Polish Society of
Composite Materials
Polskie Towarzystwo
Materiałów Kompozytowych

16: 4 (2016) 255-259

COMPOSITES
THEORY AND
PRACTICE

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Received (Otrzymano) 30.11.2016

CHARACTERISTICS OF FAILURE MECHANISMS AND SHEAR STRENGTH OF SANDWICH COMPOSITES

Sandwich composites are very popular nowadays due to their beneficial mechanical parameters and low weight. The aim of the paper was to investigate the failure mechanisms of different sandwich structures under shear stresses. Composites consisting of carbon laminate skins and cores with different geometry were tested. The core materials included various expanded polymer foams, balsa wood and honeycomb structures - aramid and cellulose. These material combinations enabled the authors to compare the specific shear strength and fracture energy of different sandwich structures, describe the factors which influence the behavior of materials under shear tension, and characterize the failure mechanisms. Sandwich composites were manufactured by two methods: the one-step method in which carbon fabric was laminated directly onto the core, and by the two-step method. The faces made employing the first method failed to meet the appropriate strength criteria, therefore the second method was used. In the first step, faces made of four layers of carbon fabric and epoxy resin were pre-manufactured by hand lay-up. After crosslinking, the faces were glued to the core and left in higher pressure conditions. Samples were cut to the required dimensions. Shear strength was tested by three point bending of a short beam. The method is simple and allows shear stresses to dominate in the sample. Tests were made on a testing machine, Zwick 1435. The density of the samples was considered as well, so as to compare their specific strength. The highest value of specific shear strength, $(8.7 \pm 0.7) \cdot 10^3$ Nm/kg, was demonstrated by the composite with balsa, whereas for the composite with the honeycomb it reached $(3.3 \pm 0.3) \cdot 10^3$ Nm/kg and for samples with foams $(4.2 \pm 0.2) \cdot 10^3$ Nm/kg. Additionally the failure energy was calculated for each material. The composite with aramid honeycomb had the highest value - it reached (9.3 ± 0.5) kJ/m^2, while value of this parameter for balsa was the lowest: (3.3 ± 0.3) kJ/m^2. The composite with balsa deformed elastically until break point and a crack between the layers appeared. The sandwich structure with the aramid honeycomb core is a promising material as it exhibited a multi-stage failure mechanism. Firstly, it deformed elastically, then the cells collapsed. Only in the composite with balsa and honeycomb with four-layer skins was shear the dominant failure mechanism. The composites with isotropic foams did not fulfill expectations, they deformed plastically and a notch appeared. That is why they need further examinations to increase their shear strength. In this study, the cracking mechanisms of the composites were evaluated based on microscopic observations using a digital microscope. Depending on the core geometry, the following mechanisms were identified: core shear for the honeycomb, delamination and crack for balsa, and notch appearance for the foam composites. The presented results are an introduction to further investigations of sandwich failure under different conditions.

Keywords: **composite, sandwich, shear, bending, strength, core, balsa, honeycomb**

CHARAKTERYSTYKA MECHANIZMÓW ZNISZCZENIA I WYTRZYMAŁOŚCI NA ŚCINANIE KOMPOZYTÓW TYPU „SANDWICH"

