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BIOCOMPOSITES BASED ON A BALSA WOOD CORE CONTAINING INTERMEDIATE LAYERS MADE OF COCONUT AND SISAL

Sandwich-type composite materials of various geometries were obtained, in which the inner layer was a laminate of glass fabric, and the core consisted of natural materials: balsa wood, coconut and sisal fibres. The materials were tested to determine the type of cracking process under static and dynamic stress conditions (impact strength). The best results were obtained for hybrid balsa/glass fabric composites with a spacer made of sisal mat. This type of system allows a controlled cracking process, which is a consequence of a different stress distribution. The research shows that the combination of different materials in a single composite, depending on their volume fraction, density and layering geometry, opens the way for use in technical constructions, especially where high specific strength is required. The work contains valuable results of research on sandwich materials, their behaviour under load, their modification, and their impact on the transfer of dynamic and static stresses. For the first time, a composition was tested containing a balsa tree core with transient elastic layers made of natural cellulose fibres.

Keywords: wood, cellulose, composites, biocomposites

Introduction

Many types of engineering materials are currently available on the market. When designing any element, the construction product should be optimized, and this should be based on the properties of the material sought, according to specific classes of criteria [Sayyad et al. 2017; Birman and Kardomateas 2018]: general (cost of the material and its density); mechanical (Young's modulus, strength, resistance to cracking and fatigue); thermal (heat resistance, melting

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point, resistance to creep); consumption (wear indicator); corrosion (corrosion index). Another important design criterion is the conditions and manner in which the material will be exploited.

Sandwich composites consist of two thin skins, made of rigid, strong and relatively dense material, often of metal or fibrous laminate, between which is a thicker but light core [Nikbakt et al. 2018; Giap and Wang 2019]. Materials of this type are characterized by high stiffness and low density. They are used in constructions where high stiffness, strength and low weight are required. The role of the core is to keep the skins the same distance apart at each point of the material, to increase the stiffness of the structure and to improve the dampening properties [Demircioğlu et al. 2018]. The mechanical parameters of sandwich composites depend on the constituent materials: skin geometry, core geometry and core structure. As the core thickness increases, the stiffness and strength of the material increase significantly, while the density increases slightly. The materials of which the skins and cores are made are of great importance in layered sandwich constructions. The cores are made of various materials, the most common being aluminium and polymer. Cores may be isotropic or strongly anisotropic (like a honeycomb core) [Chun et al. 2015; de Souza et al. 2018]. In the case of the core, an important parameter is a low value of the Kirchhoff shear transverse modulus. The main role of the skins is the transfer of tensile and bending loads. They are also responsible for transferring bending moments, while the core transfers transverse loads [Li and Wang 2017; Kulkarni et al. 2018]. The materials discussed are used in many fields due to the described mechanical properties. They are used as elements of aircraft and other means of transport, and in the construction of hulls, floors, doors, and rudders [Karthigeyan et al. 2017; Jagath and Burela 2018]. They are also used to build elements of helicopters, rockets, and satellites, as energy-absorbing protective structures, and in sports for the construction of skis, golf clubs, and snowboards.

An important goal in materials engineering is care for the environment, and thus assessment of the lifetime of the materials produced. Other important environmental aspects are the method of their storage, the recovery of components in recycling processes, and ultimately their safer storage. There are several approaches to this problem; one of them is to attempt to replace synthetic materials with natural materials that have been modified or treated. A material of interest is wood from the balsa tree, which has the lowest density among wood materials and very unusual mechanical properties [Mohammadi et al. 2017; Dian et al. 2018; Jagath and Burela 2018; Okan et al. 2018; Susainathan et al. 2018]. The use of such materials pays off in a decrease in the proportion of non-recyclable waste on landfills, and reduces the problem of toxicity of composite elements after the service life. Currently, much attention is focused on materials of natural origin, mostly of plant origin, and in particular wood [Atas and Cenk 2010]. They have unique properties and are successfully used in different

branches of the economy, and their considerable share there is an indicator of the degree of development of an economy [Saeed 2013; Khalet et al. 2019].

