Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 18(6), 218–226
https://doi.org/10.12913/22998624/191124
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.03.20
Accepted: 2024.08.15
Published: 2024.09.08

Impact Damage Tolerance of Multilayer Epoxy-Glass Composites with XPS Core and Polyurethane Prepolymer Modified Matrix

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ABSTRACT

A significant need within the design of materials for vehicles or other engineering structures is to determine their potential to mitigate impact loads. The material acting as a shield during an impact absorbs energy, dissipating the excess in a process of irreversible deformation. In order to prevent this, or to limit the areas of damage as much as possible, have begun to be used materials that absorb impact energy without drastically compromising their strength. Energy absorbing composite structures (EACS) have the ability to convert impact energy into some form of energy absorbed through deformation. Compared to homogeneous materials, a number of factors also point to the increasing advantage of using composite sandwich structures, which, in addition to their high strength ratings, have a lower weight and a much more effective ability to absorb shock or impact load energy. This paper presents the results of damage tolerance testing of epoxy-glass sandwich composites with chemical modified matrix. The damage tolerance of the composites was determined using an Instron CEAST 9340 testing machine with an impact energy ranging from 5 J to 35 J and indicated the value at which visible damage to the composite occurs while it retains some of its strength properties. It was the most important test to determine the damage tolerance, but additional tests to characterize the strength of the composite more comprehensively were also performed. Experimental studies were used to present a methodology for the preliminary characterization of the material strength and to analyse the relation between structure and mechanical response of the composite.

Keywords: composites, mechanical engineering, modification of composites, mechanical properties.

INTRODUCTION

The most commonly observed consequence when a material collides with another object with a high impact force or velocity is that it virtually destroys the material and absorbs as much of the impact energy as possible, protecting the object or users located in the area of the structure in question. Compared to homogeneous materials, a lot of factors point to the increasing advantage of using composite sandwich structures, which, in addition to their high strength ratings, have a lower mass and a much more effective ability to absorb the energy of a shock or impact load. The impact resistance of a composite material is usually determined by damage tolerance and puncture resistance. Damage tolerance is directly related to impact damage mechanisms. Improving damage tolerance is one of the parameters that is extremely important in load-bearing applications subjected to impact loading [1–3]. The puncture resistance of structural composites consists of exposing the sample to an impact and then testing a selected strength or mechanical property that, in relation to the impacted sample, will allow the determination of the residual strength.

Both the size of the load and the damage and its characteristics should be reflective of the exploitation conditions and especially the damage should be able to be located and assessed by a defined method based on unambiguous parameters. The two largest aerospace companies have defined minimum impact damage by depth and area clearly detectable by visual inspection under typical lighting conditions from a distance of approximately 1.5 m [4–5].

In order for the composite to absorb as much impact energy as possible, it is necessary to use a factor that initiates the gradual crushing process either by a geometrical feature or by an appropriate composite structure (e.g. the introduction of a core). Furthermore, an optimal composite structure should eliminate fibre delamination and strengthen the interlaminar mechanisms that absorb the most energy [6].

Foam-core structural composites are produced by methods based on layering in different configurations, which show excellent in-plane properties. However, they do not withstand the vast majority of lateral loads, which result in delamination, buckling and a drastic reduction in the lifetime of the material [7]. In order to increase a material's ability to absorb impact energy, the failure process needs to be analysed and the potential for optimisation of individual components assessed. A significant amount of impact energy is absorbed in a gradual failure process [8], among which the most common mechanisms are the occurrences of a fracture of the cladding layer and/or fibres, a local or global buckling of the structure, a delamination and a core shear.

To complement the strength characteristics of the foam-core structural composites, the impact test or short beam bending tests, three-point bending strength, compressive strength or residual strength tests are also performed [20–27].

