


An influence of low-energy impact loads on a multilayer sandwich composite

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ABSTRACT

The article aimed at reducing the impact load effect on layered structures. It proposed replacing the classic sandwich composite with a multi-core sandwich composite, hence the main objective of the research was to investigate and describe the effect of low-energy impact loads on a multi-layer sandwich composite with cores in the form of polyvinyl chloride foam and additional reinforcement inside the core. The manufactured multi-core samples were subjected to a static tensile test, impact tests and puncture resistance tests. The tests showed that the composites with a denser core exhibited 2.5 times higher impact strength under surface loading and 1.3 times higher under edge loading. It can also be seen that the permanent deformation after impact is greater for the composites with a higher-density foam core, as the average deflection after testing was 29.3% of the sample thickness, almost 10% greater than the deflection for the composites with a lower-density foam core. The composite with a lower density core has a 4.3 MPa higher tensile strength. Additionally, it was noted that using two cores with internal reinforcement in the form of a laminate made of glass fabric results in significantly better protection of the opposite cover and an increase in the impact strength of the sandwich composite.

Keywords: composite, sandwich, core, impact strength, stress.

INTRODUCTION

Due to a wide range of properties, composites have found applications in aerospace, construction, automotive, consumer goods, ship-building, furniture, and many other fields [1]. Ceramic matrix composites are used to produce heat-resistant and high-temperature-resistant components, such as exhaust nozzle parts and jet engine turbine blades, which are exposed to high-temperature and high-velocity gases [2, 3]. Metal matrix composites (MMCs), used among other applications in the production of brake discs, are characterised by high wear resistance, increased temperature strength, and lower weight compared to conventional metal alloys. In addition, cermets are used in high-temperature valves and pipes, rocket engines, and electric motor brushes. Moreover, they make it possible to reduce weight and increase fatigue strength in existing structures

by replacing the metal alloys previously used in the production of aerodynamically loaded components, such as covers, stabilisers, and stator blades in jet engines [4, 5]. In turn, the group of polymer matrix composites (PMCs), due to their high strength-to-weight ratio and corrosion resistance, is increasingly used as structural components as well as skin in both aircraft and spacecraft. In this case, the reinforcing material often consists of glass, carbon, or aramid fibres, which exhibit very good wettability by various types of polymer matrices [5, 6].

From a structural point of view, it is possible to distinguish layered composites, including sandwich-type composites made up of a lightweight core and two outer covers. This type of solution makes the resulting structure light and rigid. They are characterised by high bending strength, the ability to absorb significant amounts of energy, and excellent acoustic insulation properties. They

are a material that is readily used for load-bearing skin components in aircraft [7, 8].

Polyurethane foams is one group of materials used as cores in sandwich composites [7, 9]. Expanded polystyrene with closed cells and low density is also used for the construction of lightweight cores. However, a drawback of this material is the fact that it is dissolved by the styrene contained in polyester resins. Therefore, it must be properly protected against its effects. Using expanded polystyrene, the shape of the composite core can be largely customised through a manufacturing process in which polystyrene beads are injected between the adhesive-coated face sheets of the composite and then expanded at an elevated temperature, which makes it possible to tailor the core properties by adjusting the mould filling level. The beads expand and bond to each other, as well as to the face sheets. The disadvantage of the composites with a lightweight polystyrene core is low mechanical properties [8, 10]. The cores made of polyvinyl chloride (PVC) provide good mechanical properties, non-flammability, and a closed-cell structure. Such materials as Klegecell and the Herex C series are foams crosslinked with isocyanates, which are harder and more brittle than linear foams, such as Airex. Moreover, crosslinked materials have a higher operating temperature range and greater compressive and shear strength than linear foamed PVC of similar density. Both groups are commonly used in sandwich composites for the production of aircraft and boats [8, 11].

In order to obtain the high temperature resistance of the sandwich composite, it is worth using a polyimide foam core. For example, Upilex-Foam, produced by a Japanese company UBE Industries, despite its considerable cost, is heat-resistant up to around 400 °C, and when exposed to a temperature of 500 °C, it loses only 3% of its mass [13]. Another example is Rohacell, a polymethacrylimide (PMI) foam, which additionally offers high fatigue strength and impact resistance, but unfortunately also exhibits considerable hygroscopicity. Another solution may be a thermosetting phenol-formaldehyde foam, which is fire-resistant and can be formed in situ. Its disadvantage is high brittleness and low mechanical properties. For this reason, it can be used in fire shields that are not subjected to significant stresses. Such foams are used as structural materials in the fuselages of commercial airliners [8].

A popular form of lightweight core in the sandwich composites used in aviation is cellular

materials, such as honeycomb structures. Their cells take various forms, ranging from hexagons and quadrilaterals to many other shapes. They can be made from phenol-formaldehyde resin-impregnated paper, aluminium sheets, polypropylene, meta- and para-aramid fibres, polycarbonates, and so on. In order to ensure thermal and acoustic insulation, as well as to prevent moisture build-up within the composite, closed-cell polymer foams are additionally employed as fillers. Moreover, honeycomb cores can be shaped to match the curvature of the component, and subsequently impregnated as well as cured [8, 12, 13].

