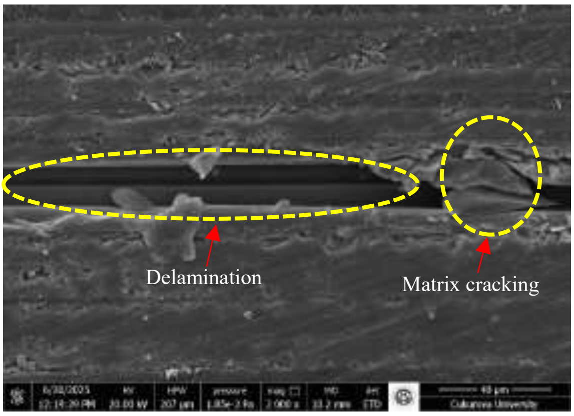


(e) 8 layers 30 J

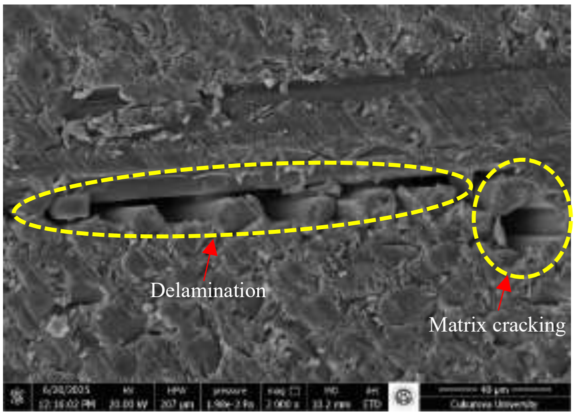


(f) 16 layers 30 J

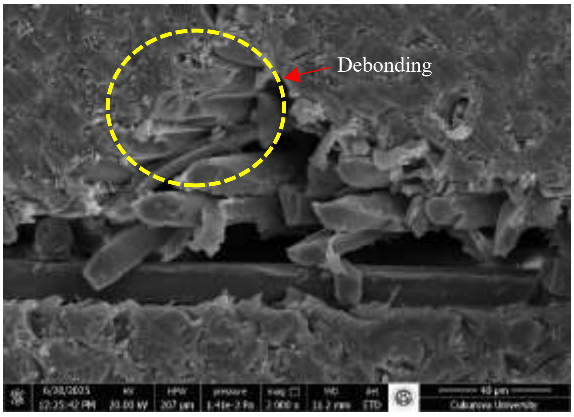
Figure 6. Damage images of **(a,c,e)** 8-layer composite plates and **(b,d,f)** 16-layer composite plates under varying impact energy conditions