Most research work on structural composites has used fibre matrix reinforcement or powder fillers. To eliminate the defects of the epoxy matrix and to improve the mechanical and processing properties of the obtained ones, it is possible to use various types of chemical modifications [9–18]. Many macromolecular compounds acting as modifiers of the epoxy resin may form a system of interpenetrating polymer networks (IPNs) with it [19]. However, no work related to the chemical modification of the matrix in the structural composite has been found. In the present study, an attempt was made to prove that chemical modification of the epoxy matrix is an extremely effective procedure also within a structural composite. Previous studies on the modification of Epidian 5 resin, carried out at the Department of Applied Chemistry at the University of Radom, have shown that the addition of up to 10% polyurethane by weight significantly improves the resin's strength properties. However, there have been no studies to date that have shown the relationship between matrix modification and the properties between the layers of the structured composite. i.e. between matrix and reinforcement and cladding and core.

Numerous experimental studies are also carried out on co-composite materials in engineering applications, among others, exposed to unfavorable operating conditions such as high temperature [28], exposure or temperature shocks [29, 30]. This type of research is required especially in aviation and space technology, where this type of fiber-reinforced composites [31, 32, 33] are used for protective elements as well as the structural elements of the aircraft themselves.

PREPARATION OF TEST MATERIALS

The epoxy resin has previously been modified with polyurethane to create IPN interpenetrating polymer networks. This solution effectively improves the strength properties of the resin, which without modification is often disqualified in structural applications due to its high brittleness and inferior strength properties compared to other plastics. The amount of modifier introduced into the resin was based on previous research into modifying epoxy resin with polyurethane [20]. Table 1 provides a summary and characterisation of the components needed to produce the structural composite.

Composites were made in moulds coated with release agent using the hand lamination method (without using a vacuum bag, at room temperature). Epidian 5 epoxy resin modified with polyurethane (Desmocap 12 at 10 wt%) and triethylenetetramine hardener Z1 were used as the matrix. A 324 g/m^2 twill glass fabric was used as reinforcement. Extruded polystyrene foam plates were used as the core.

Appropriate amo unts of EP and PU (10 wt% polyurethane) were mixed thoroughly and the composition was stirred for 10 min using a homogeniser. This was followed by ultrasonic homogenisation for 10 min. After mixing, a stoichiometric amount (12:100) of hardener was

Table 1. Characteristics of the components to produce the structural composite

Material	Material characteristics	Producer
Epoxy resin	Low-molecular-weight epoxy resin Epidian 5 Viscosity in 25 °C: 20,000–30,000 mPa·s Density in 20 °C: 1.17 g/cm^3	„CIECH – Sarzyna S.A.”, Nowa Sarzyna, Poland
Hardener	Z1 (triethylenetetramine) Density in 25 °C: 0.979-0.987 g/cm^3	
Polyurethane (polymer modifier)	Linear polyurethane prepolymer Desmocap 12 Contents of blocked groups -NCO: 1.80–2.10 % Viscosity in 25 °C: 23.000 – 43.000 mPa·s	„Bayer Material Science”, Leverkusen, Germany
Glass fabric	Glass fabric 324 g/m^2 twill	Krosglass S.A., Krosno, Poland
XPS foam core	Extruded polystyrene XPS Thickness: 3 mm Density: 0.038 g/cm^3	CEZAR Manufacturing Company Ełk, Poland

added. Mixing was continued for 5 min. The first layer of composite layer was made by soaking the glass fabric with modified resin and spreading it evenly over the entire surface of the reinforcement. On top of the layer prepared in this way, an XPS extruded polystyrene layer was applied. Another layer of resin-soaked fabric was applied to the core and these steps were repeated until 3 layers of core and 4 layers of reinforced cladding were achieved.

The specimens were cut with a diamond blade cutter according to the specifications in the experimental test standards (Figure 1).

RESEARCH RESULTS

The damage tolerance of the composites was determined using an Instron CEAST 9340 testing machine with an impact energy ranging 5–35 J to indicate the value at which visible damage to the composite occurs while it retains some of its strength properties. The specimens were placed freely on a cylindrical base with holes. A schematic of the drop weight test and the test specimens are shown in Figure 2. The tests were performed at room temperature (Table 2).