Another type of lightweight core consists of the materials combining microballoons with various types of chopped fibres and mats. This type of material is usually a few millimetres thick and is used to increase the stiffness of composites by increasing thickness. They are characterised by a lower basis weight than reinforcing fabrics and mats. Therefore, their use as a substitute for one of the reinforcement layers reduces the overall weight of the composite while simultaneously adding new properties to it [8, 14].

It is evident that the characteristics of a sandwich composite are determined not only by the material from which the covers are made, but also by the material of the core [14, 15]. In addition, there are many other materials and raw resources that can be used in the production of sandwich composite cores, such as balsa wood.

A significant drawback of layered composites, including sandwich composites, is their low resistance to low-energy impact loads [16–20]. Various attempts have been made to improve this property, e.g. by applying additional surface layers or making changes to the composite structure [21–23]. It appears that one possible way to increase, among other things, the resistance of such materials to low-energy impact loads is to incorporate more than one (layered) core into their structure. According to the authors, it is worthwhile to subject such materials to impact testing. Therefore, the main focus of the article was to investigate the effect of low-energy impact loads on a multi-core sandwich composite with cores made of polyvinyl chloride (PVC) foam and additional reinforcement inside the core. Another method of increasing the puncture resistance of sandwich composite materials may be to increase the number of reinforcement layers in the covers; however, it seems that such a solution will result in a significant increase in the surface mass of the composite, which may

be unacceptable in aircraft structures. The manufactured composites were subjected to a static tensile test, impact testing using the Charpy method, penetration resistance testing, and static bending to determine the residual flexural strength of the material after impact loading.

Methodology of research

In order to conduct the study, two double-core sandwich composites were fabricated using the vacuum bag method, in the form of plates comprising composite outer face sheets and two cores of different materials, separated by an intermediate composite layer (Figure 1). The plates were 0.4 m wide and 0.7 m long. In both composites, the core was made of 5 mm thick Herex foam, but with different densities – Herex C90 with a density of 90 kg/m³ in one panel, and Herex C55 with a density of 55 kg/m³ in the other.

In order to produce the composite layers, the following fabrics were used – a glass fibre fabric weighing 280 g/m² and a carbon fibre fabric 160 g/m² in weight. Each face sheet was reinforced with one layer of glass fabric (on the outer side) and one layer of carbon fabric, while the layer between the cores was reinforced with a single layer of glass fabric.

In order to separate the manufactured plates from the vacuum bag components, a waxed polyethylene film was applied to one side of the composite and a peel ply was applied to the other. This resulted in a smooth surface on one side of the composite and a rough surface on the other.

The composite matrix was made using aviation-certified LR 285 MGS resin (properties shown in Table 1) and LH 287 MGS hardener, mixed at a mass ratio of 100:40.

After assembling all the composite layers and auxiliary layers, the entire assembly was placed into a vacuum bag, which was sealed, and after checking for airtightness, a pressure of - 80 kPa was generated inside with a vacuum pump. This simultaneously pressed the composite layers

together and removed excess liquid matrix from the composite. The lay-up was left in this condition for 24 hours to cure, after which the plates were removed from the bag and separated from the auxiliary layers. In this way, two composite plates were obtained: one with a thickness of 11.6 mm, a Herex C90 foam core, and a weight of 3.318 g/m²; and the other with a thickness of 12.6 mm, a Herex C55 foam core, and a weight of 2.836 g/m².

The method of manufacturing sandwich composites in a vacuum bag is simple and does not require sophisticated equipment. This method allows for the production of sandwich composites in various forms, with the only limitations being the size of the vacuum bag, the capacity of the pump, and the available dimensions of the materials used in manufacturing.

The fabricated composite plates were cut using the WaterJet technology into samples of appropriate dimensions for the individual tests (Figure 2a, b). Water-jet cutting, recommended for composite materials, ensured dimensional stability and prevented the foam at the sample edges from separating from the outer face sheets, preserving the internal structure in an intact condition [25]. The samples were cut using an STM waterjet machine with a working area of 1000 ×

Table 1. Properties of the LR 285 & LH 287 MGS system [25]

Property	Value
Density	1.18–1.20 g/cm ³
Dynamic viscosity	600–900 mPa/s
Bending strength	110–120 N/mm ²
Kirchhoff's modulus	3.0–3.3k N/mm ²
Tensile strength	70–80 N/mm ²
Compressive strength	120–140 Nmm ²
Elongation	5.0–6.5%
Impact strength	45–55 ⁵ g/mm ²
Shore hardness	80–85 D
Curing time	24 h at 23 °C
	15 h at 60 °C