Kompozyty sandwich cieszą się dużą popularnością, ponieważ, posiadając niską masę, wykazują korzystne parametry wytrzymałościowe. Celem pracy było zbadanie mechanizmów zniszczenia różnego rodzaju kompozytów sandwich w warunkach ścinania. Przedmiotem badań przedstawionych w artykule są kompozyty przekładkowe, zbudowane z okładek - laminatów z tkaniny węglowej - oraz rdzeni o odmiennej geometrii. Jako materiały na rdzenie zastosowano różnego rodzaju pianki polimerowe, balsę oraz struktury typu plaster miodu - aramidową i celulozową. Dzięki modyfikacji składu kompozytu można było porównać wytrzymałość na ścinanie oraz pracę zniszczenia otrzymanych struktur „sandwich", opisać czynniki wpływające na zachowanie się materiału pod wpływem naprężeń ścinających oraz mechanizmy zniszczenia. Do wykonania kompozytów wykorzystano dwie metody produkcji okładek - jednoetapową (przyklejenie jednej warstwy tkaniny węglowej osnową epoksydową bezpośrednio do rdzenia) i dwuetapową. Okładki wykonane pierwszą metodą nie spełniły oczekiwań wytrzymałościowych, dlatego zastosowano drugą metodę. Najpierw wykonano czterowarstwowe laminaty z tkaniny węglowej i żywicy epoksydowej za pomocą metody laminowania ręcznego. Laminaty te pozostawiono do usieciowania, a w kolejnym etapie utwardzone okładki przyklejono do rdzeni. Następnie próbki przycięto do wymaganych wymiarów. Do zbadania wytrzymałości na ścinanie wykorzystano test trójpunktowego zginania krótkiej belki. Jest to prosta metoda, która pozwala wytworzyć w próbkach dominujące naprężenia ścinające. Badania zostały przeprowadzone na maszynie wytrzymałościowej Zwick 1435. W pracy uwzględniono również gęstość próbek, dzięki czemu można było porównać ich wytrzymałość właściwą. Najwyższą wartość wytrzymałości na ścinanie właściwej, $(8.7 \pm 0.7) \cdot 10^3$ Nm/kg, uzyskał kompozyt z rdzeniem z balsy, podczas gdy dla kompozytu z aramidowym plastrem miodu wyniosła ona $(3.3 \pm 0.3) \cdot 10^3$ Nm/kg i dla pianek $(4.2 \pm 0.2) \cdot 10^3$ Nm/kg. Dodatkowo obliczono pracę zniszczenia poszczególnych materiałów. Dla kompozytu z plastrem miodu była ona najwyższa i wyniosła (9.3 ± 0.5) kJ/m^2, natomiast wartość tego parametru dla balsy była najniższa: (3.3 ± 0.3) kJ/m^2. Materiał z balsą odkształca się sprężyście do momentu pojawienia się pęknięcia w rdzeniu i oddzielenia się od siebie warstw. Kompozyt z plastrem miodu również jest obiecującym materiałem. Odkształcenie jego przebiega kilkuetapowo - najpierw sprężyście, a następnie poprzez zapadanie się komórek. Tylko te dwa materiały w połączeniu z czterowarstwową okładką węglową ulegają ścinaniu. Izotro-

powe pianki w badanym zestawieniu nie spełniły oczekiwań, zaobserwowany mechanizm zniszczenia to odkształcenie plastyczne i powstanie karbu, dlatego kompozyty te wymagają dalszych badań nad poprawą ich wytrzymałości na ścinanie. W pracy na podstawie zdjęć wykonanych na mikroskopie cyfrowym scharakteryzowano również mechanizmy pękania poszczególnych kompozytów. W zależności od ich geometrii obserwowano następujące mechanizmy zniszczenia: ścinanie rdzenia w kompozycie z plastrem miodu, pękanie rdzenia i delaminację warstw w kompozycie z balsą oraz pojawienie się karbu w strukturze z pianką. Przeprowadzone badania stanowią wstęp do dalszych eksperymentów nad mechanizmami zniszczenia kompozytów przekładkowych w różnych warunkach.

Słowa kluczowe: kompozyt, sandwich, ścinanie, zginanie, wytrzymałość, rdzeń, balsa, plaster miodu