The three-point bending test after impact (BAI test) for structural composites was carried out in accordance with PN-EN ISO 14125:2001 [21] using a Zwick/Roell Z010 testing apparatus (Ulm, Germany). Rectangular specimens with a length of 100 mm, a width of 15 mm and a thickness of 10 mm (± 2 mm) were placed on supports spaced 60 mm apart. The composites were bent at a constant speed of 5 mm/min. The bending modulus, maximum bending strain and interlaminar shear strength were determined.

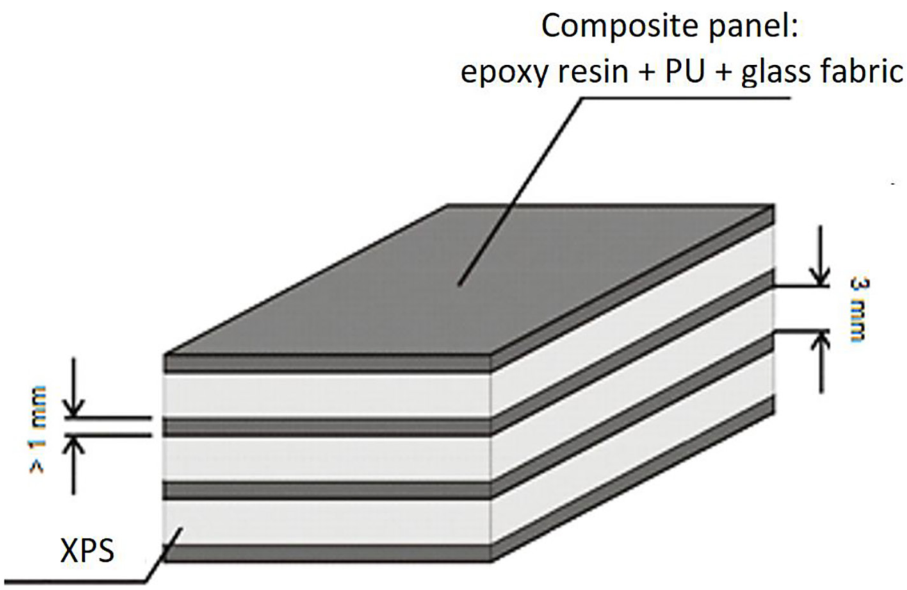

Figure 1. Scheme of composite plate

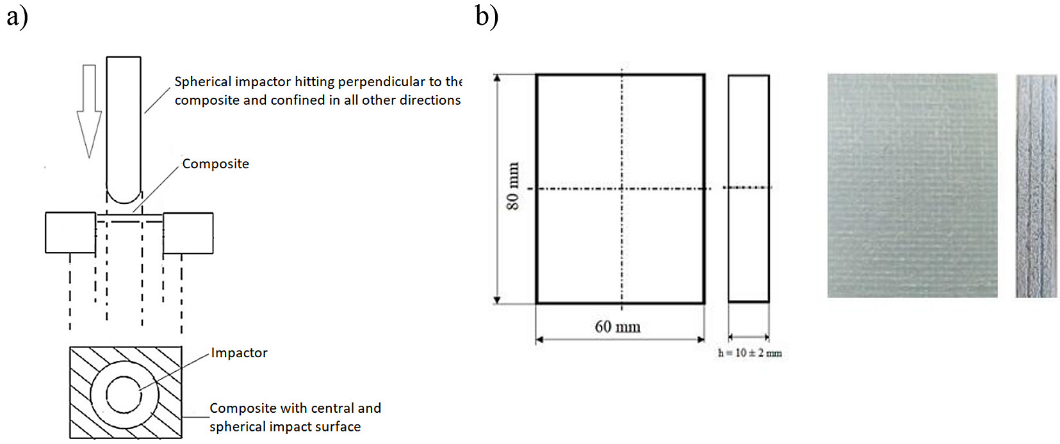

Figure 2. Scheme of (a) the drop weight test and (b) the test specimens

Table 2. Drop weight test parameters

Impact energy [J]	Total mass [kg]	Impact height [mm]	Impact velocity [m/s]
5	2.65	192	1.943
10	2.65	385	2.747
20	2.65	770	3.885
25	2.65	962	4.344
35	3.65	978	4.379

Surface testing was carried out using an optical profilometer from FRT model MicroProf100. The measurement of the step change in dimension in the vertical axis and the representation of the structure in 3D was performed with an accuracy of 100 nm in the Z-axis.

