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LOW-VELOCITY IMPACT BEHAVIOR OF GLASS FIBER/EPOXY-ALUMINUM HONEYCOMB CORE SANDWICH COMPOSITES WITH VARYING FIBER ORIENTATIONS AND CORE THICKNESSES: EXPERIMENTAL STUDY

DEĞİŞEN ELYAF YÖNLENDİRMELERİ VE ÇEKİRDEK KALINLIKLARINA SAHİP CAM ELYAF/EPOKSİ-ALÜMİNYUM PETEK ÇEKİRDEK SANDVİÇ KOMPOZİTLERİN DÜŞÜK HIZLI DARBE DAVRANIŞI: DENEYSEL ÇALIŞMA

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ABSTRACT

This research experimentally investigates the low-velocity impact response of sandwich composites with glass fiber/epoxy face sheets and aluminum honeycomb cores, focusing on face sheet layup and core thickness. Three face sheet configurations, $[0/0/0/0]_s$, $[0/90/90/0]_s$, and $[45/-45/-45/45]_s$, and honeycomb cores with thicknesses of 6, 10, and 15 mm were examined. Low-velocity impact tests were conducted according to ASTM D7136, and impact performance was evaluated through force-displacement responses and visible damage. The results showed that fiber orientation and core thickness significantly influenced impact resistance and damage mechanisms. Cross-ply specimens exhibited higher initial peak force resistance, whereas angle-ply specimens showed a more progressive and ductile failure behavior with enhanced energy dissipation over a larger displacement range. Increasing core thickness reduced impact energy transmission to the lower regions and decreased damage severity in the lower face sheet. These findings demonstrate that appropriate selection of face sheet orientation and core thickness can improve the impact performance of sandwich composites for aerospace, automotive, and marine applications.

Keywords: Aluminum honeycomb, glass fiber/epoxy, low-velocity impact, sandwich composite.

ÖZET

Bu çalışmada, cam elyaf/epoksi yüzey tabakaları ve alüminyum petek çekirdekten oluşan sandviç kompozitlerin düşük hızlı darbe davranışı, yüzey tabakası dizilimi ve çekirdek kalınlığına odaklanılarak deneysel olarak incelenmiştir. $[0/0/0/0]_s$, $[0/90/90/0]_s$ ve $[45/-45/-45/45]_s$ olmak üzere üç yüzey tabakası konfigürasyonu ile 6, 10 ve 15 mm kalınlığındaki petek çekirdekler değerlendirilmiştir. Düşük hızlı darbe testleri ASTM D7136 standardına göre gerçekleştirilmiş ve darbe performansı kuvvet-yer değiştirme tepkileri ile görünür hasar üzerinden değerlendirilmiştir. Sonuçlar, elyaf yönelimi ve çekirdek kalınlığının darbe direnci ve hasar mekanizmalarını önemli ölçüde etkilediğini göstermiştir. Çapraz katmanlı numuneler daha yüksek başlangıç tepe kuvveti direnci gösterirken, açılı katmanlı numuneler daha geniş bir yer değiştirme aralığında yüksek enerji sönümleme ile daha ilerlemeli ve sünek bir hasar davranışı sergilemiştir. Çekirdek kalınlığının artırılması, darbe enerjisinin alt bölgelere iletimini ve alt yüzey tabakasındaki hasar şiddetini azaltmıştır. Bulgular, uygun yüzey tabakası yönelimi ve çekirdek kalınlığı seçiminin havacılık, otomotiv ve denizcilik uygulamalarına yönelik sandviç kompozitlerin darbe performansını iyileştirebileceğini göstermektedir.

Anahtar Kelimeler: Alüminyum petek, cam elyaf/epoksi, düşük hızlı darbe, sandviç kompozit.

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INTRODUCTION

Sandwich composites are preferred in many industrial applications due to their superior properties such as high strength, rigidity, thermal and acoustic insulation, impact resistance, energy absorption capacity, lightness, and corrosion resistance (Zhang et al., 2014; Njuguna et al., 2011). These structures have a wide range of uses, such as aviation, marine, automotive, defense, and packaging sectors. Depending on the application areas, sandwich structures are usually exposed to impact loading, and this can lead to various types of damage (Kaveloğlu and Temiz, 2024; Alfouneh et al.,2020). Therefore, it is of great importance to predict and evaluate possible damage in advance. Researchers have used various experimental methods, such as Charpy (Chen et al., 2020), Izod (Hao et al., 2013), and low-speed impact (drop weight) (Zangana et al., 2020) tests to determine the impact resistance of sandwich composites. Among these methods, low-velocity impact testing is the most widely preferred test method for sandwich composites because it best simulates real impact conditions (Kaveloğlu and Temiz, 2024). There are many studies in the literature examining the behavior of sandwich composites under low-velocity impact.

In the study conducted by Sun et al., the effects of structural parameters such as face plate thickness, core height, honeycomb cell size, and cell wall thickness on the low-velocity impact behavior of honeycomb core sandwich panels were investigated by both experimental and numerical methods (Sun et al., 2021). In the study conducted by Zangana et al., the behavior of a new composite corrugated core sandwich structure under low-velocity impact was experimentally investigated. The effect of different geometric parameters (thickness, height, span length) was investigated, and four different core configurations were evaluated. It was determined that core thickness increased the impact capacity (Zangana et al., 2021). Öztürk and Elaldı investigated the damage behavior of honeycomb composite structures in bird strike scenarios with experimental and numerical methods. Impact tests were performed with a rubber impactor at different energy levels (224 J, 276 J, and 380 J) on sandwich samples with prepreg carbon fiber surface plates, and the damage development was evaluated with graphs such as force-time, displacement-time, and energy-time. The numerical analyses performed using Ansys software were compared with the experimental findings, and it was shown that the obtained model provided reliable results with 10% deviation (Öztürk and Elaldı, 2024). Öndürücü and Karacan experimentally investigated the impact behavior of glass fiber/epoxy based composite panels under different layer numbers and fiber orientation angles. In low-speed impact tests performed on 8- and 12-layer composite samples by applying 10 J, 20 J, and 30 J impact energies, the effect of fiber orientation and layer thickness on the impact behavior was evaluated. The findings obtained showed that as the impact energy increased, the maximum force and the amount of collapse also increased. Especially in the G38 samples with $[0°/30°/60°/0°]_s$ arrangement, the highest deformation occurred at 30 J impact energy. It was also stated that the 8-layer samples showed lower impact strength compared to the 12- layer ones (Öndürücü and Karacan, 2018). Yapıcı and Yapıcı investigated the dynamic behavior of E-glass/epoxy composite panels under low-velocity impact using the finite element method. This study contributes to the understanding of low-velocity impact scenarios by numerically revealing the changes in the dynamic response of the composite panel with the increase of the impact velocity (Yapıcı and Yapıcı, 2016). Bozkurt investigated the low-velocity impact behavior of glass fiber reinforced plastic (GFRP) surface layer aluminum honeycomb core sandwich structures using the finite element method. The effects of parameters such as plate thickness, core layer number, cell wall thickness, impact location, and impact velocity on maximum contact force, energy absorption capacity, and failure modes were evaluated (Bozkurt, 2024). Wang et al. investigated the impact response and damage mechanisms of honeycomb core sandwich structures made of carbon fiber reinforced polymer (CFRP) composites under low-velocity impact. As a result of the impact tests carried out at four different energy levels, four different damage scenarios ranging from no visible damage on the surface to full penetration were established. In addition, a refined finite element model including structural parameters such as wall thickness, cell edge length, and core height of the honeycomb core was developed to explain the deformation behavior and energy absorption mechanisms in detail. The experimental and numerical results showed high consistency in terms of maximum impact force, failure mode, and energy absorption (Wang et al., 2024). In the study of Özbek et al., the effects of fiber orientation angle on the low-velocity impact behavior of basalt fiber reinforced composite laminates were investigated experimentally. Specimens were prepared at different orientation angles (0º/90º, 15º/−75º, 30º/−60º, and 45º/−45º) and subjected to impact tests. The results showed that the fiber orientation angle plays a decisive role on the energy absorption capacity and impact toughness (Özbek et al., 2020).

This study presents a comprehensive investigation into the low-velocity impact response of sandwich composite structures comprising glass fiber/epoxy face sheets and an aluminum honeycomb core. In literature, the effects of fiber orientation sequences of the laminates or core geometry have generally been studied separately, and studies evaluating these parameters together are limited. In this study, the combined effects of varying the fiber orientation

sequences of the laminates ($[0/0/0/0]_s$, $[0/90/90/0]_s$, and $[45/-45/-45/45]_s$) and core thickness (6 mm, 10 mm and 15 mm) on low-velocity impact behavior were systematically investigated. Specimens were fabricated in compliance with ASTM standards and subjected to impact testing at multiple energy levels. The mechanical behavior was evaluated through an analysis of force-displacement histories and post-impact damage characterization. The effects of stacking sequence and core thickness on damage resistance and energy absorption mechanisms were elucidated. The findings provide critical design insights for optimizing sandwich structures tailored to specific application requirements.

MATERIALS and METHODS

Materials

In this research, aluminum honeycomb cores were integrated with glass fiber/epoxy face sheets to produce sandwich composite structures. The face sheets were reinforced with woven glass fiber fabrics, while the matrix system was composed of Araldite GY 9513 epoxy resin cured with triethylenetetramine (TETA) as the hardener. To evaluate the effect of fiber orientation on impact performance, three distinct stacking sequences were manufactured for the face sheets: $[0/0/0/0]_s$, $[0/90/90/0]_s$, and $[45/-45/-45/45]_s$. The "s" suffix denotes a symmetrical layup about the mid-plane of the aluminum honeycomb core. The aluminum honeycomb core, supplied by CEL Components Ltd. (Italy) in large flat panels, featured a hexagonal cell structure with a nominal cell size of 6 mm. With a cell wall thickness of approximately 0.05 mm, the core had a nominal density of 84 kg/m³. For this investigation, three core thicknesses were selected and used: 6 mm, 10 mm, and 15 mm.