INTRODUCTION

Recently significant progress in composite technology has been observed. The combination of different materials allows one to obtain structures with parameters which are resultant of the component properties, and thus enable the manufacture of new products for various tasks. A composite is a composition of at least two materials between which a clear boundary phase occurs. The volume fraction of the phases, their parameters, geometry and many other factors influence the final properties of composite materials [1, 2]. Among composite materials, sandwich structures are one of the most interesting. They consist of rigid covers (outer layers, skins) and a core between them, which are characterized by low density, high flexibility and high porosity. The diversity of available materials allows one to obtain unlimited combinations, and thanks to that newer and more interesting solutions are possible to achieve. The most common core materials include both natural materials, among which the most popular is balsa wood, and also synthetic foams, for example polymeric, or structures imitating a honeycomb construction. The latter can be made of many kinds of materials, but the most often used are metals, cellulose, aramid composite sheets and polymers [3]. It is possible to control the density, strength and anisotropy of the materials by modifying the porosity and microstructure of the pores and cells. Honeycomb structures are often used in load-bearing constructions, while foams are the lightest and the cheapest materials with high impact strength [4, 5]. The most commonly used skin materials are laminates made of fabrics (glass, carbon, aramid) and thermoplastic or thermoset resin. Metal sheets are also very popular due to their beneficial mechanical properties and low price, however, the disadvantage is that they increase the weight of the whole composite [3].

Understanding the failure mechanisms of sandwich materials under different conditions is required to properly select the face and core materials. The role of the core is to transfer shear stresses, while the covers carry tensile and compressive stresses [6]. For this reason, the core should have a high modulus of rigidity (shear) while the covers should possess a high Young's modulus. Adhesion at the interface is a very important feature as well [7, 8]. Sandwich panels can fail not only globally, but also locally, for example by face wrinkling or local buckling, depending on the core material. What is more, if the cover is too thin, it can buckle between the cells [9]. All of this information is a reason to search for the optimal combination of sandwich components for predetermined conditions.

The idea of using sandwich composites is to achieve the highest possible strength while maintaining low weight. The combination of a porous core glued to thin covers may result in achieving properties equal to a solid material. Depending on the geometry of the components, various effects are achieved. The ratio of core to cover thickness, the properties of the materials they are made of and the properties of the glues are very important. The mechanical properties of the core depend on its density, anisotropy and porosity. There are many different failure mechanisms of sandwich composites from global buckling of the construction, delamination, core shear, to local buckling and the presence of notches [10-12].

The area of application of sandwich composites is constantly expanding. Until now, they have been used in aircraft, e.g. elements in helicopters, airplanes, rockets (flaps, hulls, floors, doors). They also have protective and energy absorbing functions as elements of skis, snowboards and silencers [13, 14].

In the present work, sandwich composites consisting of covers - carbon fabric laminates - and different cores were manufactured and their specific shear strength was investigated (the specific parameters are their values divided by density) [15]. By modifying the composition and geometry of the components, it was possible to compare the parameters of the final structures. The factors which influence the material behavior under shear stresses were described and the failure mechanisms were characterized. Additionally, two different manufacturing methods were analyzed, followed by determination of their benefits and disadvantages.

The presented research is preliminary work that will enable further investigation of the failure mechanisms of sandwich composites. Three point bending of a short beam based on the PN-EN ISO 14130:2001 standard is the simplest way to test the shear strength of composites, but dedicated only to fiber-reinforced composites, not to sandwiches with a porous core [16]. Using this method allowed the authors to observe if the set conditions enable the samples to fail under shear stresses and to compare their behavior depending on geometry. There is a need to gain more sufficient data to design complex composite structures [17].

EXPERIMENTAL PART

Materials

To produce composite skins, carbon fabric with a weight of 160 g/m^2, epoxy resin Epidian 601 and hardener ET were used. Two types of covers were prepared: one-layer and four-layer ones. The core materials used in this work include:

- balsa (ProBalsa, DIAB) - light wood with good insulation properties, easily processable, chemically resistant, anisotropic. The arrangement of the fibers forming balsa was perpendicular to the skins.

  density ρ = 155 kg/m^3,

  shear strength σ = 3.0 MPa
- foams (DIAB) - different polymer foams with a high closed porosity, chemically resistant, isotropic. In the last stage of work, foam Divinycell H60 was investigated.

  density ρ = 60 kg/m^3,

  shear strength σ = 0.76 MPa [9]
- aramid honeycomb (Hexcel) - core with a honeycomb structure with hexagonal, anisotropic cells [13];
- cellulose honeycomb - anisotropic core with a spatial honeycomb structure.