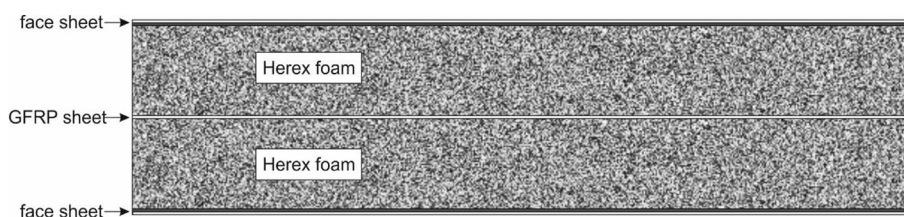


Figure 1. The scheme of the structure of the composite used in the research

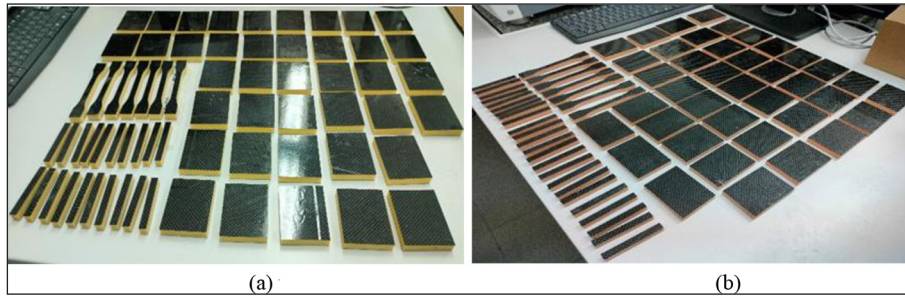


Figure 2. Cut-out samples: (a) with a Herex C55 foam core; (b) with a Herex C90 foam core

2000 mm. The water jet diameter was 1.1 mm, and the nominal abrasive grain size was 180 microns. The samples for impact strength testing, of rectangular prism shape, measured 80×10 mm were prepared in accordance with the PN-EN ISO 179-1 standard, with the thickness corresponding to that of the manufactured composite plates. The samples for the static tensile test, on the other hand, were prepared in accordance with the PN-EN ISO 527-2:2025-12 standard. The samples intended for penetration resistance testing, followed by static bending, had a rectangular prism shape with dimensions of 60×80 mm and a thickness corresponding to that of the manufactured plates and were prepared in accordance with the ISO 6603-2:2023 standard.

Charpy impact test

The Charpy impact test was carried out using a pendulum hammer manufactured by WPM Leipzig with an energy of 50 J. The series count

was 10. The fittings were surface and edge-loaded. As a result of the tests, the energy values required to destroy each sample were obtained, which was the basis for calculating their impact strength (Figure 3).

When comparing the obtained results (Figure 3), it can be seen that the surface impact strength of the composite with a Herex C90 foam core is 2.5 times higher than that with a Herex C55 foam core, whereas under edge loading this ratio is 1.3. Both materials withstand impact loads in the direction perpendicular to the face sheets (surface loading) significantly better than in the direction parallel to the face sheets (edge loading). The surface impact strength of the composite with a C90 core is 5.7 times greater than its edge impact strength, while for the material version with a C55 foam core this ratio is 2.9.

As a result of the conducted tests, the fractured samples exhibited different damage patterns, depending on the direction of the hammer impact on the sample. The fractures of both composites

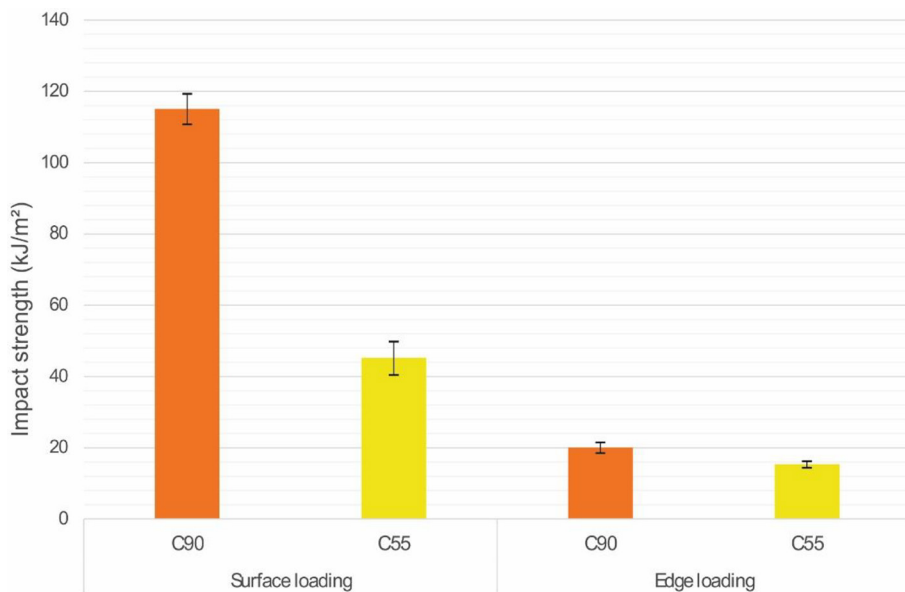


Figure 3. Average values of surface and edge impact strength of tested composites