Manufacturing Sandwich Composites

The face sheets were manufactured using a hand lay-up technique. The resin system was prepared by mixing the epoxy resin with its hardener in a ratio specified by the manufacturer. The glass fiber fabrics were then manually impregnated with the resin mixture; brushes and rollers were employed to ensure complete and uniform wetting. The impregnated plies were stacked in the designated orientation sequences.

Curing was conducted initially at room temperature for 24 hours. Subsequently, a post-curing cycle was carried out at 100°C for 2 hours to optimize the mechanical properties of the laminates.
Prior to assembly, the bonding surfaces of the face sheets were abraded with 80-grit sandpaper and subsequently cleaned with acetone to enhance adhesion at the interface with the core. The face sheets were then cut to the required dimensions and bonded to the aluminum honeycomb cores using a two-part structural epoxy adhesive (Araldite AW 106 resin with HV 953 hardener). Uniform pressure was applied during the bonding process to prevent the formation of gaps or weak interfacial bonds.

Finally, the assembled sandwich composites were cured under a weighted press for 24 hours at ambient temperature. A flowchart detailing the entire production process is provided in Figure 1.

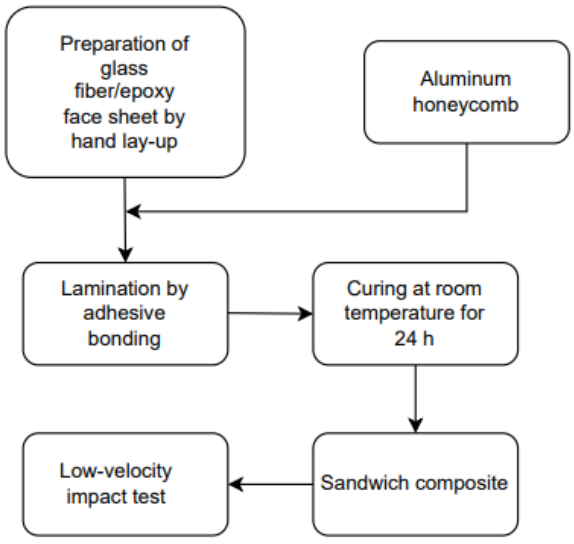

Figure 1. Flow Chart of Sandwich Composites Manufacturing Process

Testing Condition

The cured sandwich panels were sectioned into 100 mm x 100 mm square specimens using a band saw. Low-velocity impact tests were performed in accordance with ASTM D7136 standard, utilizing an instrumented drop-weight impact tester. The tests employed a 12.7 mm diameter hemispherical impactor tup. The total dropped mass, including the impactor, load cell, and crosshead, was 5 kg, and the load cell had a capacity of 22.4 kN. Throughout the impact event, force and displacement data were acquired by the integrated data acquisition system. Post-impact damage was characterized through visual inspection and documented photographically.

Experimental Details

A systematic nomenclature was developed to designate the sandwich composite specimens according to their core thickness and the fiber orientation of the face sheets. According to this system, the letter 'A' denotes an aluminum core, while 'C' indicates that both the upper and lower face sheets are fabricated from composite materials. The subsequent numerical value (6, 10, or 15) refers to the core thickness in millimeters. Finally, a hyphenated suffix defines the stacking sequence of the face sheets, as detailed below:

- The codes AC6-0, AC10-0, and AC15-0 correspond to a $[0/0/0/0]_s$ orientation.
- The codes AC6-90, AC10-90, and AC15-90 represent a $[0/90/90/0]_s$ orientation.
- The codes AC6-45, AC10-45, and AC15-45 indicate a $[45/-45/-45/45]_s$ orientation.

This coding convention allows for the clear and unambiguous identification of each specimen's architecture.

RESULTS and DISCUSSION

The present work evaluates the low-velocity impact performance of fabricated sandwich composites through an analysis of their force-displacement responses and post-impact damage characteristics. The investigation systematically examines the effects of fiber orientation ($[0/0/0/0]_s$, $[0/90/90/0]_s$, and $[45/-45/-45/45]_s$) and core thickness (6 mm, 10 mm, and 15 mm) on the impact response. Figures 2–4 depict the force–displacement responses and corresponding damage images (for both upper and lower face sheets) of sandwich composites with a 6 mm core thickness, featuring the three different fiber orientations, tested under varying impact energy levels.

When Figures 2-4 are examined, it is observed that the maximum impact force values and energy absorption capacities (represented by the area under the curve) of the specimens consistently increase with rising energy levels. At lower energy levels (e.g., 5 J), all specimens exhibit a sudden force increase upon impact, followed by a sharp drop, a behavior potentially associated with matrix cracking or initial delamination. At higher energies (15 J, 25 J, 35 J, and 45 J), the emergence of multiple peaks and fluctuations in the force-displacement curves signifies the activation of progressive and complex damage mechanisms. These include sequential core crushing, cell wall collapse, and stepwise delamination within the face sheets (Yalkın et al., 2022, Xie et al., 2018).

The influence of fiber orientation on impact behavior is clearly discernible. The AC6-90 configuration (Figure 3a) achieved higher maximum impact forces at specific energy levels compared to the other orientations. This can be attributed to the 90° fiber orientation providing reinforcement perpendicular to the impact direction, thereby enhancing initial penetration resistance (Özbek et al., 2020). Conversely, the AC6-0 (Figure 2a) and AC6-45 (Figure 4a) specimens demonstrated superior energy absorption capabilities by sustaining relatively high force levels over extended displacement ranges, particularly under high-energy impacts. This response suggests that the aligned fibers facilitate more effective load distribution and channel damage along defined paths. Notably, the ±45° orientation appears to synergize the benefits of the 0° and 90° configurations, promoting more uniform energy dissipation throughout the fiber-matrix system (Sharma et al., 2019).

At low impact energies (5 J and 15 J), all samples exhibited localized indentation or surface crushing. Nevertheless, the effect of fiber orientation became apparent even at 15 J. In the AC6-0 and AC6-90 specimens, damage propagation was primarily aligned parallel or perpendicular to the fiber direction, whereas in the AC6-45 specimens, it propagated diagonally at approximately 45°. With increasing energy impact, the extent and severity of damage intensified considerably across all configurations. The upper face sheets exhibited extensive crushing in all orientations, accompanied by core crushing and eventual perforation. However, the damage patterns on the lower face sheets most strikingly revealed the effect of fiber orientation.

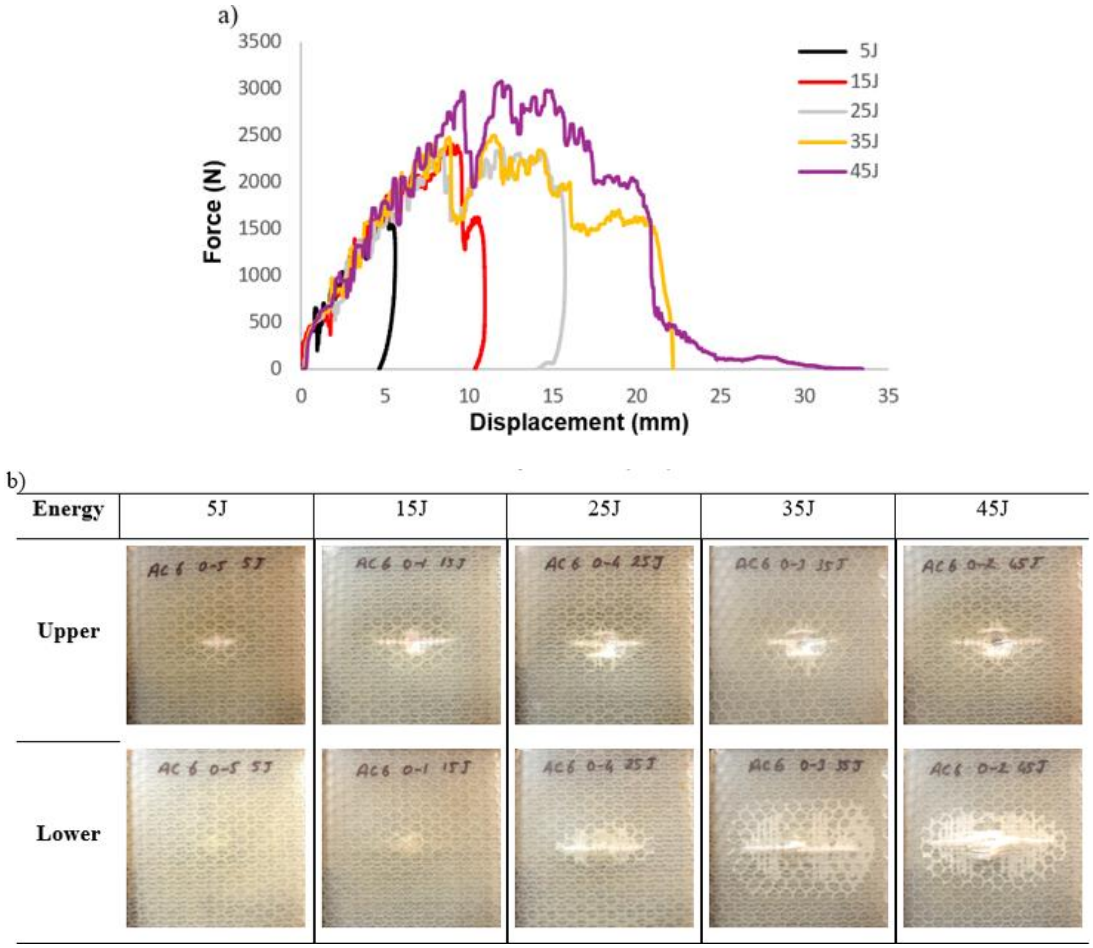

Figure 2. a) Force-Displacement Curve b) Damage Images Taken from Upper and Lower of AC6-0 Sandwich Structure for Different Energy Levels