Manufacturing

Samples were made implementing two different methods. In the one-step method, one layer of fabric was laminated directly onto the core and it was impregnated by epoxy resin mixed with hardener in a 5:1 ratio. The samples were left to crosslink at room temperature and higher pressure conditions. In the two-step method, covers - laminates of carbon fabric and epoxy resin - were manufactured in the first step. They were made by the hand lay-up method - resin-impregnated fabrics were prepared using epoxy mixed with hardener in a 5:1 ratio. The skins were left to crosslink in higher pressure conditions. Then the laminates were glued with the same resin mixture onto the core. As before, the samples were left in higher pressure conditions to remove excess air and resin. The prepared samples were cut to obtain beams with dimensions appropriate for the short beam bending test.

Testing

The composite samples were tested mechanically on a testing machine, Zwick 1435. Their specific shear strength and fracture energy were calculated. Three point bending of a short beam is based on loading a composite beam which is placed symmetrically on two supports. The load increases until the sample is deformed as expected or until it breaks. The most important requirement which has to be executed in the test is an appropriate span of the supports to the sample thickness ratio. According to the PN-EN ISO 14130:2001 standard intended for fiber composites, the ratio should be 5:1. Only by maintaining the aspect ratio will shear stresses dominate in the sample. Shear strength τ_M was calculated according to Formula (1), where: F - the maximum force, b - sample width, h - sample thickness [16].

$$\tau_M = \frac{3}{4} \cdot \frac{F}{bh} \tag{1}$$

The density was also defined for the samples and it was used to calculate their specific shear strength. After break, the samples were observed under a digital microscope (Keyence VHX-900F), high magnification (up to x200) allowing evaluation of the failure mechanisms and changes at the interface.

DISCUSSION

During the three point bending of a short beam, the behavior of the samples was observed and the failure mechanisms were investigated. In the case of composites with one-layer covers, the stress concentration on the top cover caused its plastic deformation. Cell wrinkling in the middle of the core and a notch in the spot where the load was applied were observed in the samples with aramid honeycomb. The samples with the cellulose core behaved similarly, but deformed to a greater extent. Debonding occurred in the outer layer of the samples at the interface. The foam composites deformed plastically and notches appeared in the middle of their covers. This is a simple example of buckling. It can be concluded from the above that a single layer of carbon fabric was insufficient.

Composites with four-layered covers were manufactured using the two-step method. The core materials included balsa, aramid honeycomb and foams. Only a few samples were destroyed as expected. Figure 1 shows deformations of the samples during three point bending.

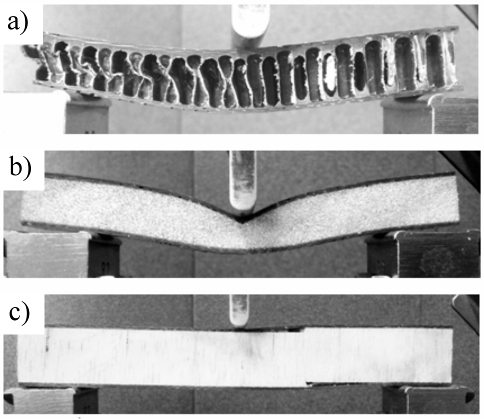

Fig. 1. Appearance of samples during 3-point bending test: a) composite with aramid honeycomb, b) composite with foam, c) composite with balsa

Rys. 1. Wygląd próbek podczas testu trójpunktowego zginania krótkiej belki: a) kompozyt z aramidowym plastrem miodu, b) kompozyt z pianką, c) kompozyt z balsą

The composites with the foam core and thicker covers deformed plastically. To test their shear strength, decreasing the support span or further modification of the geometrical parameters of the pores may be required, e.g. changing their shape from spherical to elliptical or their proper arrangement. In this way the material microstructure would change to anisotropic.

The samples with balsa and aramid honeycomb were destroyed by shearing. Their stress-deformation characteristics are shown in Figure 2.

