

Low velocity impact responses of symmetric and asymmetric curved foam core sandwich panels

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Abstract: This work aims to experimentally examine the effects of various fiber reinforcements on the low-speed impact load responses of curved sandwich composites. Plain woven E-glass, 8H satin S2-glass, plain and twill woven carbon fiber reinforcements with the same areal weight were used as face sheets and PVC foam as core material in the fabrication of sandwich composites. A low-speed impact testing apparatus including a hemispherical impactor was used to conduct low-speed impact tests at various energy levels. Impact energy levels were determined for rebound, penetration, and total perforation of the specimens. Twill woven carbon exhibited superior performance for low-velocity impact damage resistance and tolerance in comparison with plain woven carbon and glass fibers. The absorbed impact energy decreased with the asymmetrical arrangement, and the sandwich specimens with twill-woven face sheets showed the best performance among the symmetrical and asymmetrical panels.

Keywords: low-velocity impact; sandwich composite; curvature; damage.

1. Introduction

The aerospace, maritime, automotive, and other industries employ sandwich composites for lightweight constructions. They have excellent thermal insulation, sound insulation, fire protection, and moisture resistance, as well as high specific strength, stiffness, and energy absorption [1-3]. A sandwich panel is composed of two rigid, thin and strong outer layers and a lightweight core in between them. The core material resists shear stresses, while the face sheets bear tensile and compressive loads [4]. Additionally, the curved structure distributes loads more effectively under bending or torsional stresses than a flat form [5].

Curved constructions include, for example: many parts of a helicopter, such as the fuselage, wings, tail sections, propeller, canopy, ballistic helmets and shields, can be considered as the application of curved composite panels. Several studies on the impact characteristics of curved laminate composite panels were conducted recently [6]. Low velocity impact behaviors of GFRP and CFRP composite laminates with single curve were com-

pared by Seifoori et al. [7] using impactors with flat, spherical and conical tips. An increase in contact area was found to reduce both the contact time and the mid-point deflection. Compared to GFRP composites of the same thickness and curvature, cylindrical CFRP were more rigid. At intermediate impact velocities, Usta et al. [8,9] studied the influence of thickness and curvature on the performance of flat and cylindrical CFRP composite laminates. It was found that curved samples exhibit higher penetration depths compared to flat panels that are equal in thickness and area. Arachchige and Ghasemnejad [10] investigated the after-impact behavior of a CFRP composite with a cylindrical geometry under low-velocity impact by a rigid spherical impactor. The author's analytical models yielded parameters for composite laminates with varying thicknesses of curvature.

Only a few studies were reported in the literature regarding low-velocity impact tests on sandwich composite panels with curvature. Reis, P. N et al. [11] noticed an improvement of around 20.8% in energy recovery due to the hybridization of the carbon layer with the

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Kevlar layer for cylindrical sandwich shell composites. Additionally, an approximately 44.8% increase in recovered energy was achieved by incorporating the cork core into carbon laminate composites. In another work, the impact responses of curved sandwich composites with varying surface geometries produced by incorporating rubber between glass fiber fabrics were experimentally and numerically evaluated. It was found that curved sandwich panels had higher delamination areas and lower impact strength than flat panels [12]. Zhang, Y. and Zhou, Y. [13] compared the performance of curved sandwich panels against bird strike using cage, foam and cage-foam, hybrid core structures. It was found that the use of cage materials as the core in curved sandwich structures resulted in a higher resistance to impact, reduced contact force and residual kinetic energy of the bird and reduced the deformation of the backing layer. B. Arachchige and H. Ghasemneja [14] proposed an analytical model to simulate the low-velocity impact response of curved sandwich composites with foam core. The relationship between the increase in plate curvature and the increase in energy absorption of curved sandwich structures was verified by comparing numerical and analytical models. The effect of using graded foam materials on the impact behavior of sandwich composites with curvature and flat panels was explored in previous studies. It was found that the puncture energies of curved panels with uniform foam structure were higher than flat panels. However, the performance of panels with graded foam varied depending on the specific configuration of the foam layers [15]. In another study, the effects of artificial layer-core interface damage and curvature on the impact response of sandwich beams were investigated. It was found that the contact forces of sandwich beams without artificial damage increased with increasing curvature angle but decreased in damaged ones [16]. Yurdaskal M. and Baba B. [17] investigated the impact behavior and impact-induced damage modes of curved and planar sandwich composites consisting of E-glass/epoxy face sheet and PVC foam core. The failure modes varied depending on the geometry of the samples (curved or flat) and the amount of impact energy. In addition, more energy was absorbed during penetration process as the curvature radius of the sandwich panels was reduced. Liu et al. [18] investigated the effect of the radius of curvature of sandwich composites consisting of E-glass/epoxy face sheet and PVC foam core on the low-velocity impact test results. During the low-velocity impact tests, the contact forces increased while the displacement values decreased as the PVC core thickness and radius of curvature increased; however, the opposite was observed in the panels containing PVC foam with less wall thickness.