Maximum force (F_{max}), maximum displacement (δ_{max}), absorbed energy, elastic recovery ratio, energy dissipation ratio, initial contact stiffness, and first damage initiation point values obtained from force-displacement curves for AC6-0 sandwich composite are given in Table 1. The impact energies given in the experiments are nominal values, and the absorbed energy was obtained by calculating the area under the force-displacement curve. The small differences observed between the nominal impact energy and the calculated absorbed energy are due to experimental uncertainties and numerical integration and are within acceptable limits for low-speed pulse experiments. Maximum impact force increased by approximately 89% from 5 J to 45 J, while maximum displacement increased nearly sixfold. The elastic recovery ratio decreases rapidly with increasing energy, approaching zero at 35 J and 45 J, indicating a transition to fully damage-dominated behavior. The initial contact stiffness remains within a relatively narrow range (≈270–325 N/mm), indicating preservation of the laminate's elastic response during early contact. The first significant load drop corresponds to the onset of internal damage, such as matrix cracking or delamination. The displacement at damage initiation increases progressively with impact energy, demonstrating enhanced deformation capacity prior to catastrophic damage.

Table 1. Global Impact Parameters (AC6-0 Sandwich Composite)

Impact Energy (J)	F_{max} (N)	δ_{max} (mm)	Absorbed Energy (J)	Elastic Recovery Ratio (%)	Dissipation Ratio	Initial Stiffness (N/mm)	First Load Drop Force (N)	First Load Drop Displacement (mm)
5	1622.8	5.62	5.28	6.3	1.057	304.3	1478.2	4.88
15	2402.4	10.95	15.97	0.6	1.065	266.9	2214.5	8.94
25	2368.3	15.71	26.01	1.1	1.041	288.8	2146.3	12.67
35	2503	22.17	36.87	0	1.054	324.3	2335.8	17.82
45	3077	33.49	44.62	0	0.992	285.4	2751.6	24.95

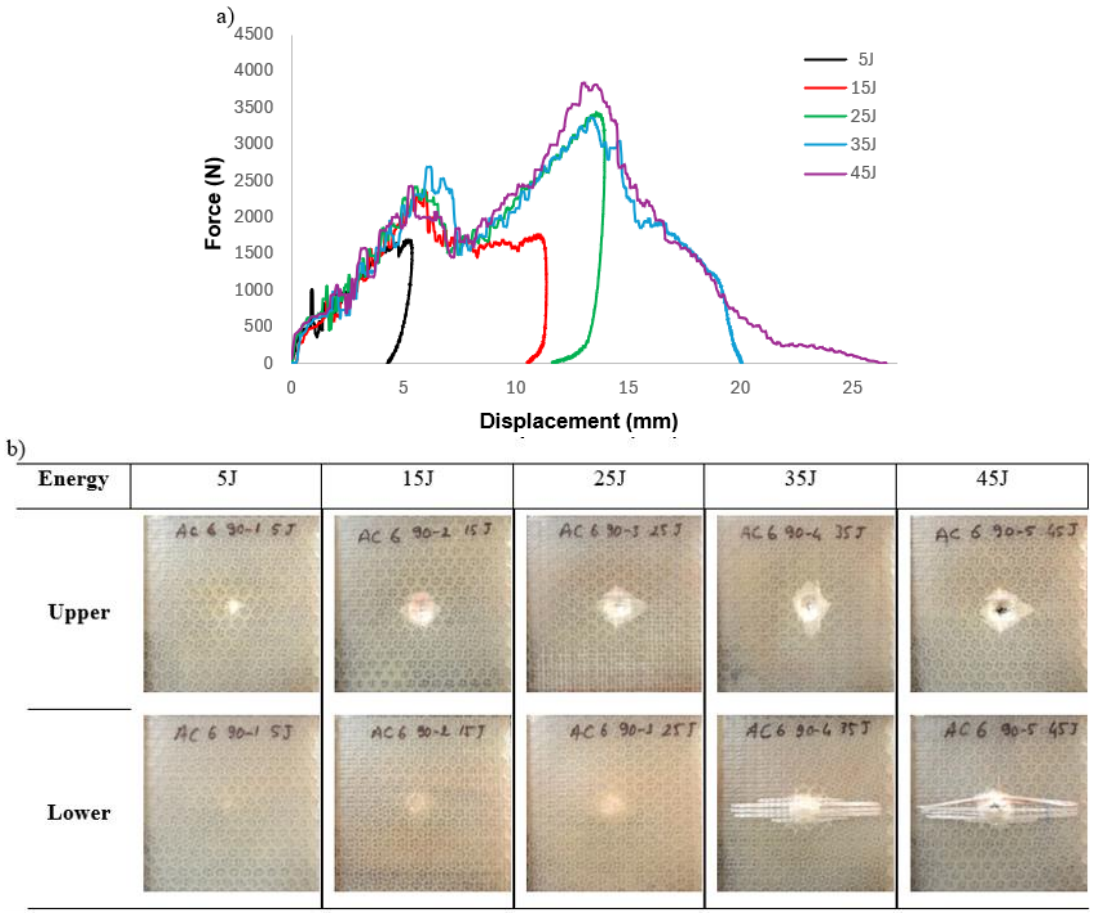

Figure 3. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC6-90 Sandwich Structure for Different Energy Levels

Global impact parameters values obtained from force-displacement curves for AC6-90 sandwich composite are given in Table 2. As energy impact increases, maximum force and displacement generally increase, while the elastic recovery ratio decreases. This indicates increasing permanent damage and dominance of irreversible damage mechanisms at higher impact levels. Initial stiffness represents the early elastic response of the structure. The first significant load drop corresponds to the onset of internal damage mechanisms such as matrix cracking or delamination.

For the AC6-45 sandwich composite, the global impact parameter values obtained from force-displacement curves are given in Table 3. According to the tabulated data, as the impact energy increases, the peak force and maximum deflection values show a corresponding increase, whereas the elastic recovery rate decreases. This behavior indicates that the structure accumulates more permanent damage at higher energy levels, where damage mechanisms become more dominant.

Table 2. Global Impact Parameters (AC6-90 Sandwich Composite)

Impact Energy (J)	F_{max} (N)	δ_{max} (mm)	Absorbed Energy (J)	Elastic Recovery Ratio (%)	Dissipation Ratio	Initial Stiffness (N/mm)	First Load Drop Force (N)	First Load Drop Displacement (mm)
5	1686.6	5.38	5.12	9.6	1.02	880.5	960.9	0.93
15	2340.0	11.34	15.84	1	1.06	532.3	873.1	1.57
25	3425.7	13.92	25.46	3.8	1.02	411.8	1051.7	1.57
35	3363.3	20.06	36.74	0	1.05	424.7	1050.2	2.05
45	3833.9	26.47	40.25	0	0.89	248.7	1067.2	2.03

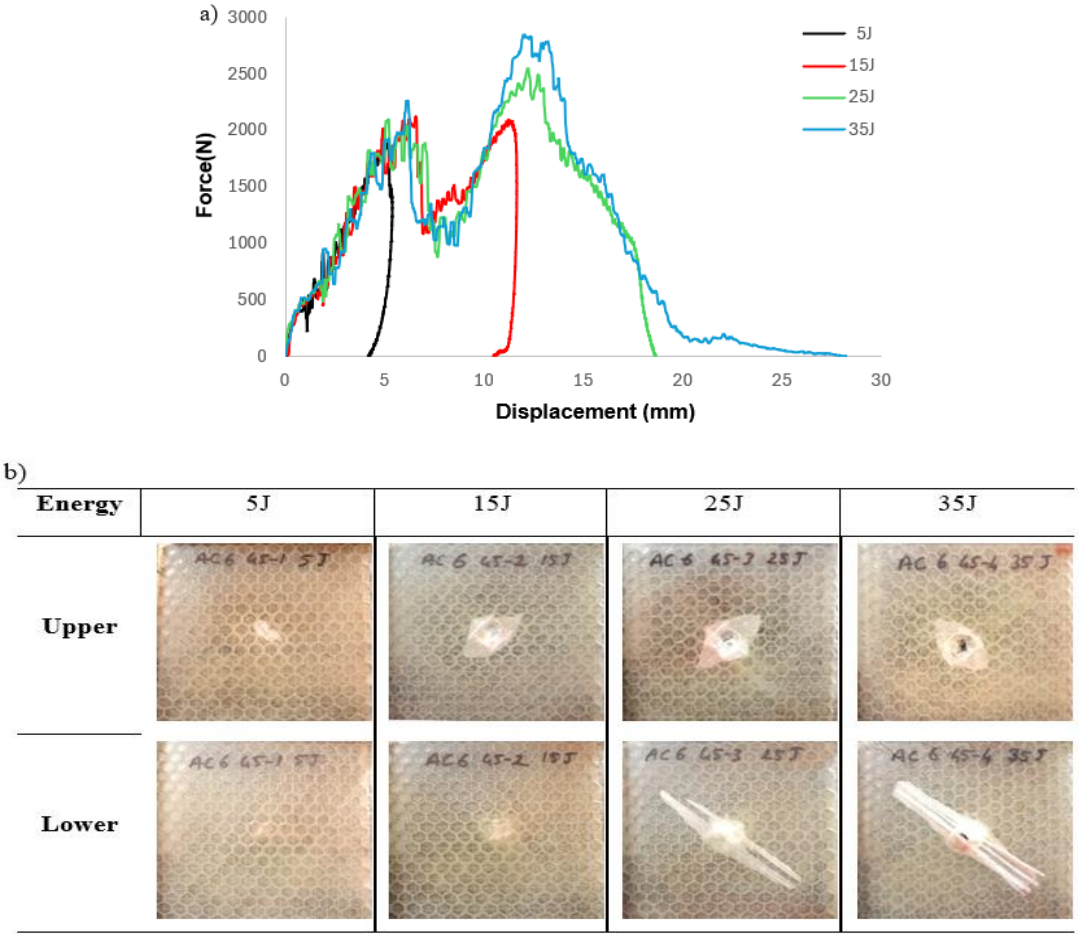

Figure 4. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC6-45 Sandwich Structure for Different Energy Levels