Based on the load-deformation diagrams (Fig. 2) and microscopic observations (Fig. 3), it can be concluded that the failure mechanism of the composite with aramid honeycomb and four-layer skins is multi-staged. Firstly, it deforms elastically, then core shear occurs. The honeycomb structure cells were deformed, but the strength increased to a certain point. The explanation is that the cells collapsed initially after loading and then their deformation was stopped in the deeper parts of the core (Fig. 3).

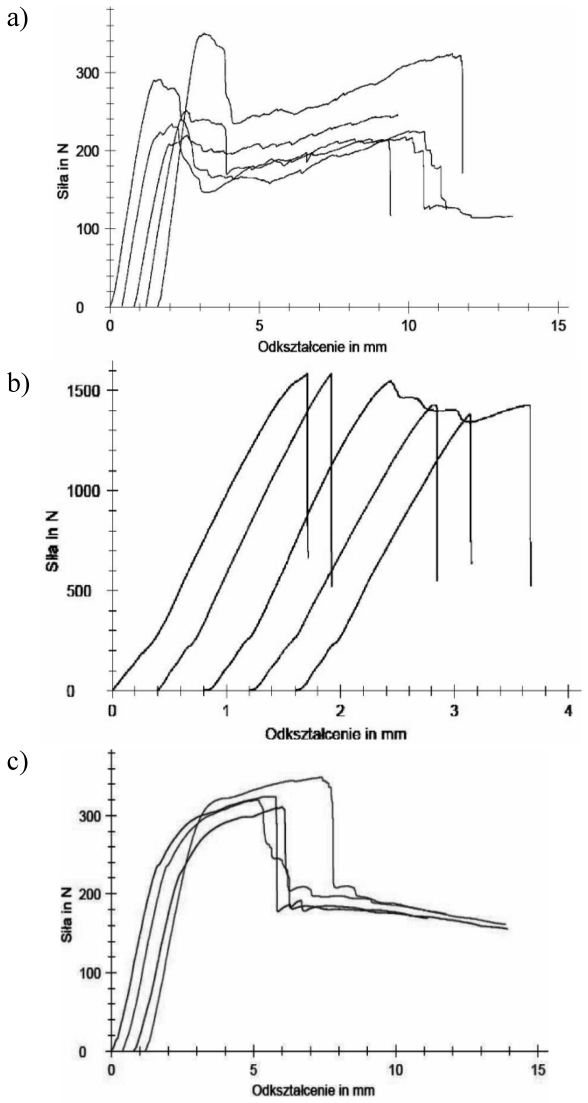

Fig. 2. Load-deformation diagrams for specimens with aramid honeycomb (a), balsa (b), foam (c)

Rys. 2. Wykresy siła-odkształcenie dla próbek z aramidowym plastrem miodu (a), balsą (b) i pianką (c)