Recent study demonstrated the crucial role of radius and angle of curvature in the impact behavior of composite sandwich panels and the design of these structures. The papers provide a basic summary of the investigation of material and geometric effects on low-velocity impact responses, highlighting the difficulties of obtaining ac-

curate results with flat panels in curved zones. Moreover, to the author's knowledge, no research has been reported in the literature on the low-velocity impact behavior of symmetric and asymmetric curved sandwich composites with varying face sheet materials. Consequently, the outcomes of this study address a gap in both scientific and practical fields and provide a foundation for future investigations, particularly numerical studies. For this purpose, this study aimed to investigate the effects of face sheet material on the contact force, absorbed energy and failure modes of curved sandwich composites under low-velocity impact tests.

2. Materials and Methods

2.1. Production of sandwich composites

Steel molds with a diameter of 250 mm were used to manufacture curved sandwich composites. Flat PVC foams (Airex® C70.75) were heated in an oven at 130 °C for 45 minutes to produce their cylindrical forms (►Figure 1). Sandbags were put on the foam as a weight. Heating temperatures and durations for thermoforming were set in accordance with the manufacturer's specifications. The detailed information is available in the Airex Processing Guidelines data sheet [19]. Plain woven E-glass, 8H satin S2-glass, plain and twill carbon fiber fabrics are used as reinforcement materials. The densities of E-glass, S2-glass, and carbon fibers are 2.55 g/cm³, 2.49 g/cm³, and 1.79 g/cm³, respectively. The layer thicknesses of carbon, E-glass and S-glass fabrics are 0.327 mm, 0.15 mm and 0.12 mm, respectively [20]. In addition, the stiffness and strength values of these fibers are different [21]. Therefore, it is possible to compare the performances of face sheets with different mechanical properties in curved structures. For face sheets, HexForce® brand yarn type EC9 E-glass and SC9 S2-glass fiber woven fabrics were preferred. Profabric® brand plain and twill carbon woven fibers produced from Tenax-E HTA 40 3k and Carbon Fiber HT 3k 200tex yarns were used. In this way, the influence of the weaving pattern of carbon fiber on impact resistance was investigated. In asymmetric structures, fibers with higher mechanical properties were placed

Table 1. Preheat-treated PVC sandwich specimen fabrication characteristics with various face sheets.

Specimen	Upper face sheet (Impact side)	Lower face sheet	Curvature [mm]	PVC [mm]
PC	Plain carbon	Plain carbon	250	15
TC	Twill carbon	Twill carbon		
SC	S-Glass	S-Glass		
EC	E-Glass	E-Glass		
PEC	Plain carbon	E-Glass		
TEC	Twill carbon	E-Glass		
SEC	S-Glass	E-Glass		

in the top face sheet, while E-glass fibers were used in the bottom face sheet to improve elastic energy absorption by providing more displacement upon impact. The fibers' areal weights were maintained constant and employed at 200 g/m². Epoxy resin (Hexion LR285 resin and LH287 hardener) was employed throughout fabrication. The hand lay-up method was chosen as the manufacturing technique (►Figure 2). Impact tests were conducted on seven types of sandwich composites using different stacking configurations, including four symmetrical and three asymmetrical specimens. Details of the sandwich specimens are presented in ►Table 1.

2.2. Drop weight test

The drop weight experiments were carried out using an Instron CEAST-9350 system (►Figure 3a). The load sensor has a maximum capacity of 90 kN. The impact resistance of the sandwich specimens was measured in a test environment in accordance with the ISO 6603 standard. The impact data was obtained by dropping a hemispherical impact tool onto the convex surfaces of curved sandwich beam specimens. The clamping mechanism was specifically designed to hold curved specimens (►Figure 3b). The bottom portion featured panels with a curvature radius, but the top section was built

around the panel thickness (►Figure 3c). The sandwich specimens were evaluated at room temperature with impact energy values of 15 J, 30 J, and 90 J. Low velocity impact energies were determined at these energy levels to ensure rebound, penetration, and complete perforation of curved composites. For each energy level, at least three specimens were tested.

3. Results and Discussions

This section evaluated the force-displacement and energy-time curves of curved sandwich specimens and analyzed post-impact damage photographs.

3.1. Force-displacement curves

Figure 4 shows force-displacement graphs for curved sandwich composites. The curves showed single or double peaks depending on the variation in impact energy. The peaks of the force-displacement graphs are given in ►Figure 5. The initial contact forces in the TC specimens are the highest among the symmetric sandwich panels at all energy levels. The superior low-speed impact resistance of twill-woven carbon textiles compared to plain-woven types aligns with earlier studies [22].