Table 3. Global Impact Parameters (AC6-45 Sandwich Composite)

Impact Energy (J)	F_{max} (N)	δ_{max} (mm)	Absorbed Energy (J)	Elastic Recovery Ratio (%)	Dissipation Ratio	Initial Stiffness (N/mm)	First Load Drop Force (N)	First Load Drop Displacement (mm)
5	1890.7	5.37	5.00	8.5	1	806.6	503.2	0.95
15	2117.5	11.64	15.62	1.6	1.04	443.6	562.7	1.58
25	2539.8	18.62	26.65	0	1.07	243.8	630.7	1.74
35	2844.6	28.21	29.08	0	0.83	254.2	919.8	2.13

Figures 5–7 present the force–displacement responses and corresponding damage images for both the upper and lower face sheets of sandwich composites with a 10 mm core thickness and varying fiber orientations. In specimens with a $[0/0/0/0]_s$ face sheet orientation, damage at energy levels up to 15 J was primarily confined to matrix cracking on the upper face sheet. The associated force–displacement curves exhibited a closed-loop profile, suggesting predominantly elastic deformation and some degree of recoverability. At higher impact energies, more severe and irreversible damage modes developed within both the core and the face sheets. Notably, for this specific core thickness (10 mm), delamination at the core-to-lower-face-sheet interface became a dominant failure mechanism, with its severity and aerial extent increasing significantly with higher energy levels.

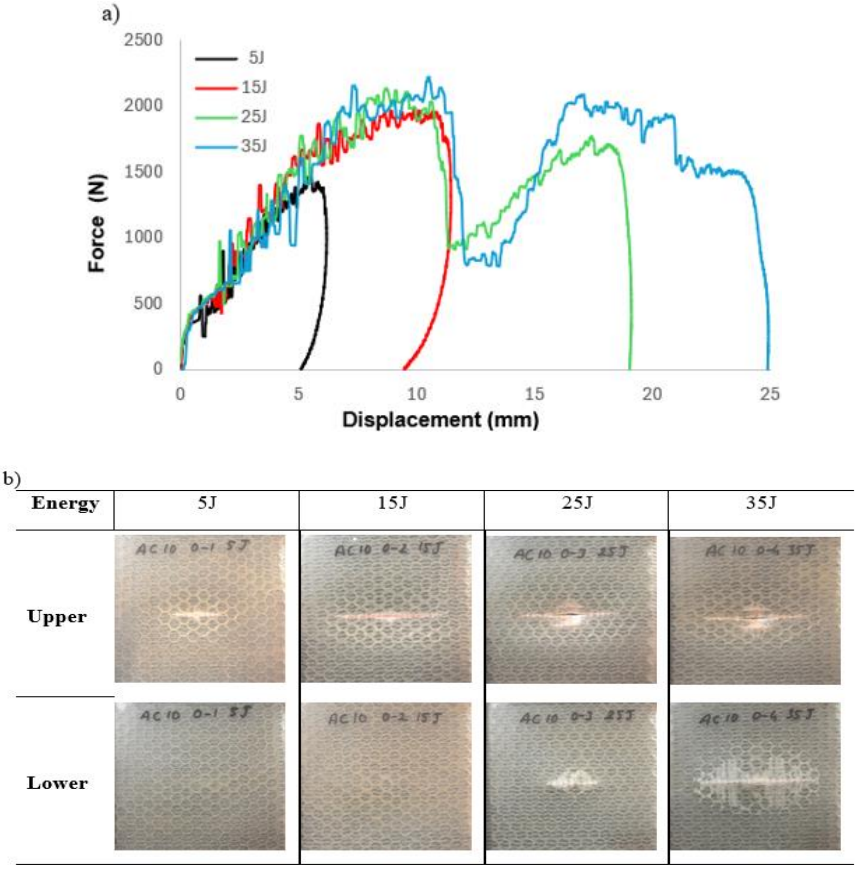

Figure 5. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC10-0 Sandwich Structure for Different Energy Levels

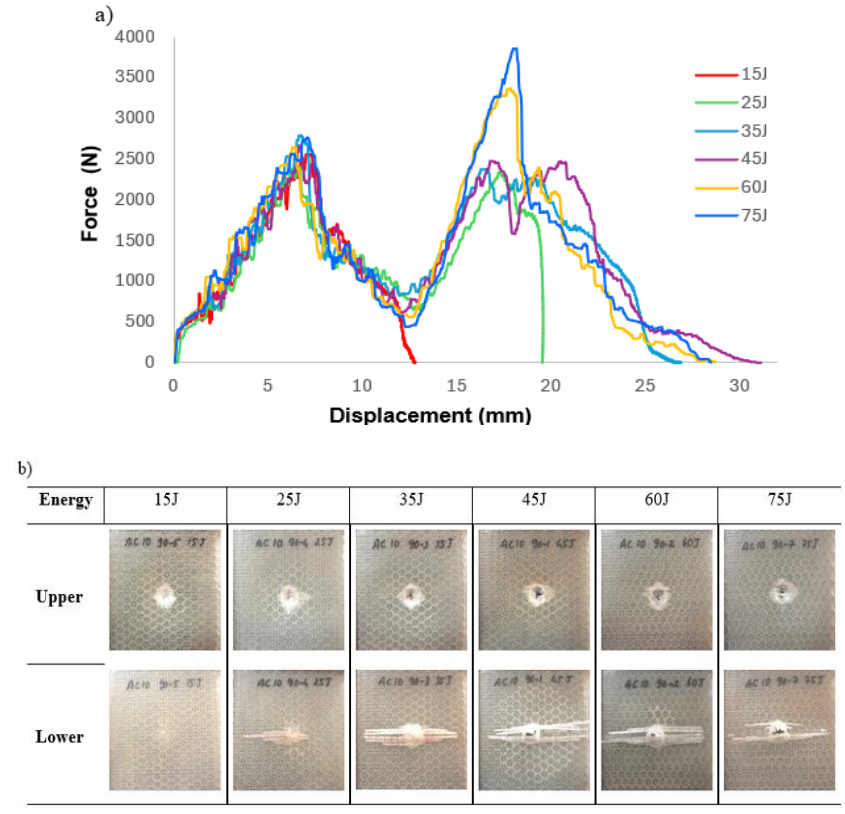

Figure 6. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC10-90 Sandwich Structure for Different Energy Levels