Materials and methods

Materials

The balsa wood used was prepared and distributed by DIAB (Sweden), with a density of 0.155 cm/g^3 and a thickness of 2 cm; the core had an anisotropic structure (the moisture content of the balsa wood was 5-8%, depending on laboratory atmospheric conditions). Balsa wood has unique properties among all tree species. It is the lightest known wood. It has a tubular construction, which makes it very mechanically strong, with high Kirchhoff modulus values. Coconut and sisal mats (0.3 cm thick) were produced by Enkev (Holland), using a latex extrusion method. Laminates for skins were made of glass fabric from Havel Composites, chosen for transparency and good mechanical properties, and having a weight of 160 g/m^2 . For the matrix an epoxy resin was used, obtained from Epidian 601 resin mixed in a ratio of 5:1 with ET hardener (Ciech Sarzyna SA, Poland). Epoxy resin was used due to its resistance to moisture and weather conditions, good adhesion to various substrates, good physical coating properties, and durability. It has good adhesive properties and is resistant to degradation under the influence of water. Epoxy resins are easy to use, and cure quickly at temperatures of 5-150°C, depending on the hardener used. (The maximum temperature of the crosslinking process, called the temperature peak, was determined according to the standard [PN 88/C-89085/21:1988]). They are also distinguished by low shrinkage during crosslinking and good electrical insulation [Chen et al. 2018]. The selected ET hardener is often used for liquid epoxy resins because it mixes with them easily due to the low viscosity.

The samples were produced in two stages.

In the first stage the skins were made and stuck to the core. Skins were prepared by a wet manual laminating method. Appropriately sized rectangular fragments were cut from the glass fabric. The first layer of glass fabric was placed on the mould, and was then filtered with epoxy resin mixed with hardener. The next layer of material was applied and again filtered with resin. Subsequent layers were applied in the same way, depending on the thickness of the skin. Excess resin and air were spread with a rubber roller. The prepared glass laminates were pressed (500 kg) and allowed to crosslink at 40°C (this temperature was selected so that the rate of crosslinking of the resin would be the same in each type of sample) under a load of 5 kg.

In the second stage sandwich composites were produced. The hardened skins were connected to the balsa core (Fig. 1A) or, optionally, to a core and a mat of natural fibres (sisal and coconut) with epoxy resin (Epidian 601 mixed with ET hardener). Smaller fragments (suitably cut) of the sisal and coconut mat

(having the same surface area as the samples) were placed between the core and the skins. The coconut and sisal fibre layers acted as a buffer between the main components of the designed sandwich. In this way, two more types of cores were formed: balsa + coconut mat (Fig. 1B), and balsa + sisal mat (Fig. 1C). Like the skins, the samples thus prepared were pressed (500 kg) and allowed to crosslink at 40°C under a load of 5 kg. The pressing served to remove trapped air and additional excess resin, as well as to tighten the layers firmly to achieve a better connection at the phase boundaries. Figure 1 shows the types of samples tested.

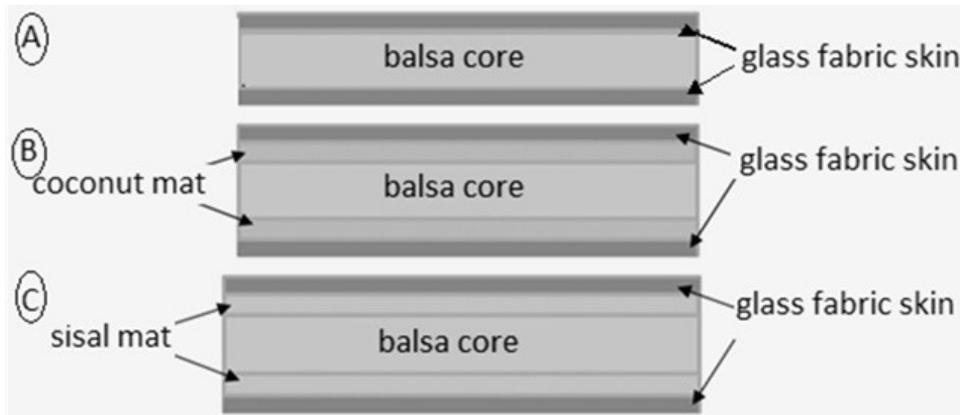


Fig. 1. Types of obtained sandwich composite

Samples prepared in this way were cut into a smaller rectangular beam and subjected to strength tests and other tests.