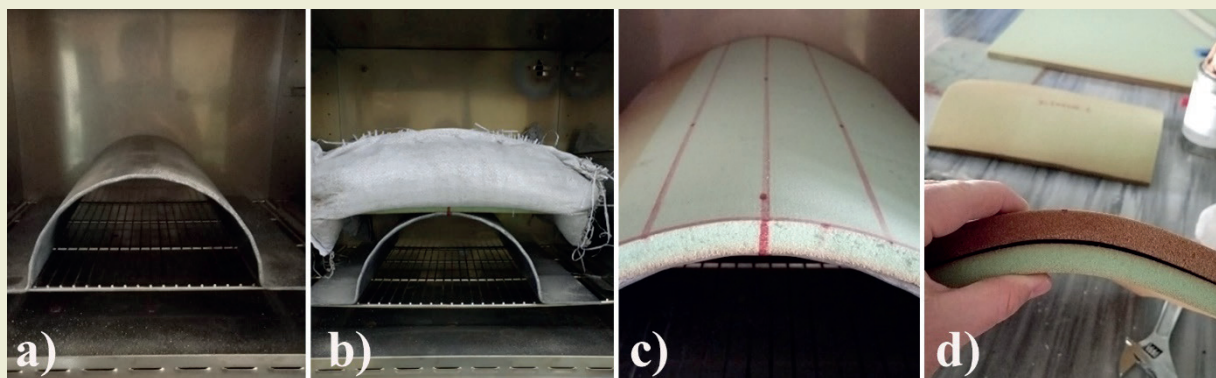


Figure 1. The process of pre-heating flat PVC foam materials. a) curved steel sheet mold, b) putting sandbags on PVC foam, c) and d) curved PVC foam parts after treatment.

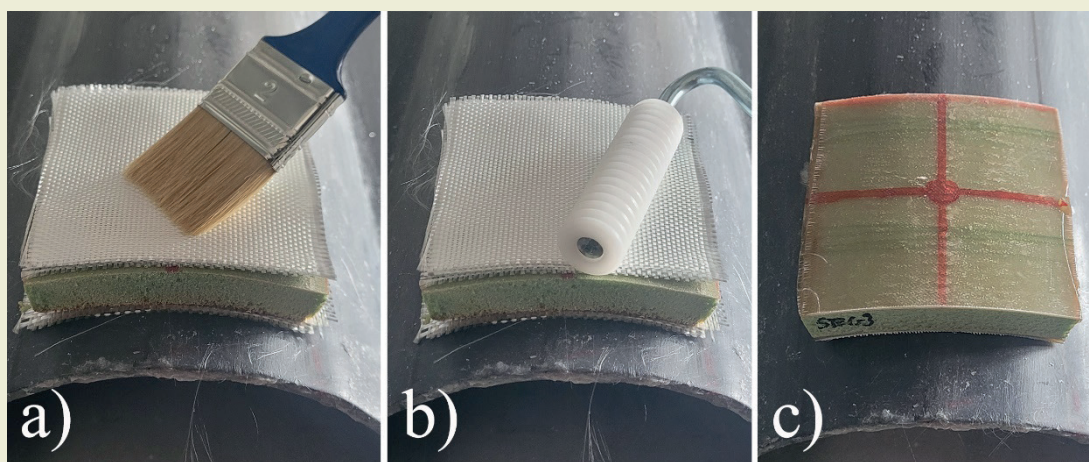


Figure 2. Production of sandwich composite specimens by hand lay-up method a) resin impregnation, b) air removal by rolling, c) sandwich specimen after curing.