Based on previous experimental studies using PU in [19–20], a modification of the matrix in the amount of wt. 10% PU, striking a balance between improving the mechanical properties of the composite and minimising material losses resulting from achieving only a slight improvement in strength parameters. In most of the research works analysed at the literature study stage, the trend was to use only fibres or powder fillers as matrix reinforcement. The liquid polymer modification has led to the formation of interpenetrating polymer network between the reactive groups - OCNs in the structural chain of the polyurethane and the resin. It was noteworthy that polyurethane can also form chemical bonds with hydroxyl groups present on the glass surface. Extensive structural studies of the bonds occurring between the layers have not yet been carried out, but basic chemical knowledge supports the confirmation of this thesis.

The composites were subjected to an impact resistance test using the drop weight method. A series of tests were performed to determine the damage tolerance of the composites. The focus was mainly on damage from BVIDs (Barely Visible Impact Damage), as these are the ones that are particularly difficult to identify, and damage from low-energy impacts can have a very negative impact on the residual strength of the material. Polyurethane improves the adhesion between the composite layers, as well as improving adhesion between the matrix and reinforcement in the cladding layer. The addition of the modifier is also credited with improving the strength properties of the matrix itself by inhibiting crack propagation. This results in more efficient behaviour of the composite in terms of impact energy absorption. The composites were visually assessed after a single point impact of the impactor. The point impact behaviour of the specimens at different impact energies caused the impactor to rebound in samples impacted with energy in the range of 5–25 J (Figure 3). At low energies, damage was observed on the top layer of the cladding, which were cracks in the matrix without fibre breakage and without permanent deformation in the core layer (Figure 4). As the energy values increased, the damage progressed, and the damage area increased significantly. There was also significantly