under surface loading did not fragment or separate, but were permanently bent (Figure 4a, b). The foam at the impact location was deformed, absorbing the impact energy. Thus, for the composites with a C90 foam core the average deflection was 29.3% of the sample thickness, while for the composites with a C55 foam core the average deflection was 19.5%. Moreover, for the samples with a C90 core, the impact-side face sheets exhibited deformation accompanied by small cracks in the matrix, with a maximum width corresponding to a single carbon fabric fibre band (2.5 mm) at the intersection of warp and weft yarns in the hammer impact plane. Importantly, no visible discontinuity of the carbon fabric was observed. The face sheets on the opposite side were also bent and exhibited straight cracks in the matrix material across the entire width of the sample, without any visible discontinuities in the carbon fabric (Figure 4b). The face sheets of the fractured samples with a C55 foam core looked different. In this case, the impact-side face sheet showed matrix cracking along the full width of the sample, whereas the opposite face sheet was only slightly bent, with isolated cracks the length of which corresponded to the width of a single carbon fabric strip, occurring in three of the ten tested samples (Figure 4a). The internal reinforcing layer was bent in all samples; however, none of the samples showed any externally visible breaks in the continuity of the internal layer reinforced with glass fabric. Additionally, in both foam layers of all samples of both composite

types, stepped cracks occurred, propagating from the boundary where the sandwich composite layers were no longer subjected to compression beneath the impact site, but were under tensile loading. It is worth noting that the foam itself fractured, leaving an adhering layer of resin-impregnated foam on the face sheets. This may indicate that the bond strength between the resin-impregnated foam and the face sheet is greater than the strength of the foam itself. The cracks are much more extensive in the C90 foam than in the C55 foam, resulting in greater permanent deformations in the C90 foam samples (Figure 4a, b).

The fractures of samples from both types of sandwich composites subjected to edge loading look different (Figure 5a, b). Each sample split into two parts at the impact site, leaving carbon fabric cracked along the tow boundaries, frayed glass fabric protruding from the face sheets, and torn foam. No visible signs were observed of residual compressive deformation, tensile damage to the composite layers, delamination of the constituent elements, or other types of failure outside an area of approximately 1-2 mm on each side of the sample separation boundary. An assessment of the damage patterns resulting from edge impact indicates that these materials exhibit high brittleness under this type of loading.

An analysis of the impact strength results and the observed damage patterns in the samples suggests that denser C90 foam absorbs surface impact energy to a greater extent through fracturing,



Figure 4. Fractured samples after surface impact strength testing: (a) the samples with a C55 core; (b) the samples with a C90 core

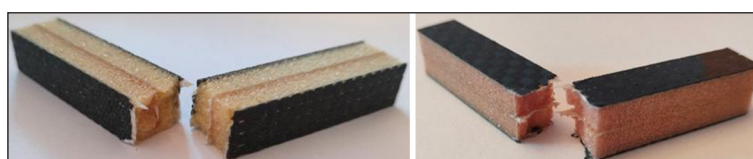


Figure 5. Fractured samples after surface impact strength testing: (a) the sample with a C55 core; (b) the sample with a C90 core

whereas the C55 foam is more resilient. Moreover, the C90 foam core more readily transfers surface impact energy into the deeper layers, as evidenced by the substantially greater damage observed on the non-impact face of the composite. In contrast, the damage resulting from edge loading appears identical in both tested materials. In this configuration, the composite with the C90 core exhibits significantly better properties, absorbing 1.3 times more energy (with the areal mass ratio of the C90 to the C55 composites being only 1.17), and is capable of stopping the impacting object over a shorter distance, thereby reducing the extent of damage. Considering the applicability of the tested materials in aerospace products, the sandwich composite with a C90 foam core demonstrated greater resistance to impact loading than the composite with a C55 core, with a disproportionate increase in mass. However, the form of material damage may prove problematic for use in aerodynamically loaded components. It is easy to imagine that a heavily deformed component, under the forces generated by the oncoming airflow, would be subjected to significant loads capable of destroying its structure. In this respect, the composite with a C55 foam core is superior, exhibiting better shape memory and absorbing a greater portion of the impact energy within the outer layers of the material.

Comparing the double-sandwich composite with a Herex C55 foam core, manufactured in the present study, with a composite having a core made of the same foam 3.8 mm thick, without internal reinforcement, and with face sheets consisting of a single layer of 160 g/m² carbon fabric on the outer side and a single 250 g/m² glass fabric on the inner side, laminated using the same resin-hardener mixture and manufactured by the vacuum bag method in previous research [16] (total thickness of this composite being 4 mm), it can be stated that in Charpy impact testing the double-sandwich composite achieved a 1.6 times higher surface impact strength and more than three times lower edge impact strength. A similar situation occurs when comparing the double-sandwich composite with a Herex C90 foam core to a composite with a Herex C90 foam core of the same face sheet construction as described above in the previous research, with a 5 mm thick core without internal reinforcement and a total composite thickness of 5.2 mm. The surface impact strength of the double-sandwich composite is 1.9 times greater, whereas its edge impact strength is

1.7 times lower. In both cases, the surface impact strength was significantly improved by the thick foam layer cushioning the impacts (at the cost of a slight increase in the areal mass of the sandwich composite). However, the same thick foam core resulted in a significantly lower edge impact strength of the material, which was not compensated for, even by the additional reinforcement layer inside the core. Thus, it can be concluded that a sandwich composite with an unprotected core edge is extremely sensitive to impact, and this sensitivity increases with the thickness of the foam layer.