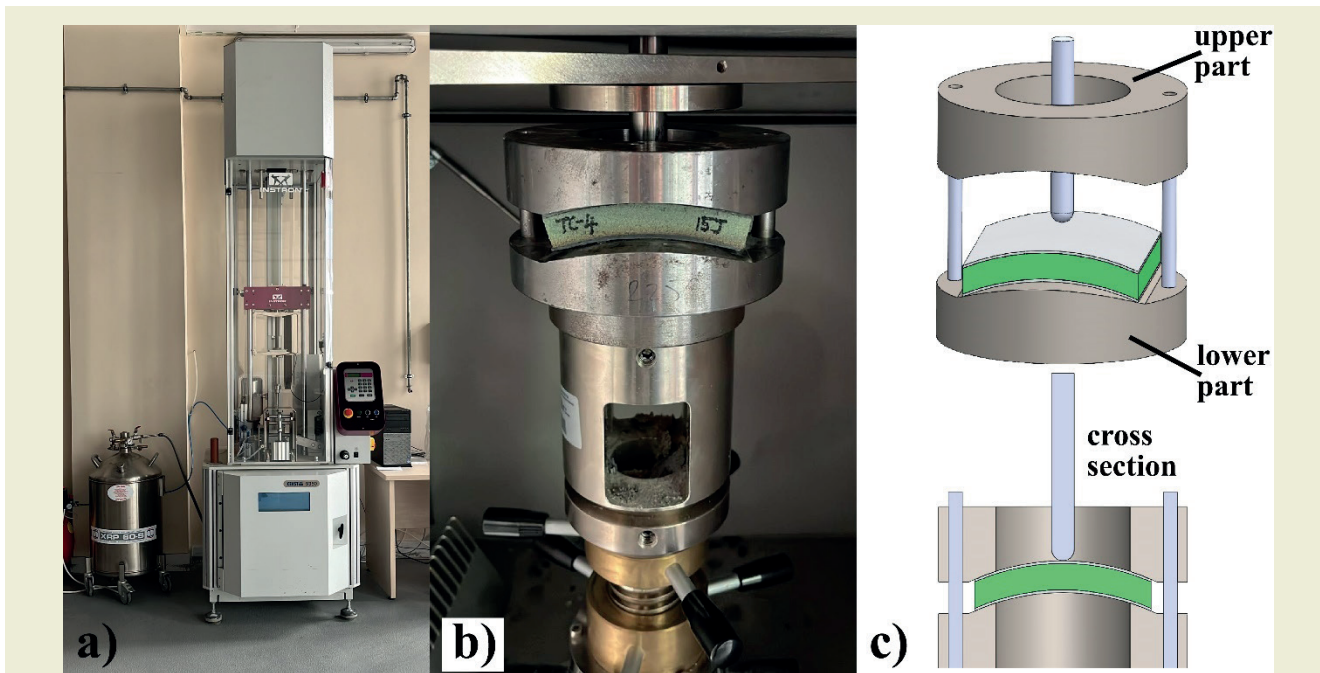


Figure 3. a) Instron CEAST-9350 drop weight impact testing equipment, b) placing of curved specimens in the testing device, c) schematic view of testing apparatus.

This result shows the effect of the weave structure on the impact behavior. The contact forces of the SC panels were higher than the EC specimens at different energy levels. In this case, it is due to the higher impact resistance of S2-glass fibers compared to E-glass [23]. Furthermore, the SC specimens had larger contact forces than the PC panels, which supported the literature [24, 25]. PC and TC specimens including plain weave and twill weave carbon fibers originally exhibited a more rigid response. In addition, the second peaks are higher in the force-displacement graphs of PC and TC specimens. This scenario opposed to EC and SC specimens containing glass fiber, with greater initial contact forces. At 15 J impact energy, rebounding was seen in EC, PC, SC and TC specimens. At 30 J impact energy values, the second peak was only shown in the PC specimen. In other specimens, the impact tip penetrated the PVC foam core material and remained stuck. At 90 J impact energy, all specimens suffered complete perforation damage. The force-displacement curves show that the impact force after perforation never drops to zero due to friction between the impactor and the specimen [26]. In asymmetrical panels, the initial stiffness of the top face sheet materials, namely plain and twill woven carbon PEC and TEC specimens, was increased. The second peak had a greater value than the initial contact force just in the PEC sample within the asymmetrical specimens. This result is consistent with previous research, indicating that glass fiber reinforcements have better impact resistance than plain woven carbon textiles [27]. The first peaks in TEC and SEC specimens showed higher values. This suggested an increase in the initial penetration resistance. PEC showed resistance in the bottom face sheet to prevent total perfora-

tion. The penetration values of the impact tip into the specimens at different energy values were determined from the force-displacement graphs. At 15 J impact energy, the impact tip penetration depths of the EC, PC, SC and TC specimens were determined as 9.328 mm, 9.960 mm, 10.575 mm and 7.251 mm, respectively. The penetration depths of the impact tip in PEC, SEC, and TEC specimens with an energy value of 15J are 11.592 mm, 8.823 mm, and 8.010 mm, respectively. At the 30 J energy level, the impact tip clearly penetrated the foam core material and stopped in all panels. At 30 J impact energy, the penetration depths of the impact tip into the EC, PC, SC, and TC specimens were measured as 19.405 mm, 19.631 mm, 19.876 mm and 14.013 mm, respectively. As the penetration increased, the damage resistance of the curved sample consisting of twill carbon became noticeable. In the PEC, SEC, and TEC specimens, penetration depths were determined at 21.447 mm, 16.797 mm, and 15.39 mm, respectively, at an energy level of 30 J. The asymmetrical configuration of carbon-reinforced sandwich specimens with E-glass bottom face sheets resulted in an increased penetration depth. Additionally, SEC panel was superior to the SC specimen in terms of impact resistance and penetration depth.

3.2. Energy absorption-time curves

The energy absorbed by sandwich specimens under impact load equals to the area under the force-displacement curve. The energy absorption-time curves of the curved sandwich samples subjected to varying impact energies showed different shapes, as shown in ► **Figure 6.** At a 15 J impact load, the energy curves of