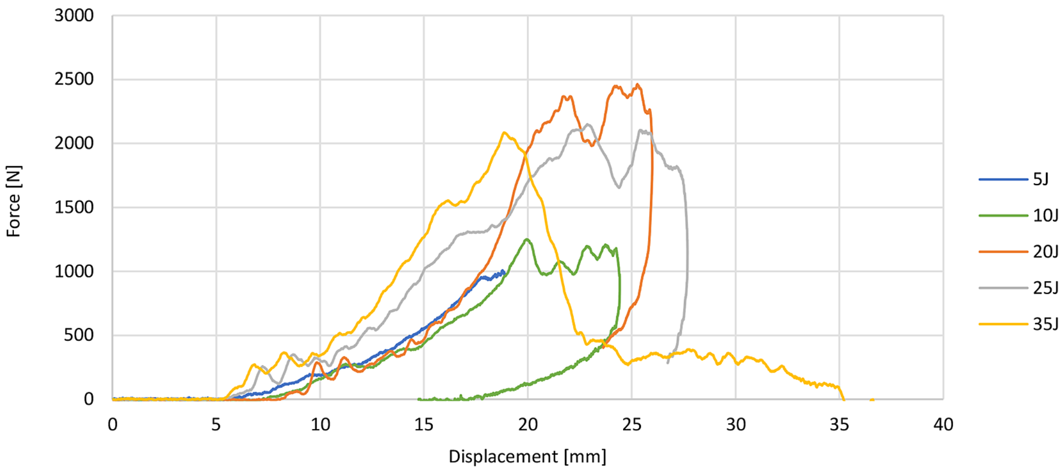

Figure 3. Force-displacement correlation diagram

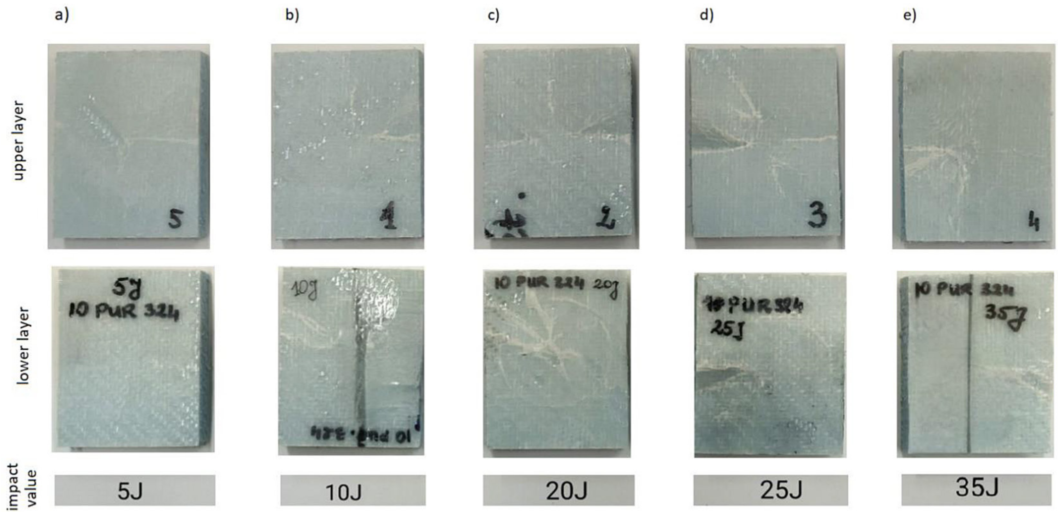

Figure 4. Samples after the drop weight test - upper and lower composite layer impacted with an energy of (a) 5 J, (b) 10 J, (c) 20 J, (d) 25 J, (e) 35 J

more damage at the interlayer. An impact with an energy of 35 J caused complete failure of the composite (total penetration). Although this is not indicated by a visual assessment of the composite after impact, it is clearly indicated by the curve shown in the graph.

The difference in the structure of composites impacted with an energy of 10 J and 35 J is shown in the optical profilometer images in Figure 5. There is a noticeable difference in the surface damage of the material itself after impact when analysing the 3D surface topography of a section of the test specimen. A dent is observed in the material after impact with a drop hammer pin at an impact energy of 10 J (Figure 5 a), but without a break in the material continuity. In contrast, for a specimen impacted with an energy of 35 J, the continuity was broken and a step change in the material dimension is visible (Figure 5 b). The indentation alone of the material impacted with 10 J at 6 mm is approx. 400 µm (Figure 5c), while the indentation of the material impacted with 35 J at 6 mm is approx. 650 µm, of which approx. 200 µm is the abrupt change (Figure 5 d).

Bending after impact (BAI) test are only presented for the composite impacted with an energy of 10 J and this composite type was chosen for the next research stage into modified composites. In subsequent impact resistance and residual strength tests, the composites were impacted with an energy of 10 J, as the composite showed BVID damage under this impact, and a higher impact value generated visible damage in the composite structure. The results presented in this report are part of a more