Penetration resistance test

The purpose of the puncture resistance test was to evaluate the permanent deflection and the structural damage in the composite resulting from point impact loads. In order to perform the impact loading, an INSTRON CEAST 9340 drop tower impact system was used, equipped with a spherical striker of 20 mm in diameter and a support table with a circular opening of 50 mm in diameter. The samples, measuring 60 × 80 mm and having a thickness corresponding to each composite type, were placed freely on the table (Figure 6a). The energies used in the study were as follows: 3 J, 5 J, 7 J, 10 J, 15 J and 29 J.

In order to measure the permanent deformation of the samples after impact, a dial gauge mounted on a stand was used (Figure 6b) to determine the deformation depth. These measurements showed that the average depth of permanent sample deformation increases along with impact energy. Moreover, in the groups of samples tested with a falling striker at the same impact energy, the range of permanent deflection values increases along with impact energy for the C55 composite, whereas for the C90 composite, it is the greatest in the group of samples loaded with 10 J. This behaviour is influenced by the occurrence of numerous cracks in the composites, with the deflection depth depending on the size of the face sheet cracks. It can also be observed that the permanent deformations are deeper in the composites with a Herex C90 foam core than in those with a Herex C55 foam core. This situation, similar to the impact strength tests, indicates greater elasticity of the C55 foam, which results in a significantly smaller range of permanent deformation depths when the same impact load values are applied to this composite.

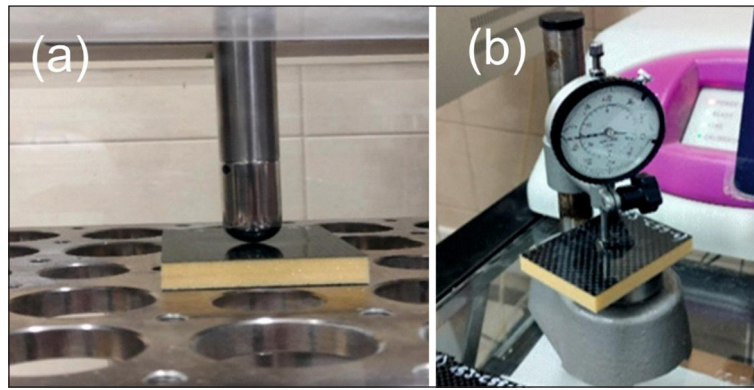


Figure 6. (a) Spherical striker with the sample placed on the support table; (b) dial gauge for measuring composite deformation after impact

The damage pattern of the composite caused by the striker varied from slight indentation to cracking of the outer face sheets, and even their perforation (Figure 7). The type of damage depends largely on the impact energy and the type

of sandwich composite core. Due to its greater elasticity compared to the C90 foam, the C55 foam tends to distribute loads over a larger volume of material, creating branched cracks that absorb energy across a significant area of the outer face

Table 2. Description of double-sandwich composite damage resulting from impact loading

Energy of impact loading [J]	Core material and density	
	Herex C55 (55 kg/m ³)	Herex C90 (90 kg/m ³)
	Damage	
3	Indentation of the loaded face sheet with a diameter of 30–35 mm. No externally visible damage to the opposite face sheet.	Indentation of the loaded face sheet; no externally visible damage to the opposite face sheet.
5	Indentation of the loaded face sheet with a diameter of approximately 30 mm. Straight and stepped cracks in the face sheet at the fabric fibre boundaries, measuring between 5 and 25 mm in length. No externally visible damage to the opposite face sheet.	Step-like cracks in the loaded face sheet along the fabric fibre boundaries, up to 7.5 mm in length, at the impact site. No externally visible damage to the opposite face sheet.
7	Denting of the loaded cover 25–30 mm in diameter. Single L-shaped cracks inside and around the indentation. Radial cracks in the loaded face sheet extending from the impact centre to the edge of the face sheet. No deformation of the opposite cover.	Cracks in the loaded face sheet at the centre and around the indentation, with lengths of several millimetres. Visible break in both layers of fabric. No damage to the opposite cover.
10	Indentation of the loaded face sheet with a diameter of approximately 30 mm. Cracks with visible rupture of both face sheet fabrics around and at the centre of the indentation, along with radial cracks propagating from the edge of the indentation to the sample edges. No externally visible damage to the opposite face sheet.	Denting of the loaded cover 25–30 mm in diameter. Cracks in the loaded face sheet at the centre and around the indentation, with lengths of several millimetres. Visible break in both layers of fabric. No damage to the opposite cover.
15	Indentation of the loaded face sheet across the full width of the sample. Cracks within the indentation with a frayed face sheet. Radial cracks extending from the centre towards the sides of the sample in a cross-shaped pattern. Foam rupture, a few millimetres in length, located just below the surface of the loaded face sheet and visible along the sides of the sample. No deformation of the opposite cover.	Denting of the loaded cover 30–35 mm in diameter. Cracks in the loaded face sheet at the centre and around the indentation, with lengths of several millimetres. No damage to the opposite cover.
29	Indentation across the full width and radial cross-shaped cracks on the loaded face sheet. Foam rupture near the outer face sheets and the internal reinforcement layer in the core, several millimetres in length, visible from the side. Perforation of the loaded cover in 3 of the 5 samples. Bulging of the opposite face sheet at the centre of the circular imprint originating from the plate on which the sample was resting. Cracks in the opposite face sheet, several millimetres in length.	Perforation of the face sheet material, foam layer, and the reinforcement in-between the foam cores, with a diameter of 20 mm. Indented second foam layer. Deformations with a diameter of 30–35 mm around the impact site. Bulging of the face sheet on the opposite side of the composite, with cracks in the centre up to 2.5 mm in length.