Test methods

Intermediate shear strength was tested according to PN-EN ISO 14130:2001. For this purpose, a Zwick 1345 strength machine was used. The method applied is called the short beam method, and is mainly used for thermosetting and thermoplastic fibre-reinforced composites.

The impact dynamic strength was measured by a percussive bending test using a Charpy hammer. The test consisted of breaking the specimen, supported at both ends, with a single swinging shuttle hammer. Composite materials prepared for impact tests had the shape of rectangular beams with a rectangular cross-section. The work of breaking the sample was calculated based on the following relationships:

$$K_I = mgR(1 - \cos_\alpha) \quad (1)$$

$$K_{II} = mgR(1 - \cos_\beta) \quad (2)$$

$$K = K_I - K_{II} = mgR(\cos_\beta - \cos_\alpha) \quad (3)$$

where K_I is the initial hammer energy, K_{II} is the final hammer energy, K is the work of destruction of the sample, m is the mass of the pendulum, g is the acceleration due to gravity, R is the distance from the pendulum axis to the centre of the sample, α is the angle defining the position of the pendulum before breaking, and β is the angle defining the position of the pendulum after breaking.

Samples after destruction were subjected to microscopic observations, mainly at points that had been subject to load, material stratification and fracture. For this purpose, the Keyence VHX-900F stereoscopic microscope was used. The most popular methods for determining density are the hydrostatic and geometric methods. The first test consists of filtering the samples by boiling in distilled water and then weighing them in water and air. In this work the geometric method was used, due to the structure of the samples, the microstructure of the balsa core, as well as the presence of natural material, which could degrade and swell under the influence of water.

Results and discussion

The mechanism of shearing of a balsa core in sandwich structures

All composites underwent destruction in a similar way when tested on the shear testing machine. Figure 2 shows how the samples deformed.

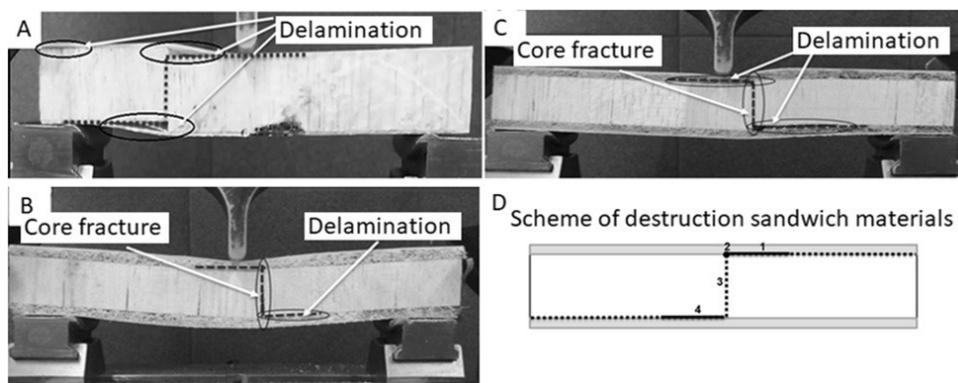


Fig. 2. Composite samples: A – with balsa core and four-layer glass skins, B – with balsa core and sisal mat and four-layer glass skins, C – with balsa and coconut mat core and carbon skins; D – composite destruction pattern

Vertical core fractures were observed due to the high proportion of bending stresses.

The development of the fracture mechanism is shown in Figure 2D, and consisted of several stages:

1. The presence of defects at the place where stress is concentrated (near the action of the applied stress) results in heterogeneity at the border between the skin/core layers, and the appearance of a crack (Fig. 2D, point 1).
2. Propagation of the crack parallel to the axis of the boundary layer (Fig. 2D, point 2).
3. Disintegration of the core at the incision site (made in the balsa by the manufacturer) or at a point with a high concentration of stresses (Fig. 2D, point 3).
4. Skin resistance, delamination of the lower skin and propagation of the crack parallel to the axis of the interlayer boundary (Fig. 2D, point 4).
5. Layer disintegration, propagation of the crack until complete destruction.