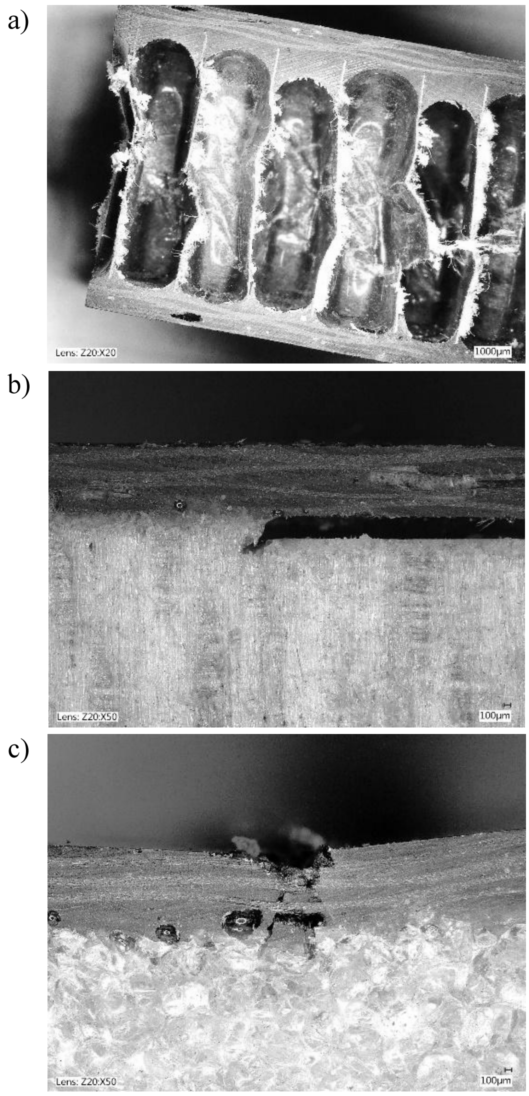

Fig. 3. Micrographs of fractured specimens: a) with aramid honeycomb (x20), with balsa (x50), with foam (x50)

Rys. 3. Zdjęcia mikroskopowe zniszczeń w próbkach: a) z aramidowym plastrem miodu (x20), b) z balsą (x50), c) z pianką (x50)

Elastic deformation was observed during bending of the balsa beams until vertical crack in the core and debonding at the interface near the crack appeared (Fig. 3). The direction of crack propagation indicated a significant amount of shear stresses in the samples. Longer beams fail under bending stresses, which is confirmed by the appearance of vertical cracks [8]. The materials with the foam core deformed plastically, a notch appeared in the spot where the load was applied. Foam cores differ from honeycombs and balsa in structure - they are isotropic, hence they are characterized by other properties and other failure mechanisms.

The highest shear strength values were shown by the composite with the balsa core. It behaved like a solid material in the tested direction, but it is highly anisotropic due to its microstructure - balsa consists mostly of long and thin cells [18]. In all the other samples, excluding the composite with aramid honeycomb, no conclusions regarding shear strength could be made. It is because the failure mechanisms of these samples underwent plastic deformation or buckling. Since the composites with foam cores did not break under shear stresses, the authors will perform further investigations related to their geometry.

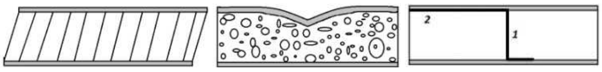

Fig. 4. Schematic failure behaviour of specimens after 3-point bending test

Rys. 4. Schematyczny wygląd próbek po zniszczeniu - od lewej: z aramidowym plastrem miodu, z balsą, z pianką

Summing up, the types of damage of the tested samples are:

- in the composite with aramid honeycomb - core shear resulting in displacement of covers parallel to each other, then collapsing of the cells
- in the composite with balsa - vertical cracking of the core and debonding at the interface
- in the composite with foam - plastic deformation, presence of a notch (Fig. 4).

In Table 1 the results of calculating the fracture energy and the average specific strength for the tested composites are presented. The sandwich with aramid honeycomb had the highest fracture energy, which is caused by the multi-stage failure mechanism.

TABLE 1. **Results of testing mechanical parameters of specimens**

TABELA 1. **Wyniki pomiarów parametrów mechanicznych dla badanych kompozytów**

Core material	**Aramid honeycomb**	**Balsa**	**Foam**
Fracture energy [kJ/m^2]	9.3 ±0.5	3.3 ±0.3	7.6 ±1.4
Average specific shear strength [10^3 Nm/kg]	3.3 ±0.3	8.7 ±0.7	4.2 ±0.2

CONCLUSION

The results showed that the failure of sandwich composites under shear stresses depends on their geometry and anisotropy of the core material. Composites with aramid honeycomb and balsa have promising strength parameters relative to their density. The sandwich with aramid honeycomb turned out to be the material with the highest fracture energy, which is caused by its multi-stage failure mechanism. The balsa sandwich had the highest specific shear strength among the tested samples. The composites with foams in the tested combination need further investigation to increase the shear modulus. Four-layer covers, manufactured in the two-step method are more promising than the one-layer skins. The obtained results are preliminary but they enable further investigation of sandwich failure under different conditions, in relation to their microstructure and components.

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