Figure 7. Examples of sample damage resulting from puncture resistance testing

sheet, thereby preventing perforation of the tested material and better retaining the original shape of the component. On the other hand, under impact, its internal structure is more easily damaged in the vicinity of the rigid elements of the face sheets and internal reinforcements. In contrast, the composite with a C90 foam core does not form extensive cracks but rather holes at the impact site, resulting in the damage zone encompassing a much smaller volume of material (Table 2).

When comparing the results obtained in this study with those for single-core materials [16], a significantly higher puncture resistance of multi-core composites can be observed, as evidenced by the considerably smaller damage in the multi-core samples for each of the applied energy levels. For example, under a 15 J load applied to the samples with a Herex C90 core, no damage to the opposite face sheet was observed in the double-core samples, whereas in the single-core composite, matrix cracks on the opposite face sheet were clearly visible already at a load of 10 J. Comparing the puncture resistance test results of the tested material with Herex C50 foam, which has a slightly higher surface mass than a classic 7-layer composite reinforced with 280 gsm glass fabric (unpublished study by the authors), reveals distinct differences in their damage. In the dual-core composites loaded with an energy of 15 J, no damage to the opposite cover was observed, whereas in the classic laminate, at a load of 10 J, extensive damage to the opposite composite layer was observed (matrix losses, torn and cracked reinforcing fibres, and penetration).

Residual flexural strength testing

The aim of the study was to obtain information on the flexural strength and Young's modulus of the samples previously subjected to impact loading in a drop-weight tower, as well as of samples not subjected to impact. Three-point bending of samples measuring 60×80 mm, with thickness corresponding to the respective materials, was carried out using a Zwick/Roell 5 kN testing machine at a speed of 1 mm/min. The samples were centrally loaded using a loading element with a diameter of 10 mm and a length of 70 mm. The support span was equal to 60 mm (Figure 8).

An analysis of the results shows that, as the impact energy applied to the sample increases, its flexural strength decreases in both composites. Comparing the flexural strength of the sandwich



Figure 8. A sample during flexural strength test

composite with a C90 foam core under a 29 J load to that of the sample not subjected to impact shows a 30% decrease in strength. In contrast, for the samples with a C55 foam core, the decrease is 54%. An impact load of 3 J has a negligible effect on the decrease in flexural strength of both materials (Figure 9).

For the tested composites, an impact energy of 3 J increases the flexural Young’s modulus by 6% for the composite with C90 foam and by 17% for the composite with a C55 core, compared to the samples not subjected to impact (Figure 10). Each

impact with higher energy causes a decrease in the value of this parameter for the examined sample. The C55 foam samples subjected to a 29 J impact test exhibit a very wide range of flexural strength values, indicating considerable variation in the damage within their structures. This range is confirmed by the inspection of the samples carried out after the puncture resistance test. Perforation of the loaded face sheet occurred in only 3 out of the 5 tested samples. In the remaining samples, cracks were visible in the face sheet, but without larger openings.

Static tensile test

The static tensile test was carried out to determine the tensile strength of both types of materials and to examine the nature of the damage that occurred in the composites as a result of the tests. Paddle-shaped samples (in accordance with Type 1B of the PN-EN ISO 527-2:2012 standard) were mounted in an INSTRON Series 6800 testing machine using two wedge grips, in such a way that only the ends of the composite were clamped (Figure 11a).

The average tensile strength of the samples with Herex C55 foam was 23.4 MPa, which was higher than the tensile strength of the composites with C90 foam, at 19.1 MPa.

Conversely, the Young’s modulus was higher for the composite with C90 foam, at 2.7 GPa, while for the composite with the C55 core it was 2.4 GPa.