The sandwich samples with the balsa core were destroyed due to delamination and shearing of the core. The mechanism of destruction was a multi-stage one, as evidenced by the force–deformation characteristics (Fig. 3). The materials deformed elastically to reach almost the maximum force (Fig. 3, point A). The balsa wood core burst in a short time before the sample was destroyed. In addition, delamination was observed at the interface near the fracture. In each case the core was damaged. The skins were not destroyed, but they carried traces of stress transfer. Their colour changed to milky, which may indicate internal defects of the skin. The reason for this was the microcracks formed in the matrix under the influence of the load, which dispersed light on their surfaces. They also provide evidence that the balsa core gives resistance to stress, spread over the surface of the skin. All materials underwent shearing; however, the vertical core fractures may indicate a significant share of bending stresses.

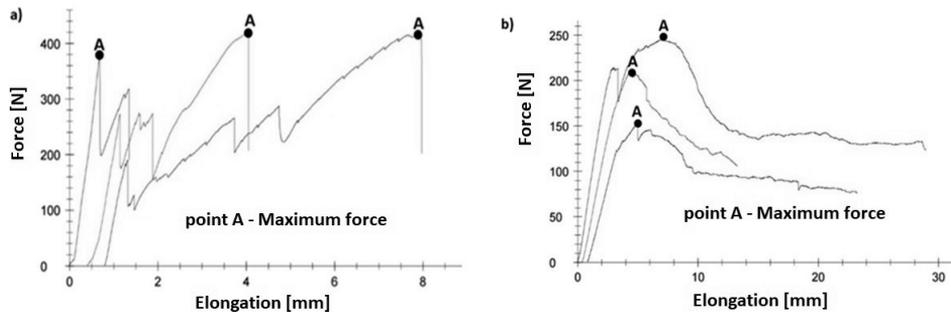


Fig. 3. Strength and strain characteristics for sandwich composites: with balsa and four-layer glass skins (a), with balsa and coconut mat and four-layer glass skins (b)

The presence of a coconut mat significantly changes the destruction characteristics of the composite under the influence of bending strains. This is caused by the spreading of stresses via the coconut layer over the whole surface of the sample. Many conclusions can be drawn from analysis of the behaviour of the tested composite materials under the influence of stress. Samples containing

only the glass skin and the balsa core (Figure 3a) achieved the maximum force transmission, then the fibres in the bottom skin that were stretched to the greatest extent ruptured. This resulted in a sharp drop in the force transmitted by the tested element. After breaking, the whole stress focused on the subsequent layers of the glass fabric, slightly exceeding the maximum force that the material could carry, followed by breaking, and the pattern was repeated. This characteristic of material destruction under the influence of stresses is beneficial, due to the increase in the work of destruction needed for complete disintegration of the tested sample. In the case of samples with coconut and sisal mats between the core and the skin, the destruction characteristics were very different from those without mats. The applied mats were elastic, and in the first stage, elastic distribution of the applied tension took place from the glass laminate skin through the elastic mat to the core. Cracking of the stretched laminates took place from the bottom skins, which is advantageous from the point of view of the use of such a material for structural applications.

Density values

The table (Table 1) presents the results of density determination for all prepared samples. The reason for the low density of sandwich composites is the presence of pores and voids that result from the core structure, both in the wood balsa and in the aramid honeycomb. The specific density of the samples was used to calculate the specific shear strength. The table (Table 1) presents the densities of all samples prepared in the second stage of work, as well as composites with a balsa core and four-layer glass skins made in the first stage of work.

Table 1. Comparison of sample density

Material of core	Type of skin	Number of layers	Density [g/cm ³]
Balsa	glass	4	0.27
Balsa and sisal	glass	4	0.29
Balsa and coconut	glass	4	0.29

Density measurements did not indicate significant differences between the samples tested. The sisal and coconut mat present in the sandwich material causes a slight increase in density.

Strength properties

On the basis of the shear test, the maximum shear stresses occurring in the composite samples were calculated, as well as the force and work required to destroy them. The specific shear strength was also determined; this is the ratio of the calculated shear strength to density. This made it possible to compare the strength of different materials with regard to their construction.