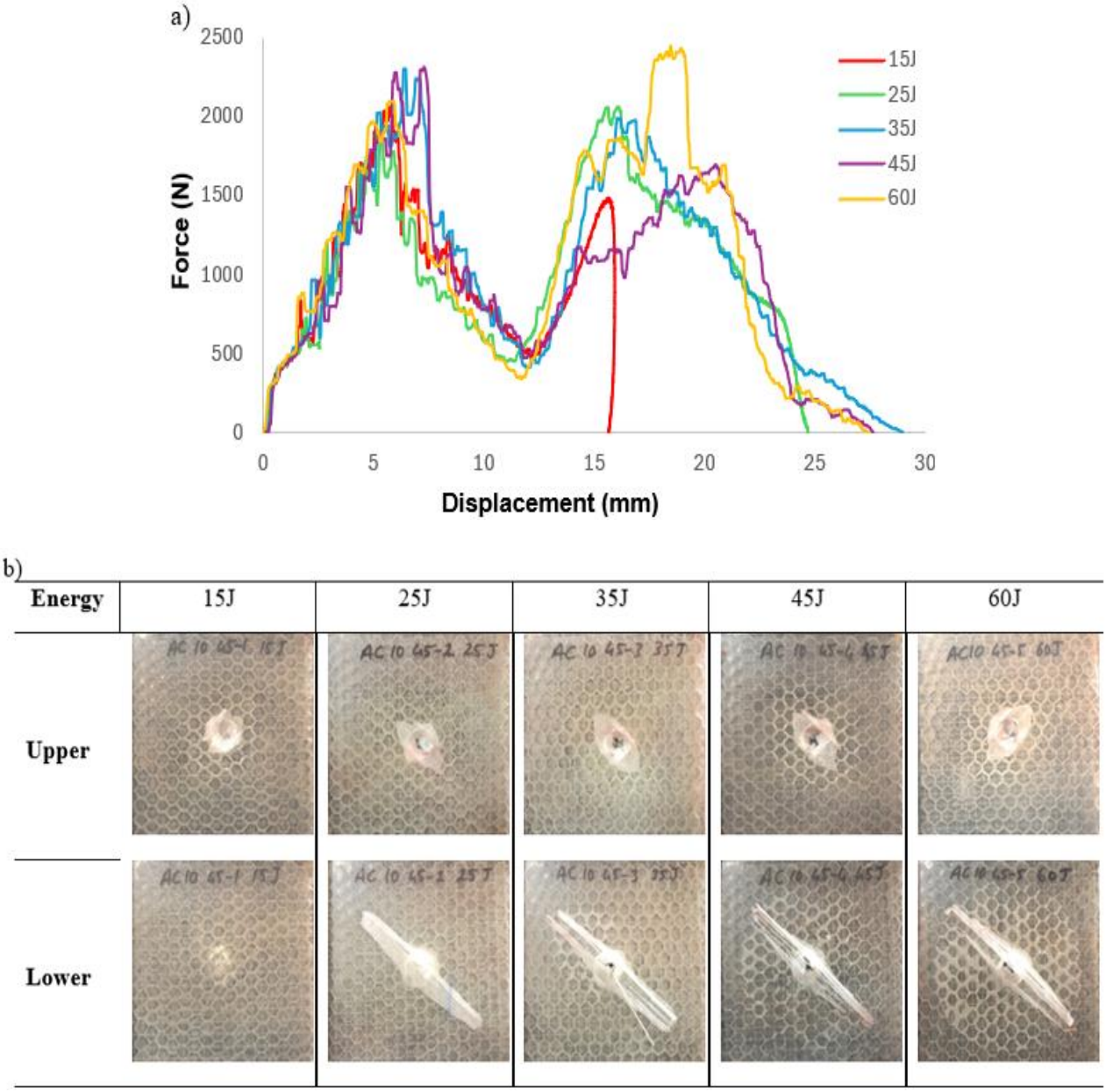

Figure 7. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC10-45 Sandwich Structure for Different Energy Levels

Figures 8–10 illustrate the force-displacement responses and corresponding damage imagery (captured from both upper and lower face sheets) for sandwich composites featuring a fixed core thickness of 15 mm and three distinct fiber orientations.

Analysis of these figures reveals that the damage mechanism is highly dependent on fiber orientation. In composites with a $[0/0/0/0]_s$ face sheet configuration, increasing impact energy induces permanent damage within the core and the lower face sheet, affecting both the matrix and the fibers. For the $[0/90/90/0]_s$ configuration, comparable damage to the core and lower face sheet becomes apparent starting at 15 J. The $[45/–45/–45/45]_s$ orientation exhibits the most pronounced susceptibility to damage; matrix and fiber damage are observed throughout the core, lower face sheet, and upper face sheet, commencing at the lowest energy level of 5 J. Furthermore, delamination at the core-to-lower face sheet interface is evident at energy levels of 25 J and above all fiber orientations at this core thickness.

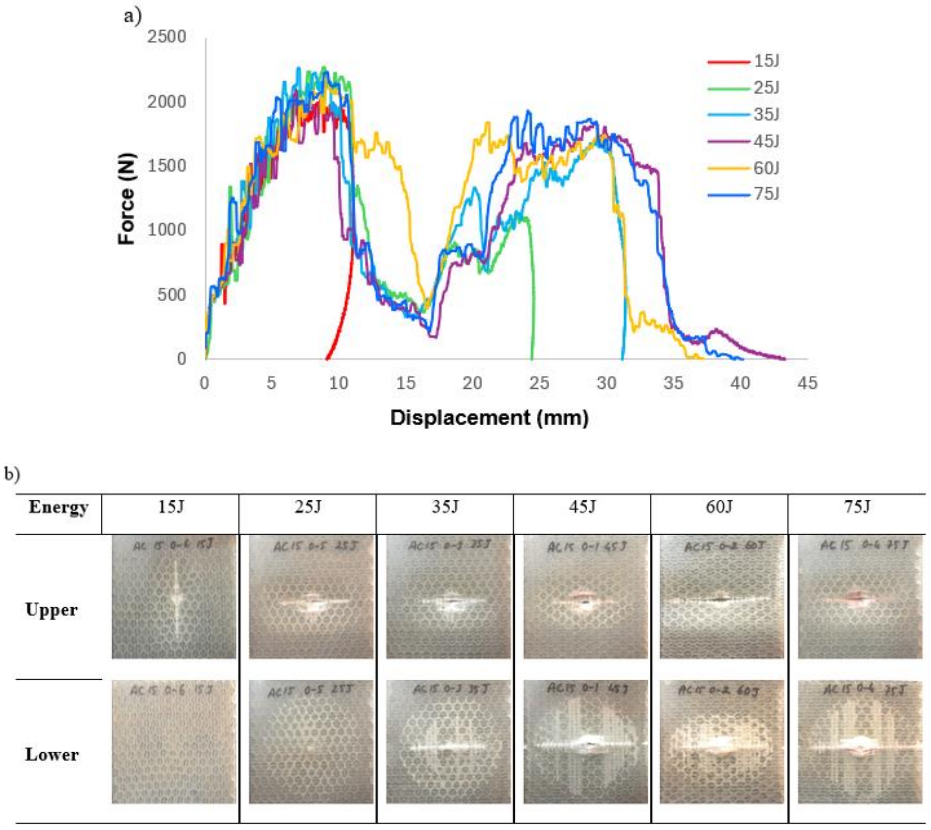

Figure 8. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC15-0 Sandwich Structure for Different Energy Levels

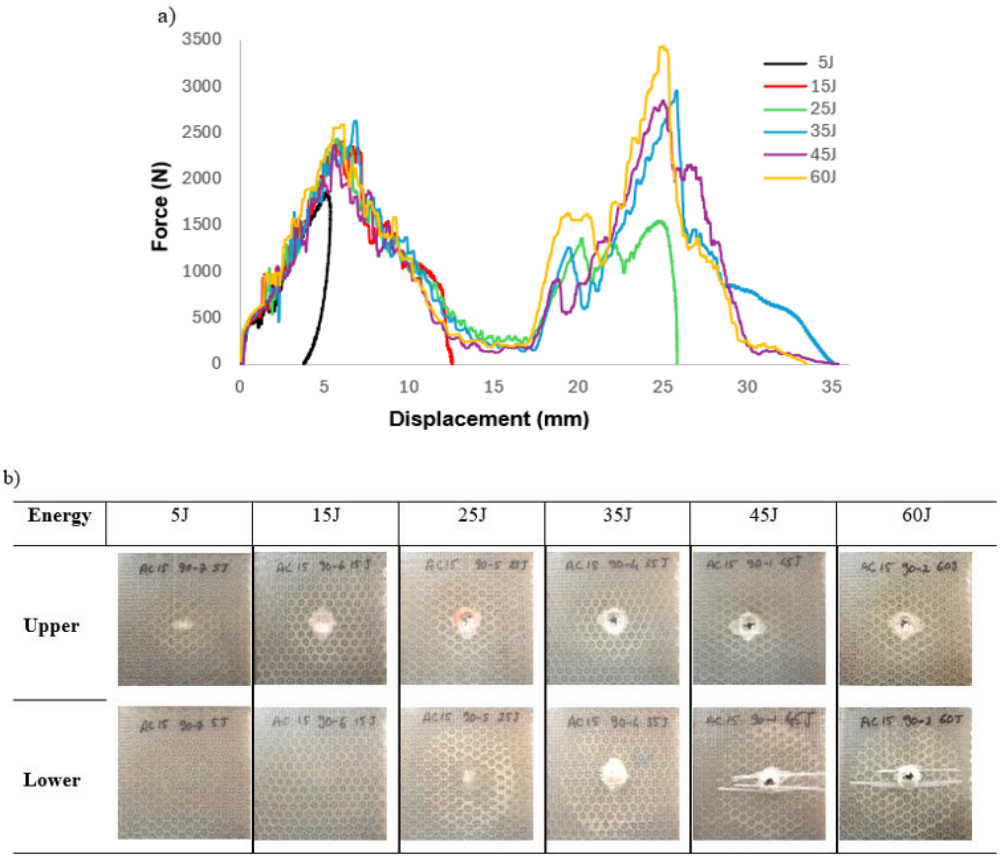

Figure 9. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC15-90 Sandwich Structure for Different Energy Levels