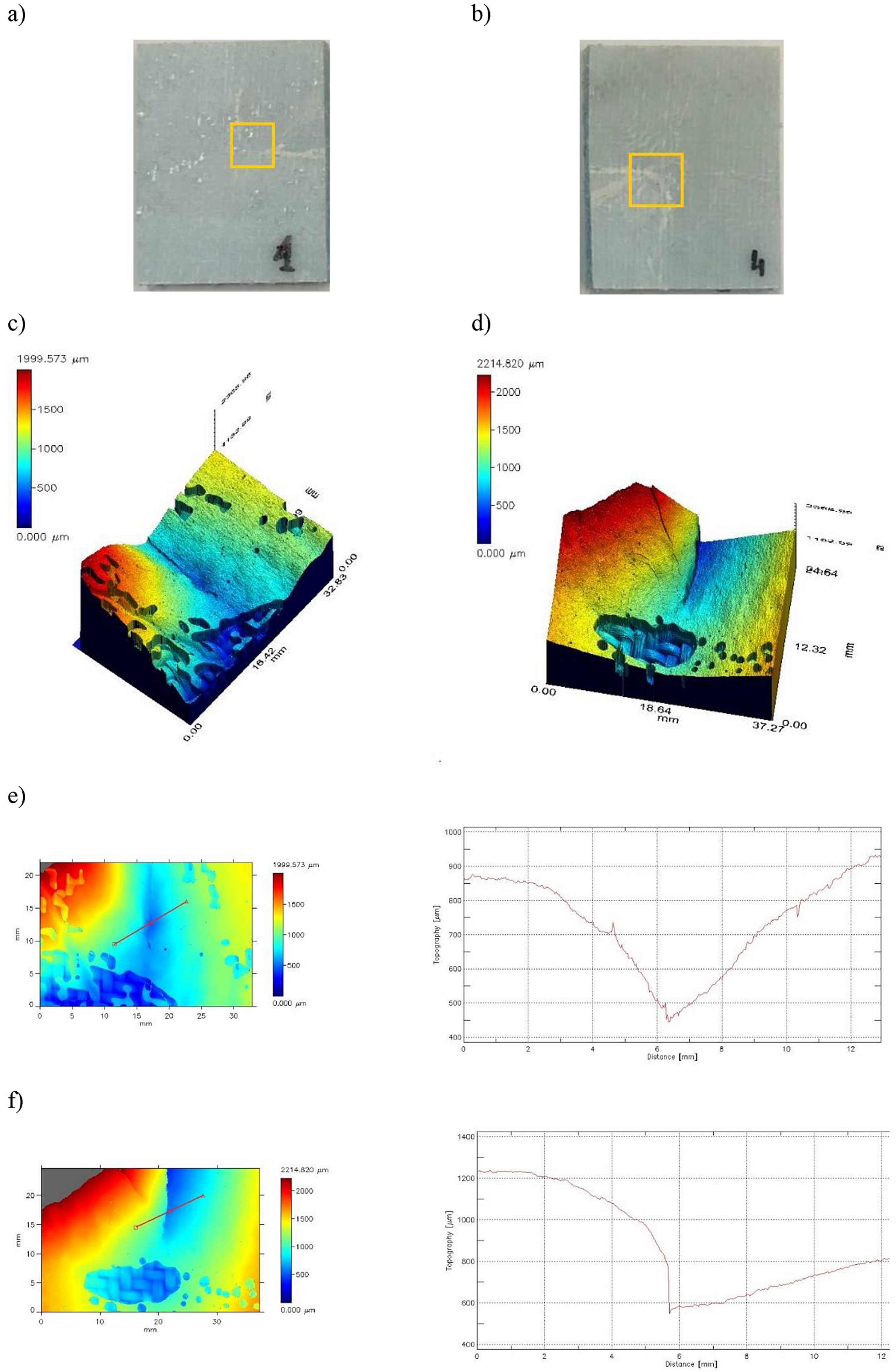

Figure 5. Areas of composites tested on an optical profilometer impacted with energies (a) 10 J (b) 35J and 3D imaging of the composite after impact with energies of (c) 10 J, (d) 35 J. Photo of a section of the specimen with the indicated line of fault measurement at the point of impact and the values of the specimen fault itself after impact with energies of (e) 10 J and (f) 35 J.

Table 3. BAI test results

	Energy at break [kJ/m^2]			Flexural modulus [MPa]			ILSS [MPa]
10PU324GF3XPS	BO	BAI	Residual strength	BO	BAI	Residual strength	
	8.55	5.61	35%	42.20	23.15	45%	0.32