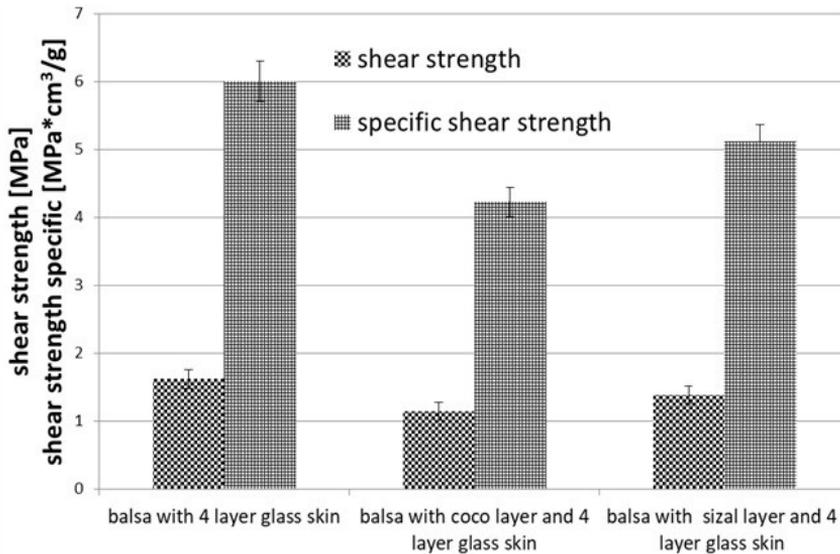


Fig. 4. Comparison of shear strength and bending strength

Shear strength for three types of samples is in a similar range, but the sandwich composite made of pure balsa and skins has the highest shear strength. The studied composites show greater differences when the results are calculated by density, because low mass is their greatest asset. The presence of mats as intermediate layers reduces the static strength by 15% in the case of sisal mats and 26% in the case of coconut mats. The difference between samples with coconut fibres and sisal fibres lies in the construction and strength of the fibres. Sisal fibres contain in their structure twice as much cellulose as coconut fibres, which positively affects the strength properties (a higher share of cellulose improves the strength of the natural fibre).

Dynamic impact stress

After the impact tests, the samples were destroyed. Cracks in the core and skins are visible, as well as the delamination of mats. The composites split into three parts (Fig. 5). During destruction, the dynamic stresses accumulated in the central part of the sample (Fig. 5, point 2). The materials became V-shaped when damaged. The research shows that the surface perpendicular to the impact direction of the hammer, which accumulates and absorbs impact, is crucial. It was observed that the thicker the gap between the skin and the core, and the more resilient the material filling this gap, the area absorbing the impact (Fig. 5) is larger. Coconut and sisal mats shrink and spring during the test; the impact is spread perpendicularly, while the skin collapses, distributing stresses along the length of the sample. Sisal has greater elasticity, and is therefore more resistant to impact.



Fig. 5. Samples after impact test. Composites with four-layer glass skins, balsa wood core and A – sisal mat, B – coconut mat

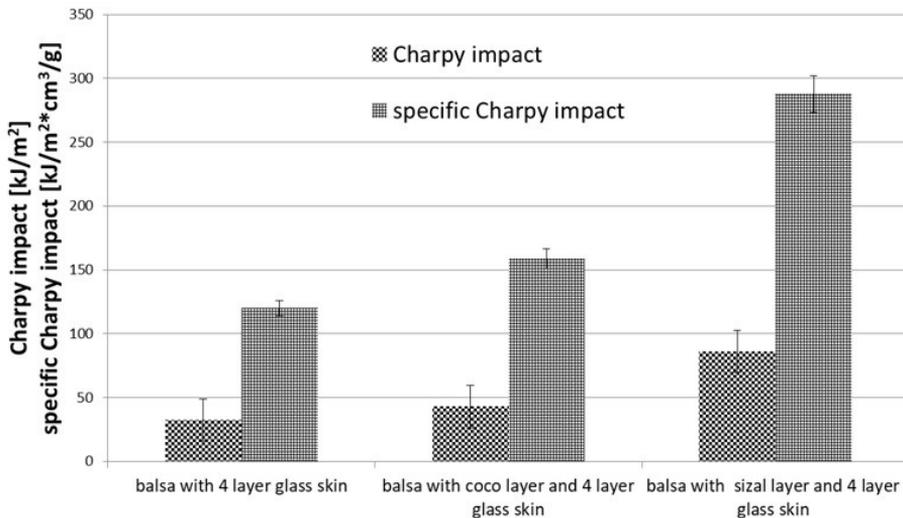


Fig. 6. Comparison of impact strength of composites with four-layer glass skins and balsa core and their modifications