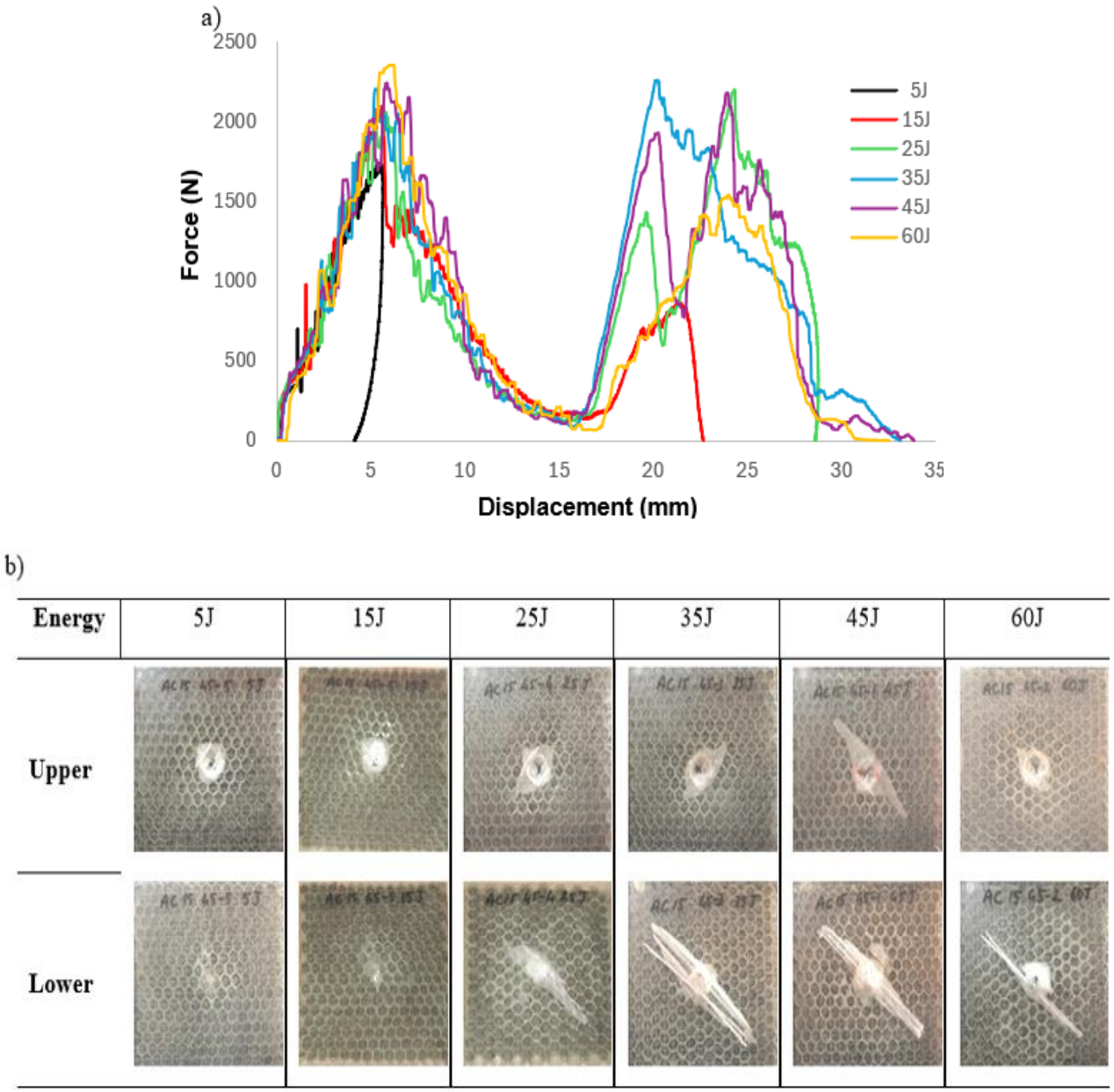

Figure 10. a) Force-Displacement Curve b) Damage Images Taken from the Upper and Lower of AC15-45 Sandwich Structure for Different Energy Levels

Figures 11–14 present the force–displacement curves and the corresponding damage images (captured from both the upper and lower face sheets) of sandwich composite specimens with $[0/0/0/0]_s$, $[0/90/90/0]_s$, and $[45/–45/–45/45]_s$ face sheet configurations. These specimens were subjected to two distinct impact energy levels (15 J and 35 J) with varying core thicknesses to evaluate the influence of core geometry on impact response.

At the 15 J impact energy level, increasing core thickness generally enhances both the impact resistance and energy absorption capacity across all fiber orientations. Among the configurations, the $[0/90/90/0]_s$ orientation demonstrates higher initial peak forces, while the $[45/–45/–45/45]_s$ orientation facilitates more sustained energy absorption and greater damage tolerance. At this energy level, greater core thickness contributes to improved damage resistance and a notable reduction in damage propagation within the lower face sheet.

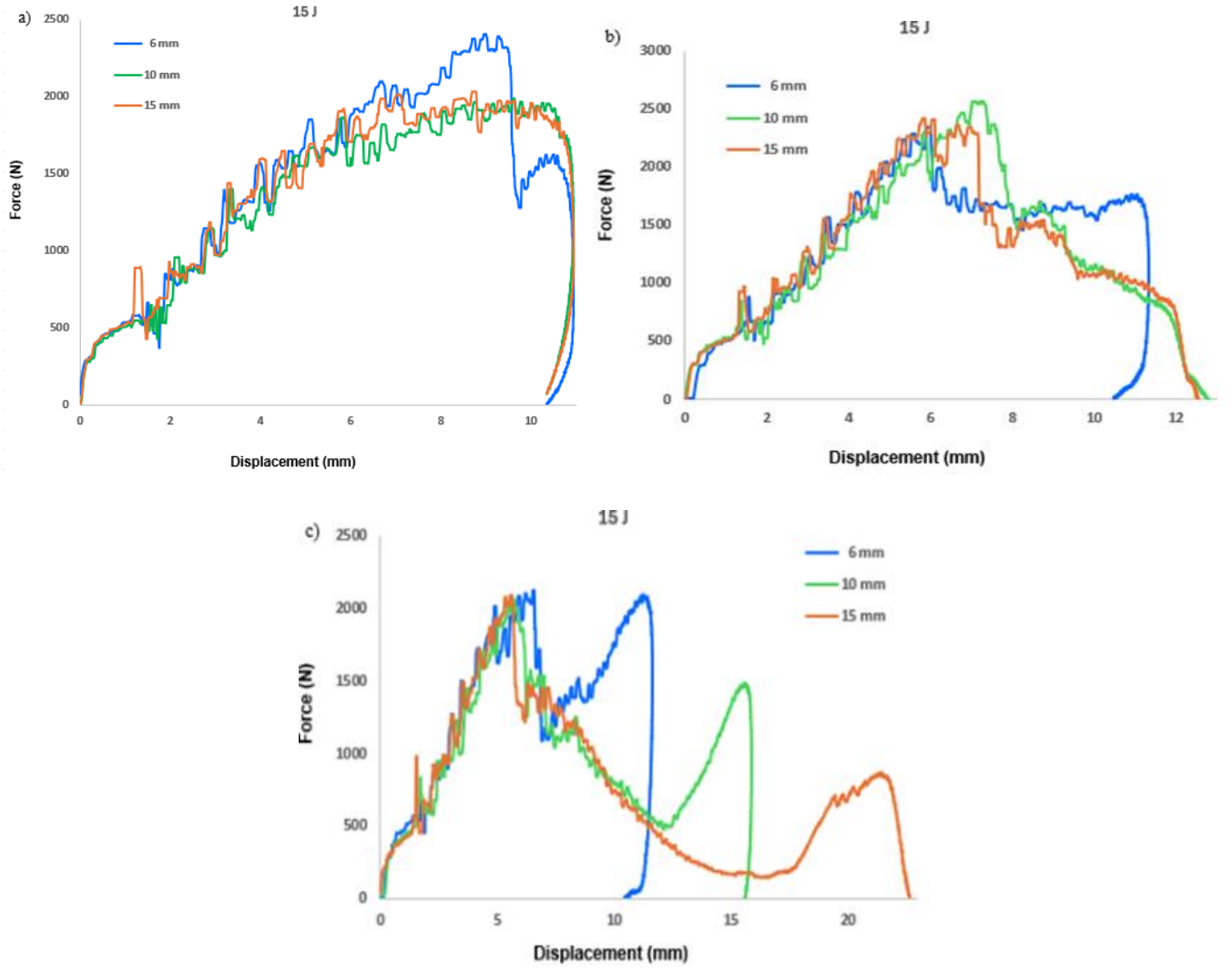

Figure 11. Force-Displacement Curve of the Sandwich Structure with a) 0° b) 90° c) 45° Orientation Angle and Different Core Thicknesses at 15 J Energy Value

Figure 12 shows that all samples exhibit local crashing and buckling at the impact point on the upper surface. Fiber orientation has a significant effect on the direction of damage propagation; in samples with 0° and 90° orientation, the damage develops parallel or perpendicular to the fiber directions, while in samples with 45° orientation, the damage spreads diagonally. Examination of the lower surface images reveals that the damage is spread over a wider area compared to the upper surface and is particularly pronounced in samples with thinner core thickness. This indicates that under impact load, local crushing occurs in the core and deformation occurs in the honeycomb cell walls, and the damage propagates along the thickness. The decrease in the damaged area on the lower surface with increasing core thickness suggests that the thicker core absorbs impact energy more effectively and reduces tensile stresses on the back surface. Although no sectioning or tomographic examination was performed in this study to directly determine the internal damage mechanisms, the combined assessment of anterior and posterior surface damage provides indirect evidence that the damage progresses along the thickness.