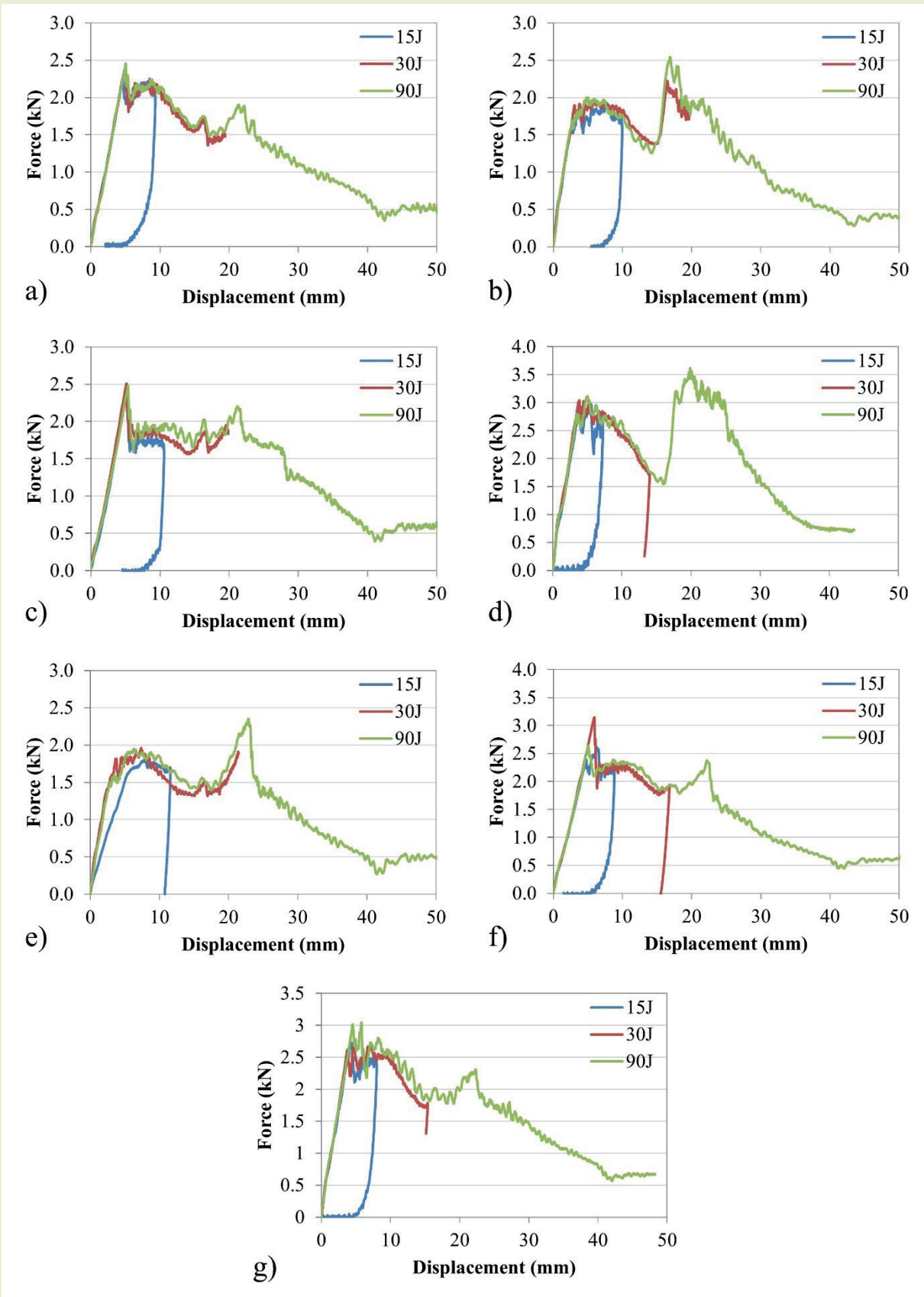


Figure 4. Force-displacement curves of curved sandwich specimens a) EC, b) PC, c) SC, d) TC, e) PEC, f) SEC, g) TEC.

curved sandwich specimens exhibited a rise with time, followed by a slight decrease after reaching the peak. This is related to rebounding. Elastically, some energy is recovered during the impact. Asymmetric sandwich composites showed rebound behavior like that of symmetric composites at an impact energy of 15 J. At an impact energy of 30 J, the rate of energy absorption decreased after the breakage of the upper face sheet, allowing the PVC foam to absorb energy via compression.

Curved symmetric and asymmetric specimens exhibited entirely plastic behavior, indicating the absence of rebounding. In all sandwich panels, the energy absorption rate increased due to the impactor reaching the lower faces sheet at 90 J of impact energy. The energy absorption rate experienced a gradual decrease as the lower face sheet was damaged, causing the curve to tend to be horizontal. At a total impact energy of 90J enough for a perforation, the curved panel specimens