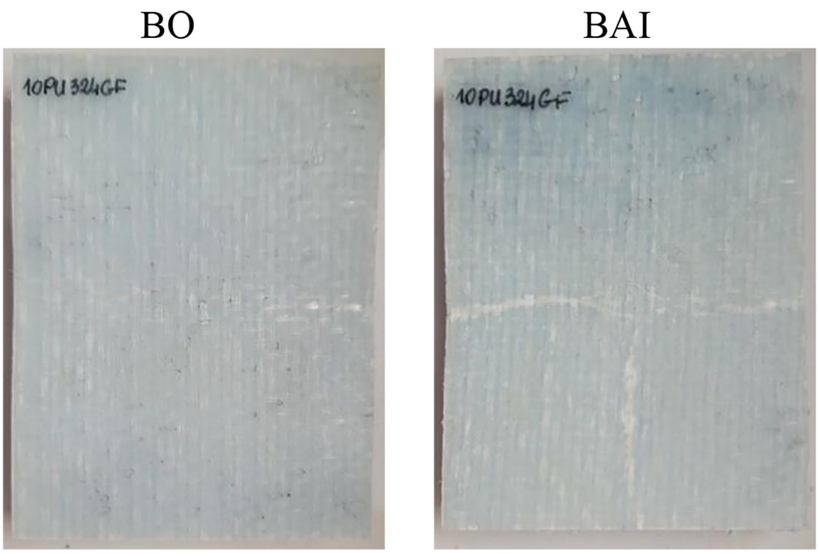

Figure 6. Composites after BO and BAI testing

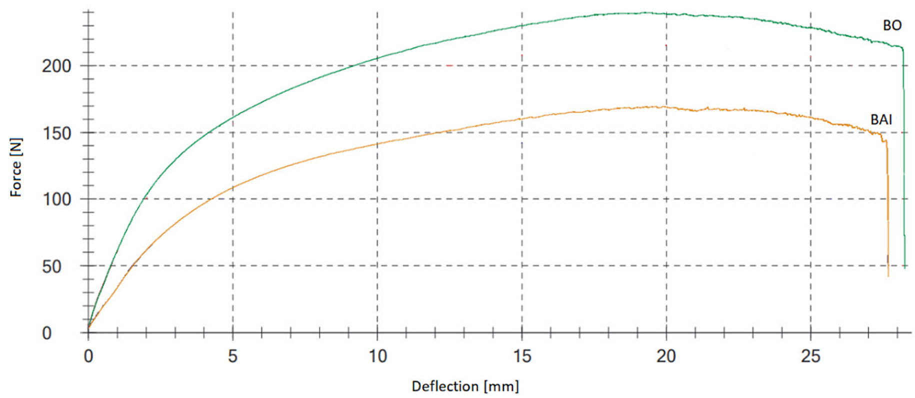

Figure 7. Three-point bending test curves (BAI method)

extensive research study. The choice of such an impact energy value best reflects the low-energy impact that can be established for materials to be used to cover various elements or objects. The reference values are bending only (BO) test samples. Analysis of the results indicates a 45% decrease in strength of the composite with 10% PU. Its preliminary value of energy at break was 8.55 kJ/m^2 and the value after impact and bending was 5.61 kJ/m^2. The determined values of the bending modulus of the materials tested by the BAI method indicate that the composites with 10% PU content have a decrease in stiffness while retaining 55% of the previous stiffness.

After the three-point bending test. a barely visible trace of deflection of the specimen was observed on the upper layer of the cladding (Figure 6). However. no cracking was observed in the bottom layer or in the middle layers for which a characteristic crack sound would be heard. This is also evidenced by the curve on the graph. which shows no kinks inherent in damage in the composite interlayer (Figure 7). Radial matrix cracking (without fibers damage) after BAI testing also indicates that the composite retains a good level of strength and structural integrity despite being exposed to different loads.

CONCLUSIONS

Modification with the liquid polymer leads to the formation of interpenetrating polymer networks (IPNs) between the reactive groups -OCNs in the structural chain of the polyurethane and the resin. It was noteworthy that the polyurethane also forms chemical bonds with the oxygen present in the glass structure. The modification improved the strength properties of the composite.

Composites impacted with energies of 5–10 J showed the least damage in the top layer of the composite layer. with no significant visible damage at the interlayer. The mechanisms of damage that followed the impact were solely matrix fracture without fibre rupture. The impactor was rebounded by the composites. As the impact energy increased. the damage increased significantly in area. and at energies of 25–35 J the damage mechanisms progressed deep into the composite.

Visual assessment of the impact damage to the composites allows an assessment of the damage tolerance of the composite – it shows very good resistance to low-energy loading. but the application of higher energies does not preclude the use of the material in energy-intensive applications.

An impact with an energy of 10 J was selected for the next stage of testing as the best value in a study of composites for use as protective structures exposed to low-energy impacts.

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