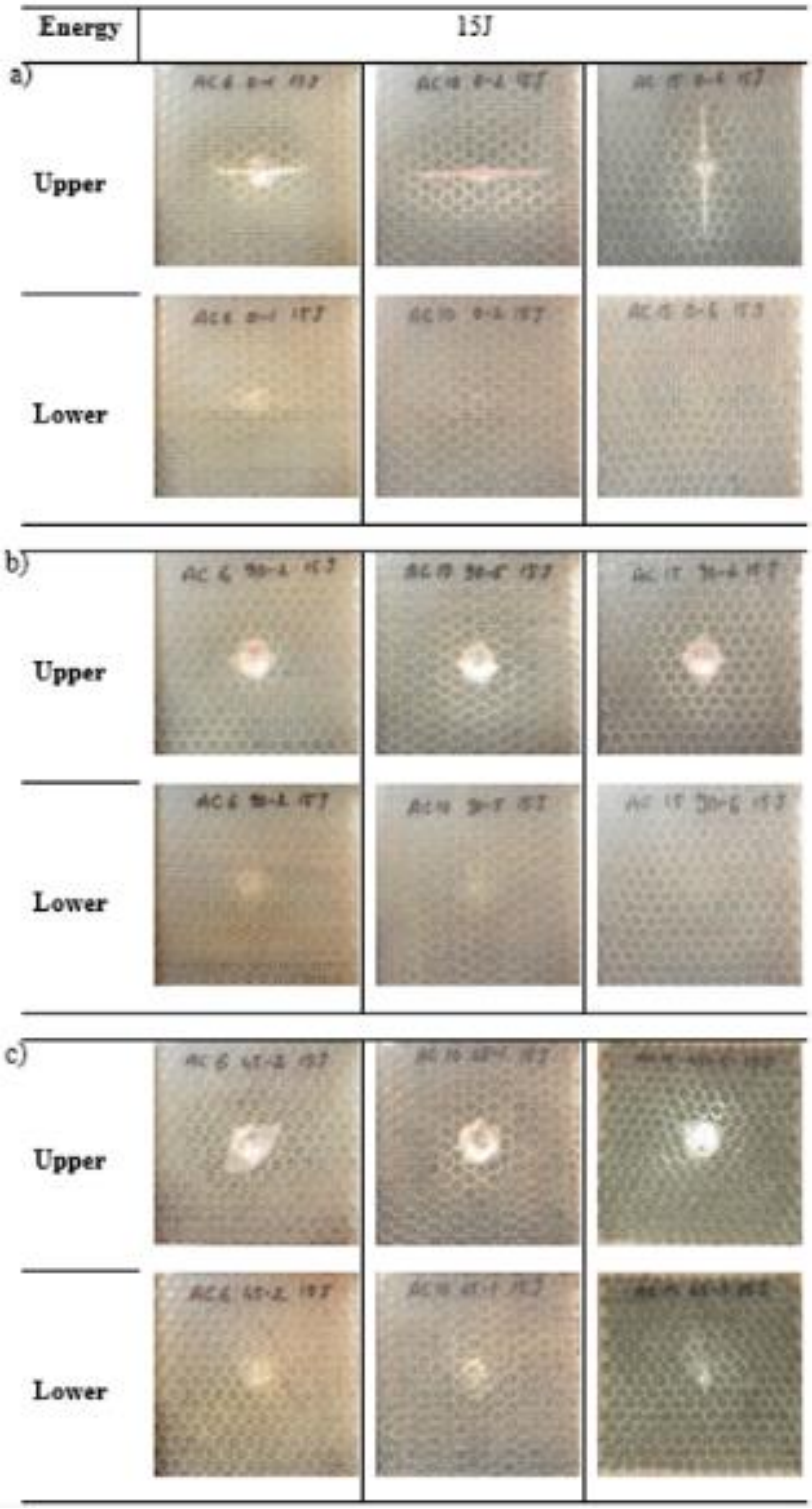

Figure 12. Damage Images Taken from the Upper and Lower of the Sandwich Structure with a) 0^O b) 90^O c) 45^O Orientation Angle and Different Core Thicknesses at 15 J Energy Value

At an impact energy level of 35 J, damage severity increases markedly across all specimens, with force–displacement curves indicating more profound damage mechanisms. Among the fiber orientations, the $[0/90/90/0]_s$ configuration exhibits higher peak forces, whereas the $[45/–45/–45/45]_s$ orientation demonstrates superior impact tolerance, accommodating larger displacements and promoting more gradual damage progression. The $[0/0/0/0]_s$ configuration dissipates energy through a relatively linear damage path aligned with the fiber direction. Severe and extensive damage is observed in all specimens at this energy level. Although increasing core thickness enhances overall impact resistance and energy absorption capacity (Nassir et al., 2023), damage to both the face sheets and the core remains inevitable under these high-energy conditions.

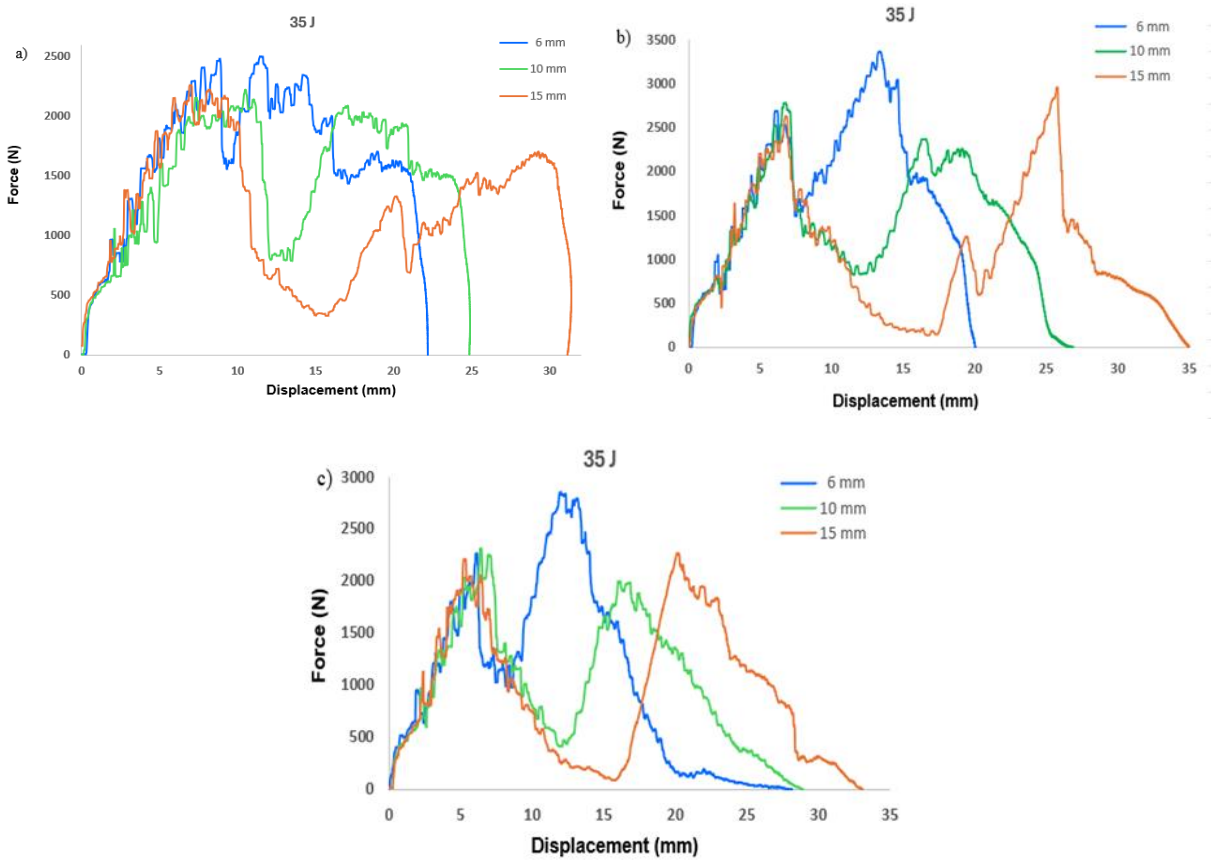

Figure 13. Force-Displacement Curve of the Sandwich Structure with a) 0° b) 90° c) 45° Orientation Angle and Different Core Thicknesses at 35 J Energy Value

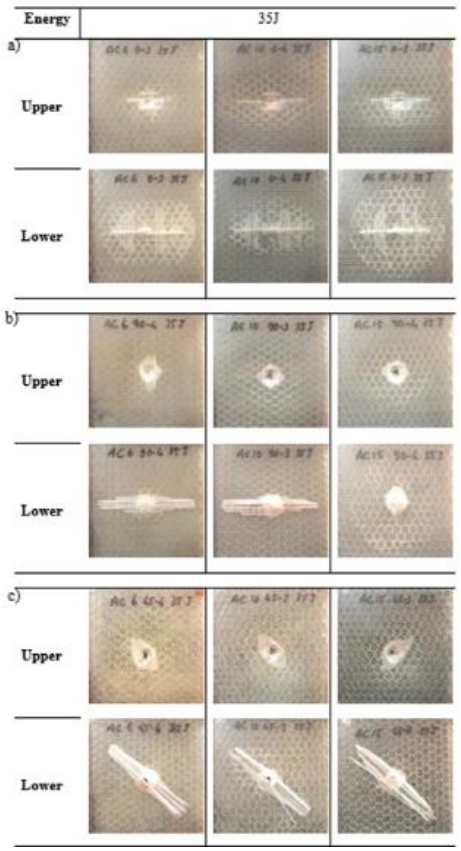

Figure 14. Damage Images Taken from the Upper and Lower of the Sandwich Structure with a) 0° b) 90° c) 45° Orientation Angle and Different Core Thicknesses at 35 J Energy Value

Figures 15 and 16 depict the force–displacement responses of sandwich composites with varying face sheet fiber orientations and core thicknesses (6 mm, 10 mm, and 15 mm) under a 15 J impact energy. These figures emphasize the influence of core thickness on the overall impact response and damage behavior across different fiber configurations.

As clearly demonstrated in Figure 15, increasing core thickness significantly enhances both the peak impact force and energy absorption capacity of composites. Fiber orientation also critically influences the mechanical response: the $[0/90/90/0]_s$ configuration exhibits higher initial stiffness, while the $[45/–45/–45/45]_s$ orientation promotes more progressive damage evolution and sustained energy absorption—particularly at greater core thicknesses—though often at the expense of more extensive damage. The $[0/0/0/0]_s$ orientation serves as a comparative baseline, with behavior intermediate to the other two and similarly influenced by core thickness. Figure 16 collectively illustrates that increased core thickness generally mitigates damage severity on the lower face sheet, primarily by enabling greater energy absorption through core crushing.