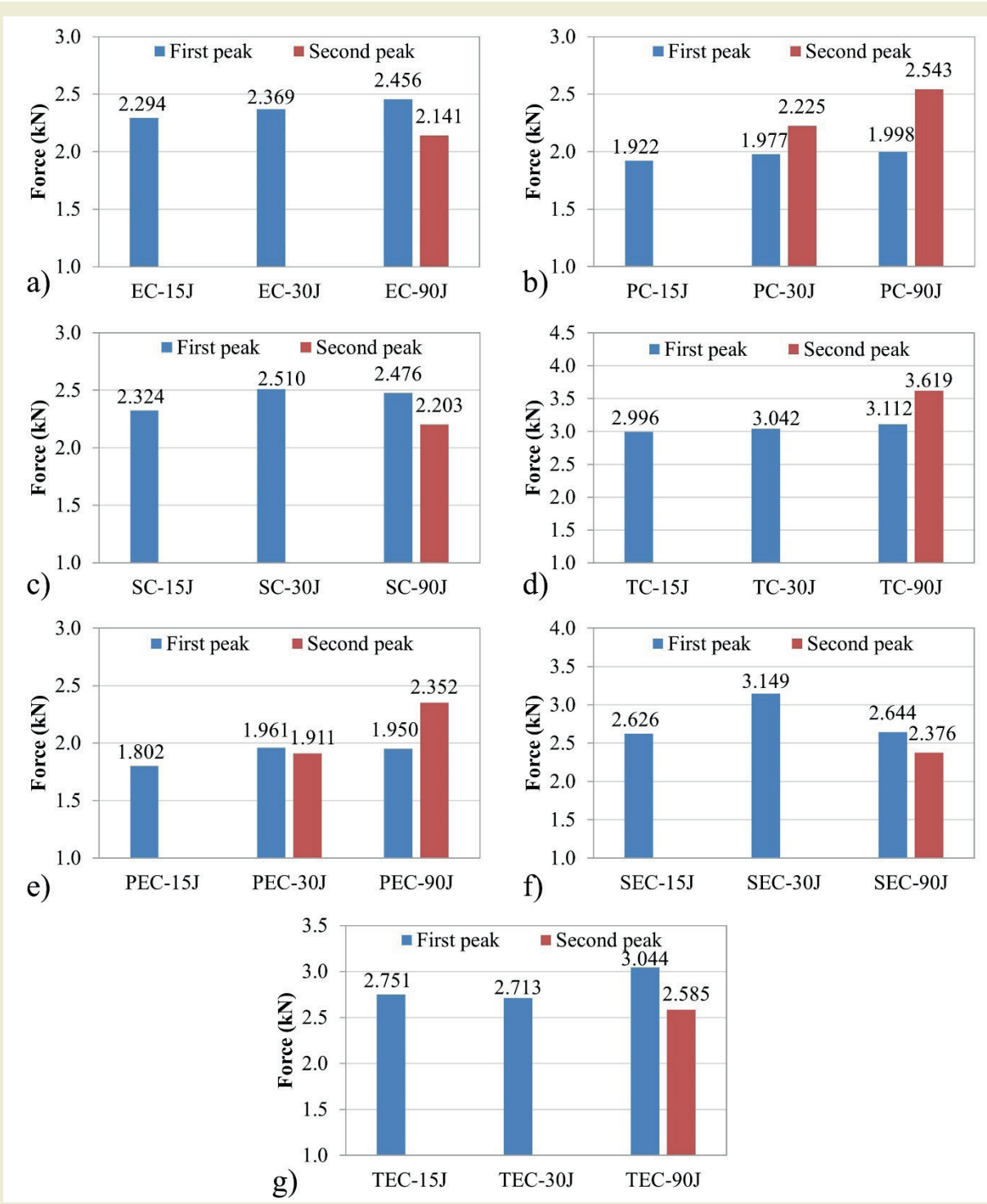


Figure 5. Peak contact forces of curved sandwich specimens a) EC, b) PC, c) SC, d) TC, e) PEC, f) SEC, g) TEC.