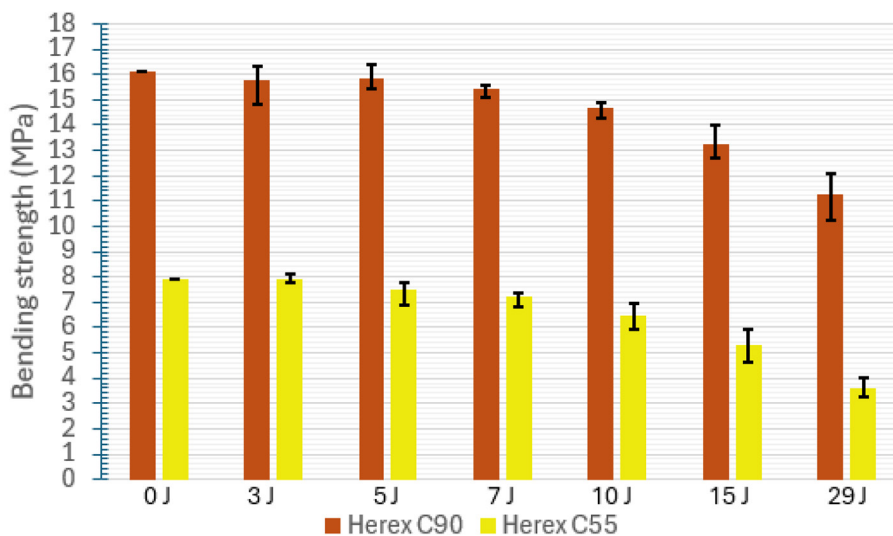


Figure 9. Residual flexural strength of the samples after penetration resistance test

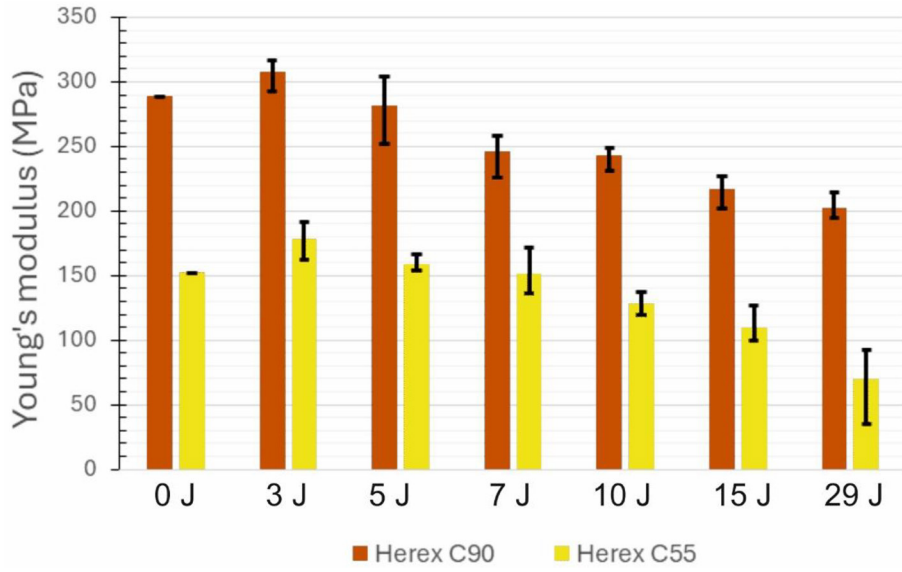


Figure 10. Young's modulus of the tested composites after impact tests

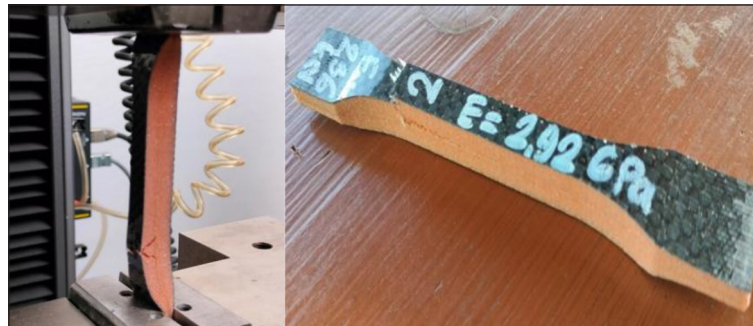


Figure 11. (a) mounting of a sample in the wedge grip; (b) example of a sample after testing