As can be seen from the graph (Fig. 6), the highest dynamic impact load transfer capacity was observed for material modified with a sisal mat (Fig. 6). The addition of coconut fibres also increased the impact strength, but not as much as the sisal. Sisal contains up to 22% of water in its structure, which makes the fibres more elastic and better at withstanding impacts. Coconut fibres are dry enough that they contain only 45% cellulose, and the amount of water in the structure is up to 8%. Modification with coconut fibre results in an increase in the examined properties by approximately 32%, while the sisal gives a 166% increase in comparison to samples of composites with a balsa core without an intermediate layer. The last comparison was of the energy of destruction

calculated by the static test method in bending tests and the dynamic value calculated in the impact test (Fig. 7).

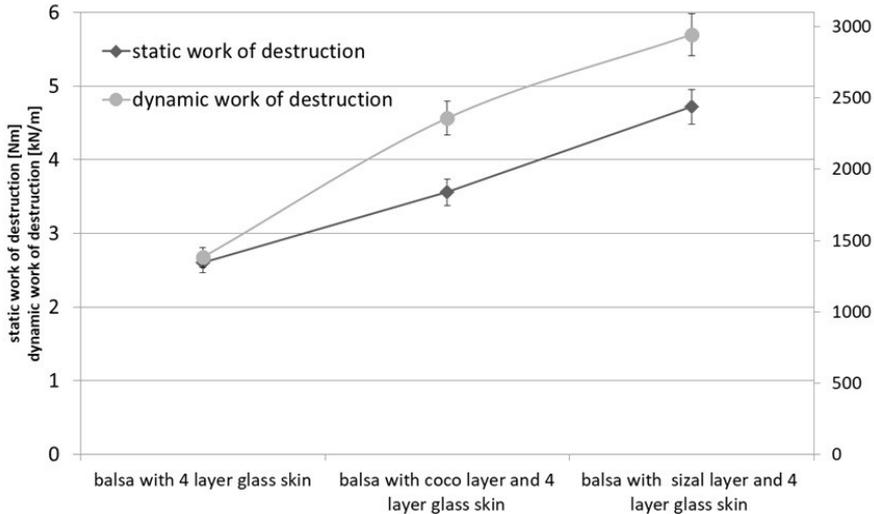


Fig. 7. Comparison of static and dynamic work of destruction in composite samples

Composites without a sisal or coconut layer have a 50% lower energy of destruction than samples with intermediate layers. The higher the energy needed to destroy the material, the better. The energy absorption mechanism is multidimensional in this case. The difference between a sandwich material without coconut and sisal mats and composites modified with such mats is significant, which means that their presence significantly improves the absorption and distribution of accumulated stresses occurring during the impact test. The mat is elastic because its component fibres (coconut and sisal) are bound by natural latex. This combination allows the dissipation of energy to a large extent before reaching the destructive stress to the core, decreasing the value of the expansion after which the composite deformation takes place. The tests did not show any abnormal adhesion at the interface or transfer of stress from the skins to the core.

Discussion

Method of production of sandwich composite materials with wood balsa core

A two-stage method was used to prepare the composites, which consisted of making the skins by means of manual lamination and subsequently gluing them to the core. The advantages of this method include above all its simplicity and low tooling costs. In addition, it did not require the use of high temperatures, and

enabled the use of minimal amounts of resin, the excess of which is removed under a load (thanks to which no resin is observed in the pores of the balsa core). As for the disadvantages of the two-step method, it was found that it is very time-consuming, as the samples have to remain under load for at least a few days, to thoroughly squeeze the resin and obtain a good connection at the phase boundaries. When preparing composites using the contact method, it should be remembered that their quality will largely depend on the production technology, compliance with the procedures and operations contained therein, as well as the skills and experience of the person performing the task. In all the samples in which a natural balsa core was used, the skins were not damaged; only traces of stress transfer and a slight change of colour at the point of load application were noted. This shows good adhesion at the phase boundaries.