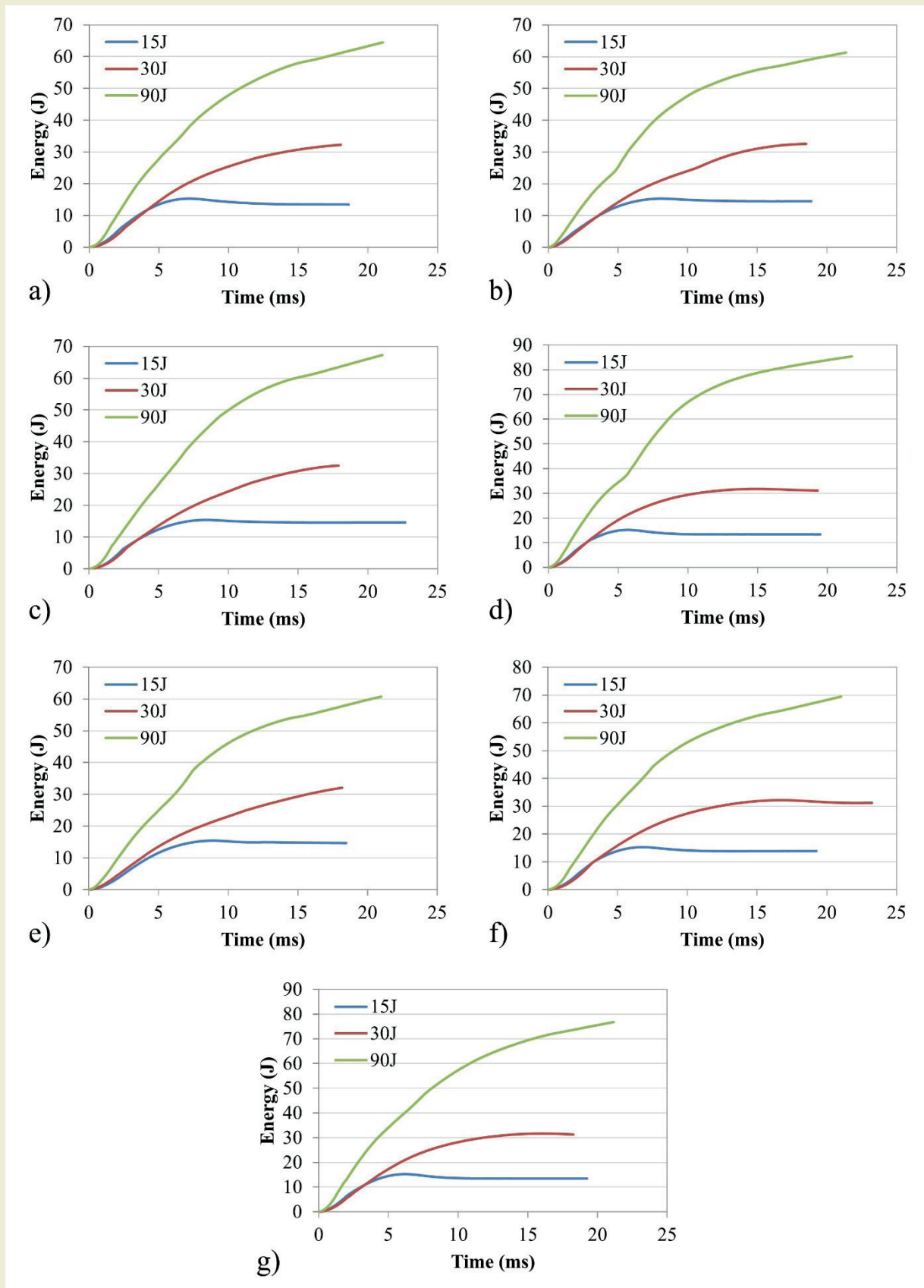


Figure 6. Energy absorption-time curves of curved specimens a) EC, b) PC, c) SC, d) TC, e) PEC, f) SEC, g) TEC.

exhibited similar curves. As can be seen in ►Figure 7, at energy levels of 15 J and 30 J, the impact energy was completely absorbed in all specimens. However, it is crucial to consider that the path of the impactor in the specimens at these energy levels varies from one specimen to another. Therefore, the energy levels required for the impactor to completely perforate the specimens were found to be different (►Figure 7). The standard deviation of the contact forces and absorbed energy at 15 J and 30 J in the samples were found to be negligible. The standard deviations of the perforation energy (90J) values for EC, PC, SC, and TC symmetric specimens were ± 2.9 , ± 1.7 , ± 3.8 , and ± 6.5 , respectively, whereas for PEC, SEC, and TEC specimens, these were ± 1.1 , ± 4.2 , and ± 5.4 . The contact forces obtained during complete perforation showed standard deviation values of ± 66.1 , ± 148.5 , ± 111.4 , and ± 264.1 for symmetrical EC, PC, SC, and TC samples, and ± 185.7 , ± 251.7 , and ± 350.7 for asymmetrical PEC, SEC, and TEC specimens. The twill carbon-reinforced specimen exhibited the maximum energy absorption through complete perforation in both symmetrical and asymmetrical panels. The perforation energy values of asymmetrical panels were lower than those of symmetrical panels (►Figure 7).

3.3. Post-impact section views

This section experimentally evaluated the failure modes of impact sandwich panels. ►Figure 8 shows damage section photos of curved sandwich composites after impact loads. Examination of the impacted regions indicates that the modes of failure are dependent on the properties of the sheet material or the symmetric/asymmetric arrangement of the sandwich panel. In the symmetric and asymmetric curved specimens,

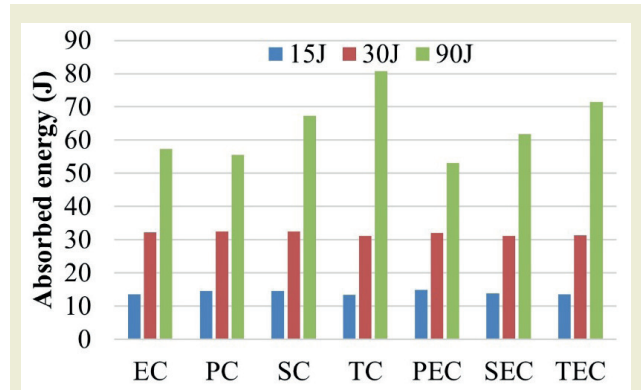


Figure 7. Absorbed impact energy values of curved specimens.

significant upper face fiber breakage, core crushing and fracture damage occurred at 15 J and 30 J impact energies (►Figure 8a-d). At 30 J impact energy, the upper face sheets of the symmetric PC and TC specimens were completely perforated. In PC and TC specimens, interlayer delamination in the bottom face sheets at an energy value of 90 J is more noticeable than in other symmetric specimens. Glass fibers can withstand higher deformations before fracture, thus minimizing the spread of cracks to the inner plies [28]. The asymmetric PEC and TEC specimens showed a lower resistance to low velocity impact damage. It was noted that the delamination damage in the bottom face sheets of PEC and TEC specimens was less severe than that of their symmetric counterparts (►Figure 8e, g). It can be said that the E-glass bottom face sheet in the PEC specimen resisted total perforation failure.