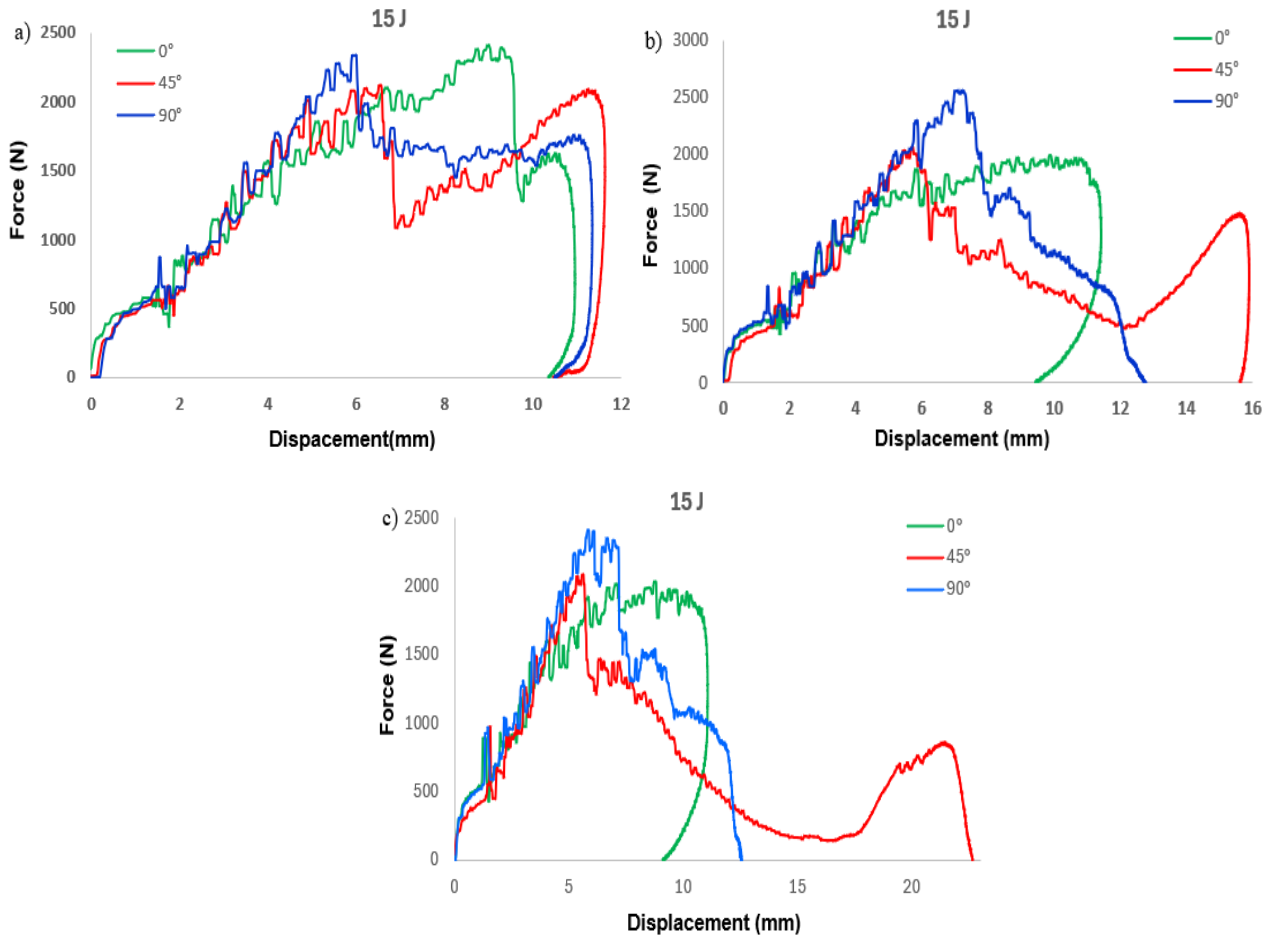

Figure 15. Force-Displacement Curve of the Sandwich Structure with the a) 6 mm b) 10 mm c) 15 mm Core Thickness at 15 J Energy and Different Orientation Angles

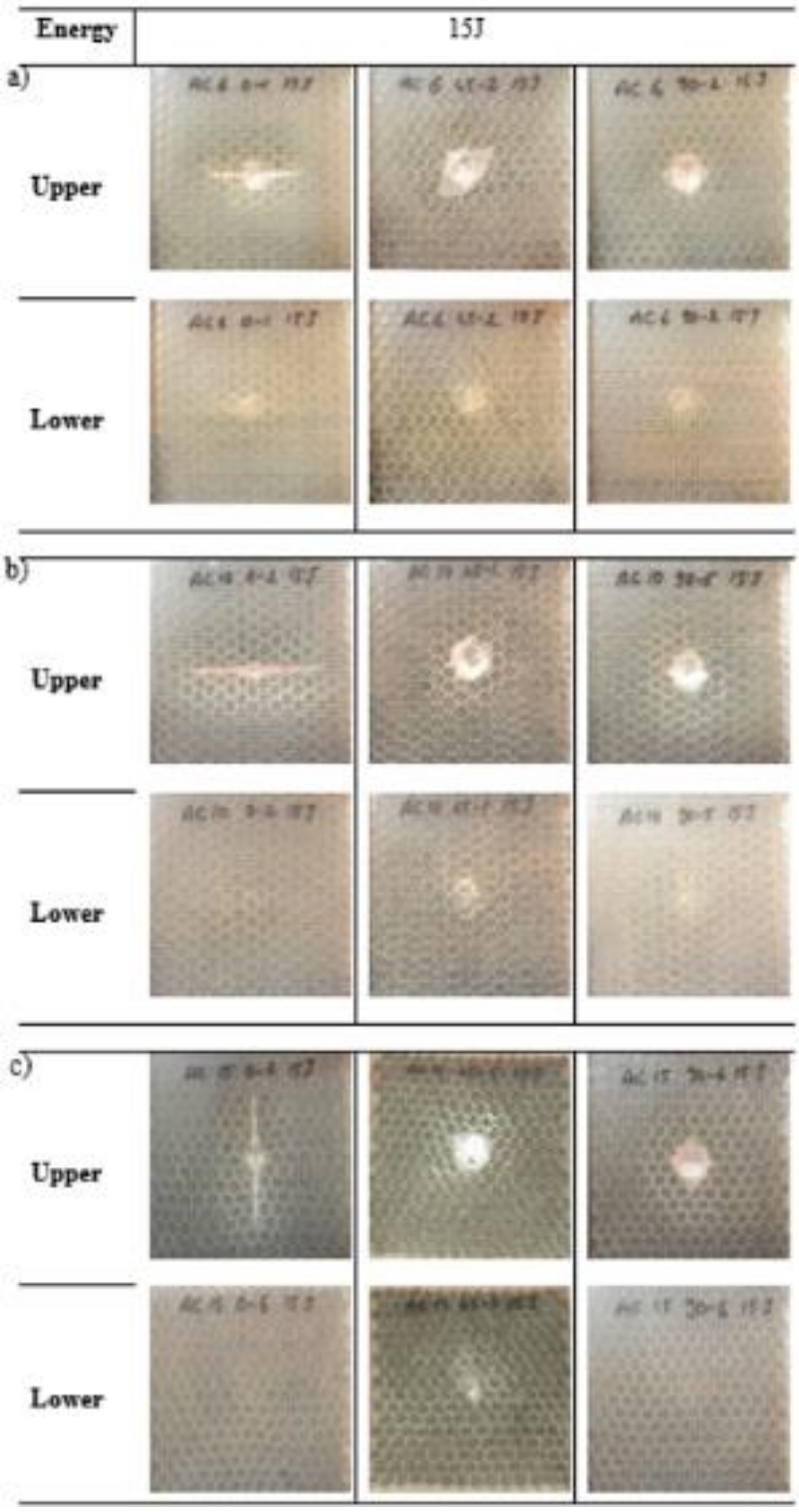

Figure 16. Damage Images Taken from the Upper and Lower of the Sandwich Structure with the a) 6 mm b) 10 mm c) 15 mm Core Thickness at 15 J Energy and Different Orientation Angles

CONCLUSIONS

This study presents a systematic investigation into the low-velocity impact response of sandwich composites, with a specific focus on the effects of fiber orientation and core thickness. The analysis is based on force-displacement data and damaged morphology obtained from impact tests.

- The findings indicate that for a constant impact energy level of 15 J, an increase in core thickness consistently resulted in a higher maximum impact force and enhanced energy absorption capacity, regardless of the fiber

orientation. The thicker core structures effectively mitigated damage propagation to the bottom face sheet, facilitating greater energy dissipation through core deformation. However, at a higher energy level of 35 J, all specimens exhibited catastrophic failure, including face sheet fracture and core crushing. This suggests that beyond a certain energy threshold, damage becomes inevitable, even in configurations with a thick core.

- Regarding fiber orientation, specimens with a $[0/90/90/0]_s$ layup demonstrated superior initial stiffness and peak strength. In contrast, the $[45/–45/–45/45]_s$ orientation, particularly when coupled with a thick core, promoted more progressive damage development and sustained energy dissipation. This ductile-like behavior facilitated a more uniform distribution of stress throughout the structure, thereby directing damage progression more effectively. The $[0/0/0/0]_s$ orientation exhibited intermediate characteristics, with a comparatively linear damage progression.

The force-displacement responses and subsequent damage analysis conclusively demonstrate that both fiber orientation and core geometry are critical design parameters that significantly influence the impact performance of sandwich composites. The selection of these parameters should be carefully considered based on the specific application requirements, whether the priority is high initial stiffness and strength or superior energy absorption and damage tolerance.

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Author Contributions

Mustafa YAMAN carried out experimental studies, collected the data within the scope of a TUBITAK project, managed project tasks, and contributed to funding acquisition. Kübra Çağla ÇIBIKÇI contributed to data visualization and manuscript writing. All authors read and approved of the final manuscript.

Artificial Intelligence Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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