Models of the destruction of the materials

The tests and observations enabled a description of models of the destruction of samples of composite material with a balsa wood core. Both static and dynamic tests were carried out. The samples with a natural core deformed under the influence of static loads in a similar way. The destruction occurred due to delamination and shearing of the core. The mechanism was several-fold. Initially, until the maximum force was reached, the materials deformed elastically, and the successive appearance of vertical balsa cracks was observed. Also visible was delamination at the interface, and – in the case of mouldings modified with mats – delamination of the mats. The balsa core was destroyed first, which proves good adhesion at the interface, thanks to which the stresses were transferred from the skins to the core. All samples with a natural core were bent into a V-shape during destruction. It was observed that in this case the surface perpendicular to the impact direction of the hammer, which accumulates and absorbs impacts, is crucial. It was found that the greater the gap between the core and the skin, and the more resilient the filler material, the greater is the absorbing area. During the tests, the mats shrank, the impact was distributed perpendicularly, and the skin collapsed, distributing stresses to the sides. The final strength and energy values recorded in the conducted tests are influenced by the following factors: continuity and homogeneity of the layers, especially layers of coconut and sisal mat; adhesion at the interface between layers; the mechanical properties of the substrates forming the layered biocomposite; the properties of the natural fibres and the balsa.

Proposals for future research

In the future, the materials prepared in this work will be subjected to fatigue tests, in which their strength under the influence of cyclically variable loads will be determined. In the case of structural composites, this is an important parameter. Fatigue of the material lowers its durability and is often the cause of

cracks in components made of it, which can lead to serious accidents. Based on the research and observations made, it was concluded that in order to obtain more natural materials in the future, the focus should be on the preparation and examination of the properties of sandwich composites made of a natural core (balsa, mats) and natural skins; for this purpose, for example, natural fibre fabrics can be used.

Conclusions

All of the tests and observations made allowed conclusions to be drawn regarding methods of production, parameters of the component materials of the prepared composites, and the mechanism of their destruction. In the production of materials based on sisal and coconut fibres, it is difficult to reproduce the same type of materials with identical mechanical properties. Thus, one can speak of a natural sandwich material having properties within a range of $\pm 8\%$ of the measured average value. This is a significant problem that can be minimized by taking care to ensure the appropriate level of substrate moisture.

The research enabled an evaluation of all of the prepared materials in the context of specific technical applications. The highest static strength is exhibited by samples with a balsa core and glass skins, which are destroyed by shearing of the core and delamination. The most resistant to impact resistance are materials with a natural core – balsa, sisal mat – and glass skins. Coconut and sisal mats dampen internally very well, and do not allow stress concentration in the balsa core. Balsa is not resistant to impacts parallel to the direction of wood cells. Despite the identical chemical structure of coconut and sisal fibres, differences in impact resistance were noted. Sisal fibres are more impact-resistant than coconut fibres. The fibres differ on the structural level: sisal fibres have longer cellulose chains in their structure, which favours the dissipation of the impact energy. These materials are characterized by low density and ease of manufacture, while a disadvantage is their lower static strength. This material was considered the most universal sandwich composite of all the prepared samples.

In conclusion, sandwich-type composites are a very wide and promising group of materials, but they require proper selection of components and examination of their behaviour in a specific application. In the materials tested here, the mass fraction of synthetic components was 7% (resin and glass fabric), which is a highly satisfactory value. Sandwich compositions containing wood and other cellulose structures will be increasingly studied. This is part of a global trend, resulting from the significant waste management problems that arise when materials based on synthetic polymers reach the end of their lifetimes.