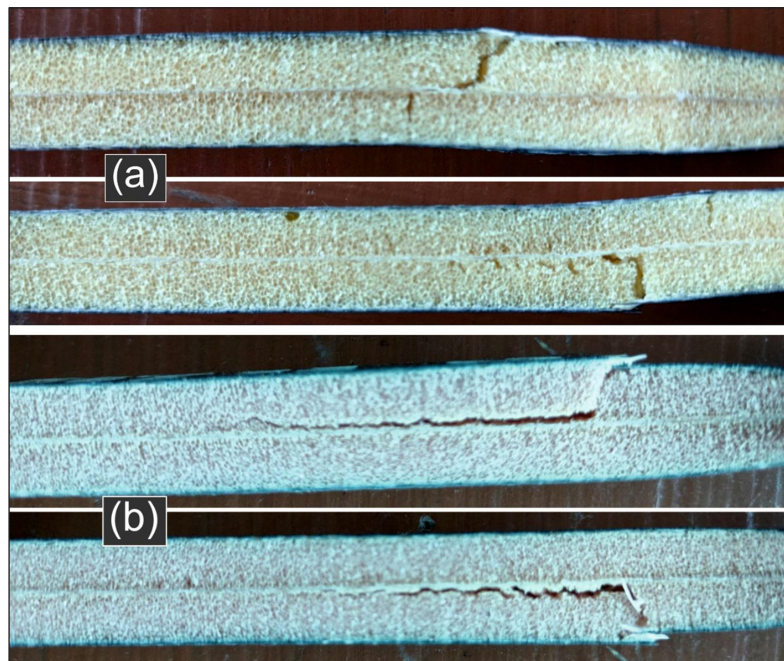


Figure 12. Damage to samples in the static tensile test: (a) double-sided view of damage to the sample with a Herex C55 core; (b) double-sided view of damage to the sample with a Herex C90 core

The results indicate that the sandwich composite with a Herex C55 foam core has 18% higher tensile strength and 10% lower Young's modulus. The C55 composite is also characterised by 36% greater deformation at failure compared to the composite with a C90 core. When comparing the tensile test results of single-core and double-core composites, it can be seen that the tensile strength of the single-core composites (one core with a thickness of 3 mm) [16] is several times higher than that of the double-core composites (two cores, each 5 mm thick). This was expected, as the foam, which constitutes a significant portion of the composite cross-section, has a low tensile strength compared to the laminate face sheets. Also, the Young's modulus of the single-core composites was approximately 25% higher than that of the double-core composites.

It is also worth noting that the damage to the samples in both composites takes the form of stepwise discontinuities in the foam, extending from the point where one of the face sheets was damaged, through a parallel tear of the foam along the plane of the internal reinforcement, and then in a direction perpendicular to the other face sheet (Figure 12a,b).

CONCLUSIONS

On the basis of the data obtained from the tests, the following properties of sandwich composites with a PVC foam core can be identified:

- The puncture resistance of double-core composites is significantly higher than that of single-core composites, which in turn are characterised by higher puncture resistance than classic laminates with a similar surface mass reinforced with glass fabric.
- The edge impact strength of the sandwich composite decreases with increasing core thickness.
- The composites with a denser core exhibit higher impact strength values under both surface and edge loading. In the tested materials, the adhesion forces between the foam core and the face sheet are greater than the forces required to destroy the internal structure of the foam.
- A sandwich composite with a lower-density core, when subjected to impact loading perpendicular to the plane of the face sheets, exhibits better shape memory (less permanent deformation of the structure after the load is removed).

- The composite core made of lower-density foam is more elastic, which results in the dispersion of the impact energy into the face sheet over a larger volume of material. As a result of this property, the damage to the outer face sheet and the core is considerably more extensive, while the opposite face sheet has a greater chance of avoiding damage.
- The use of a thicker core with internal reinforcement in the form of a laminate layer with glass fabric reinforcement provides significantly better protection for the opposing cover and increases the impact strength of the sandwich composite. Furthermore, in the tested composites, the elastic middle layer causes damage to the lower cover at significantly higher impact energy values than in single-core composites, ensuring that the internal structure of the composite remains tight, preventing environmental factors from penetrating the interior of the composite element.
- The residual flexural strength of sandwich composites decreases with increasing impact load energy. The loss of strength due to 15 J impact loads in the composites with a thicker layer of foam reinforced in the middle was 28% lower for the composite with a Herex C90 core and 12% lower for the composite with a Herex C55 core, compared to the variants with more than twice thinner cores without internal reinforcement.
- The composite with lower density and a more elastic core exhibits higher tensile strength.
- As the thickness of the core(s) increases, the tensile strength of the sandwich composites decreases, which is associated with a significant increase in the cross-sectional area with a slight increase in load-bearing capacity.

Considering the above properties of the tested sandwich composites, it can be concluded that the materials with a more elastic core are better suited for the applications where it is essential to maintain both leak-tightness and shape after impact loading. It appears logical to conclude that an adequate level of puncture resistance for this type of material can be achieved by using thicker and stronger face sheets, as well as a greater number of internal reinforcements with superior strength properties within the composite core. Thus, such materials are well-suited for the construction of tanks and aerodynamic profiles exposed to impacts from stones, birds, and similar hazards.

Conversely, for the internal structural elements subjected to bending loads, where shape memory is not required to such a great extent, the composites with denser foam are a better choice. They exhibit significantly higher residual flexural strength after impact, while having a much lower material mass. Unfortunately, a clear disadvantage of the composites with a denser Herex foam core is the deterioration of strength properties under tensile loading with a higher weight of the material.

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