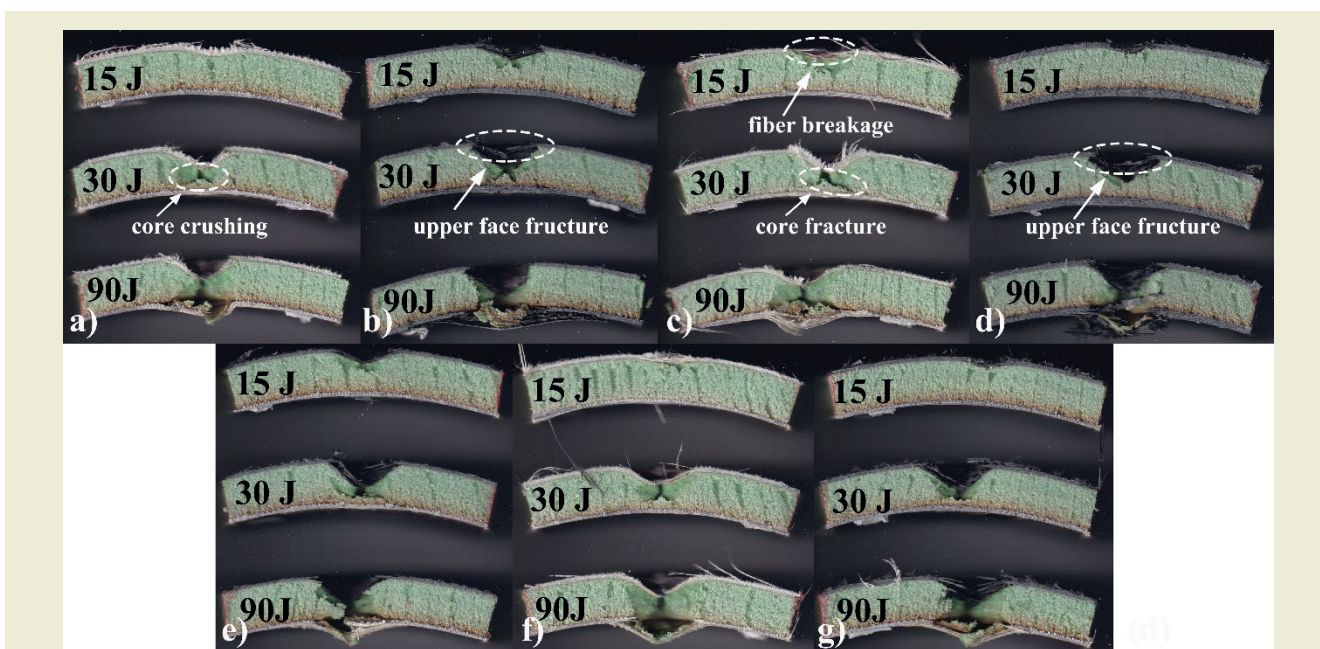


Figure 8. Damage section images of curved sandwich specimens after impact test a) EC, b) PC, c) SC, d) TC, e) PEC, f) SEC, g) TEC.

4. Conclusions

This work experimentally investigated the effect of fiber reinforcement used in the face sheets on the low-speed impact load responses of curved foam core sandwich composites. The Twill carbon fiber woven face sheet showed the highest penetration resistance under low velocity impact loads, whereas the plain-woven carbon fiber sandwich specimen had the lowest impact resistance. The impact strength and energy absorption capacity decreased in asymmetric sandwich specimens. The use of S-glass and twill carbon in the impact direction of asymmetrical specimens improved initial impact resistance. The use of E-glass as the lower face sheet instead of plain-woven carbon fabric improved the perforation resistance in asymmetric specimens. This scenario provides details on resistance to penetration and perforation damage in cases of asymmetrical arrangement. Future study might include interlayer hybridization of the top and bottom face sheets of curved sandwich composites subjected to low-velocity impacts.

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Research ethics

Not applicable.

Author contributions

Conceptualization: [Fatih Balikoğlu], Methodology: [Fatih Balikoğlu, Tayfur Kerem Demircioğlu], Investigation: [Fatih Balikoğlu, Tayfur Kerem Demircioğlu, Mehmet Özer, Berkan Hizarcı], Data Curation: [Tayfur Kerem Demircioğlu, Berkan Hizarcı], Writing - Original Draft Preparation: [Fatih Balikoğlu], Writing - Review & Editing: [Fatih Balikoğlu, Tayfur Kerem Demircioğlu], Visualization: [Tayfur Kerem Demi]

Competing interests

The author(s) state(s) no conflict of interest.

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Data availability

The raw data can be obtained on request from the corresponding author.

Peer-review

Externally peer-reviewed.

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