References

- Atas C., Cenk S.** [2010]: On the impact response of sandwich composites with cores of balsa wood and PVC foam. *Composite Structures* 93 [1]: 40-48
- Birman V., Kardomateas G.A.** [2018]: Review of current trends in research and applications of sandwich structures. *Composites Part B: Engineering* 142: 221-240
- Chen P., Yuan W., Jianchao L., Hui W., Lei Z.** [2018]: Adhesion and erosion properties of epoxy resin composite coatings reinforced with fly ash cenospheres and short glass fibers. *Progress in Organic Coatings* 125: 489-499
- Chun L., Zhao M., Jie L., Jing Wang J., Gao Y., Cui X., Chen P** [2015]: Stress distribution on composite honeycomb sandwich structure suffered from bending load. *Procedia Engineering* 99: 405-412
- de Souza E., Ferreira Gomes G., Ancelotti A.C., Cunha S.S., Antonio José Faria Bombard A.J., Junqueira D.M.** [2018]: Experimental dynamic analysis of composite sandwich beams with magnetorheological honeycomb core. *Engineering Structures* 176: 231-242
- Demircioğlu T.K., Balıkoğlu F., İnal O., Arslan N., Ay İ., Ataş A.** [2018]: Experimental investigation on low-velocity impact response of wood skinned sandwich composites with different core configurations. *Materials Today Communications* 17: 31-39
- Dian Z., Shi H., Fang H., Liu W., Qi Y., Bai Y.** [2018]: Fiber reinforced composites sandwich panels with web reinforced wood core for building floor applications. *Composites Part B: Engineering* 150: 196-211
- Giap H.X., Wang M.Z.** [2019]: Experimental study and finite element simulation of novel nap-core sandwich composite. *Composites Part B: Engineering* 158: 117-130
- Jagath N.K., Burela R.G.** [2018]: A review of recent research on multifunctional composite materials and structures with their applications. *Materials Today: Proceedings* 5 [2]: 5580-5590
- Karthigeyan P., Senthil Raja M., Hariharan R., Karthikeyan R., Prakash S.** [2017]: Performance evaluation of composite material for aircraft industries. *Materials Today: Proceedings* 4 [2]: 3263-3269
- Khaled L., Korhonen O., Zrida M., Hamzaoui A.H., Budtova T.** [2019]: All-cellulose composites from alfa and wood fibers. *Industrial Crops and Products* 127: 135-141
- Kulkarni P.V., Sawant P.J., Kulkarni V.V.** [2018]: Design and development of plane bending fatigue testing machine for composite material. *Materials Today: Proceedings* 5 [2]: 11563-11568
- Li T., Wang L.** [2017]: Bending behavior of sandwich composite structures with tunable 3D-printed core materials. *Composite Structures* 175: 46-57
- Mohammadi S., Meisam, Nairn J.A.** [2017]: Balsa sandwich composite fracture study: Comparison of laminated to solid balsa core materials and debonding from thick balsa core materials. *Composites Part B: Engineering* 122: 165-172
- Nikbakt S., Kamarian S., Shakeri M.** [2018]: A review on optimization of composite structures. Part I: Laminated composites. *Composite Structures* 195: 158-185
- Okan O., Oztoprak N., Kandas H.** [2018]: Single and repeated impact behaviors of bio-sandwich structures consisting of thermoplastic face sheets and different balsa core thicknesses. *Composites Part B: Engineering* 149: 49-57
- Saeed K.N.** [2013]: Use of recycled plastics in wood plastic composites – A review. *Waste Management* 33 [9]: 1898-1905
- Sayyad S., Atteshamuddin S., Ghugal Y.M.** [2017]: Bending, buckling and free vibration of laminated composite and sandwich beams: A critical review of literature. *Composite Structures* 171: 486-504

Susainathan J., Eyma F., De Luycker E., Cantarel A., Castanie B. [2018]: Experimental investigation of impact behavior of wood-based sandwich structures. *Composites Part A: Applied Science and Manufacturing* 109: 10-19

List of standards

PN88/C-89085/21:1988 Żywice epoksydowe – Metody badań. Oznaczanie szczytu temperaturowego (Epoxy resins – Test methods. Determination of the temperature peak

PN-EN ISO 14130:2001 Kompozyty tworzywowe wzmocnione włóknem – Oznaczanie umownej wytrzymałości na ścinanie międzywarstwowe metodą krótkiej belki (Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method

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