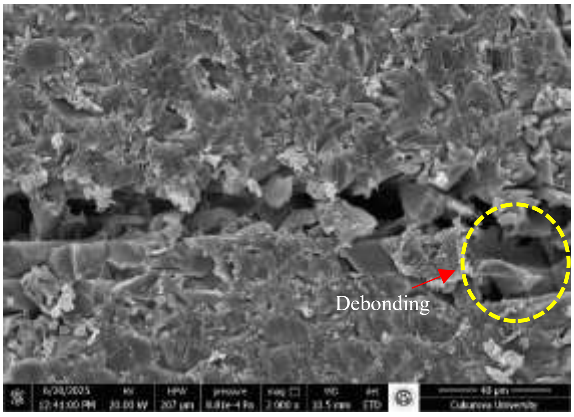
(a) 8 layers 10 J



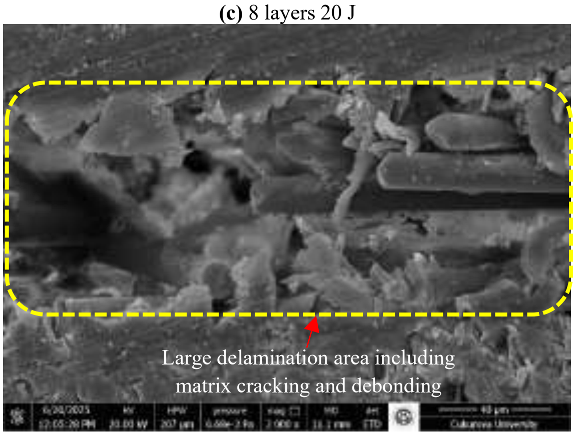
(b) 16 layers 10 J



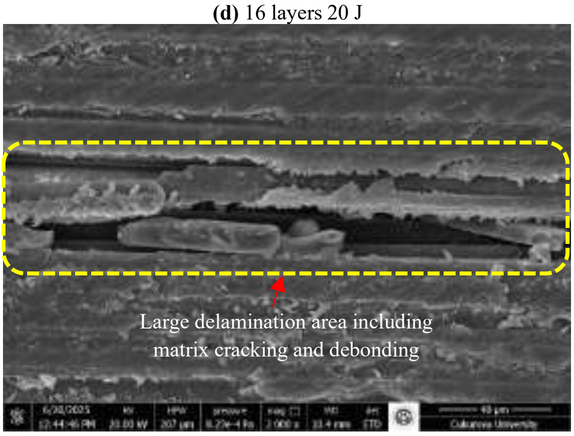
(c) 8 layers 20 J



(d) 16 layers 20 J



(e) 8 layers 30 J



(f) 16 layers 30 J

Figure 7. SEM images of **(a,c,e)** 8-layer composite plates and **(b,d,f)** 16-layer composite plates under varying impact energy conditions

IV. CONCLUSIONS

Composite plates are commonly employed in advanced engineering applications—including aerospace, automotive, and structural systems—where impact resistance is a critical design criterion, as exemplified by their use in aircraft fuselages, automotive body panels, wind turbine blades, and protective barriers. In this context, understanding how different parameters—such as the number of layers and impact energy—affect the low-velocity impact response of composite materials is essential for optimizing their performance in real-world applications. The findings of this study provide valuable insights into the energy absorption capacity, damage tolerance, and rigidity behavior of unidirectional E-glass/epoxy composite plates, which can inform the design of safer and more efficient composite components in various industries.

This study examined the effect of layer number on the impact behavior of unidirectional E-glass fiber epoxy plates at impact energies of 10, 20, and 30 J. The outcomes derived from low-velocity impact tests can be outlined as follows:

- The maximum contact force values obtained for the 8-layer composite plates under impact energies of 10, 20, and 30 J were 2811.95 N, 4278.56 N, and 5520.45 N, respectively. For the 16-layer composite plates, these values were 3439.46 N, 5133.06 N, and 6769.05 N, respectively.
- The displacement values for the 8-layer composite plates were recorded as 8.96 mm, 11.68 mm, and 13.44 mm under impact energies of 10, 20, and 30 J, respectively. For the 16-layer composite plates, the corresponding displacement values were 5.91 mm, 8.01 mm, and 9.71 mm.

- The 8-layer composite plates absorbed approximately 57%, 63%, and 76% of the applied 10, 20, and 30 J impact energies, respectively. The 16-layer composite plates absorbed 51%, 61%, and 66% of the energy at these levels, respectively.
- For the same impact energy, increasing the number of layers led to a rise in the maximum contact force and bending rigidity of the composite plates, whereas it resulted in a decrease in displacement and absorbed energy.
- At all energy levels, the damage in the 8-layer composite plates was observed to extend over a wider area compared to the 16-layer plates.

These findings are of significant practical value for the design and optimization of composite structures in various engineering applications. For instance, the enhanced energy absorption capacity and damage tolerance observed in thicker laminates are critical in applications where structural integrity must be maintained after accidental impacts—such as in automotive body panels, aerospace fairings, and protective casings. The increase in bending stiffness with increasing layer count is beneficial in applications requiring high dimensional stability and vibration resistance, such as floor panels or load-bearing elements in vehicles and aircraft. Meanwhile, the reduced displacement and more localized damage in multi-layered composites contribute to improved service life and post-impact performance, which are vital for safety-critical systems. Overall, the results of this study offer useful guidance for engineers aiming to tailor composite performance according to specific structural demands.

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