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COMPOSITES THEORY AND PRACTICE

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COMPARATIVE ASSESSMENT OF MECHANICAL PROPERTIES OF GLASS AND BASALT FIBERS REINFORCED POLYESTER RESIN WITH ST3S STEEL

The aim of the study was to develop a laminate composite that can be an analog for St3S steel in the case of corrosion problems and excessive product weight. E-glass fibers in the form of mats and fabrics with different reinforcement direction, unsaturated polyester resins, and basalt woven fabrics with a grammature of 180 g/m^2 were used in the study. Polyester laminate composites of 300x200 mm were manufactured using the vacuum assisted resin transfer molding method. The mechanical properties of the laminate composites in the form of plates were compared with the mechanical properties of the St3S steel serving as a reference material. Selected glass fiber-reinforced polyester composites with the best mechanical properties were additionally modified with basalt fabric. The flexural strength, elasticity modulus and work up to fracture were determined in the three-point bending mode. The values of the mechanical parameters of the composite samples were compared with the mechanical properties of St3S steel. The highest elasticity modulus of the laminate samples was found for the composite reinforced with a unidirectional glass fabric, while the maximum flexural strength was attained by the composite samples reinforced with three and four directional fibrous reinforcement. Their differences amount to several percent. The composite samples representing the best strength properties were further modified using a fabric made from basalt fibers. The use of hybrid fiber reinforcements (glass fiber, basalt fiber) allows for an over 20% increase in the flexural strength of the composite samples. Comparable strength characteristics to the steel samples were achieved. The flexural strength of the hybrid composite samples was 415 MPa, and 429 MPa for the St3S sample. The hybrid laminate composite with basalt woven fabric has a distinctly higher work up to fracture value in comparison with the unmodified laminate composite related to the same cross section unit.

Keywords: **glass fiber, basalt fiber, polyester resin, St3S steel, mechanical properties, flexural strength**

ANALIZA PORÓWNAWCZA WŁAŚCIWOŚCI MECHANICZNYCH KOMPOZYTÓW Z ŻYWICY POLIESTROWEJ WZMOCNIONEJ WŁÓKNEM SZKLANYM I BAZALTOWYM ZE STALĄ St3S

Celem badań było opracowanie laminatu, który może stanowić analog dla stali St3S w przypadku pojawiających się problemów z korozją i zbyt dużym ciężarem użytkowym. W pracy wykorzystano włókna szklane w postaci mat i tkanin o różnym kierunku wzmocnienia, żywice poliestrowe nienasycone oraz płótno bazaltowe o gramaturze 180 g/m^2. Metodą próżniowego przesycenia wytworzono laminatowe kompozyty poliestrowo-szklane o wymiarach 300x200 mm. Właściwości mechaniczne próbek kompozytowych wykonanych z laminatów w formie płytek porównywane były z właściwościami próbek wykonanych ze stali St3S, jako próbek referencyjnych. Laminat poliestrowo-szklany o najlepszych parametrach mechanicznych zmodyfikowano płótnem z włókna bazaltowego. Badanymi parametrami były wytrzymałość na zginanie, moduł sprężystości oraz praca zniszczenia. Wyznaczone wartości parametrów mechanicznych laminatów porównano z właściwościami mechanicznymi dla stali St3S. Dla kompozytów laminatowych ze zbrojeniem z włókna szklanego najwyższy moduł sprężystości posiada próbka wykonana z tkaniny szklanej jednokierunkowej, natomiast najwyższą wytrzymałość na zginanie posiadają laminaty zbrojone włóknem szklanym w postaci tkaniny o trójkierunkowym oraz czterokierunkowym wzmocnieniu. Ich różnice wynoszą kilka procent. Próbki kompozytowe o najkorzystniejszych parametrach wytrzymałościowych poddano modyfikacji z zastosowaniem tkaniny z włókna bazaltowego. Zastosowanie hybrydowego włóknistego wzmocnienia (włókna szklane, włókno bazaltowe) pozwoliło na ponad 20% zwiększenie wytrzymałości na zginanie próbek kompozytowych. Uzyskano porównywalne parametry wytrzymałościowe laminatowego kompozytu hybrydowego do stali. Wytrzymałość na zginanie otrzymanych próbek wynosiła 415 MPa, a dla stali St3S 429 MPa.

Słowa kluczowe: **włókna szklane, włókna bazaltowe, żywica poliestrowa, stal ST3S, właściwości mechaniczne**

INTRODUCTION

The development of modern materials used in various industries indicates that one of the promising constructional materials which is gaining increasingly more interest are fiber-based polymer composites (FRP-Fiber-reinforced Polymer), in which a fibrous reinforcement is used in the form of roving, a mat or fabric. Such materials are today considered as a replacement for steel and concrete. It is due to the fact, that such composites display high mechanical properties and corrosion resistance, and in relation to the density of the material (the so-called specific strength) they are much lighter than steel. FRP can be more resistant and stiffer (e.g., in the case of carbon fiber reinforcement) than conventional materials used for construction, and when the weight of the structure is a relevant feature, composites can become a very attractive solution [1]. Moreover, depending on the type of polymer matrix, composites can withstand a longer period of time in an aggressive environment [2].

Polymer matrixbased composite technologies are constantly being improved and modified, thus the production efficiency and quality of the final products are increasing. Moreover, processing and fabrication automation is slowly replacing traditional manual methods of manufacturing laminates, making it possible to obtain composites with the desired high mechanical properties. Modern technologies that are commonly used in the industry include e.g. hot pressing after prior impregnation with a liquid; injection, pultrusion, RTM and vacuum infusion [3, 4]. For the process and final laminate to be satisfactory (having desired parameters), one must pay attention to the appropriate type of resin and its viscosity [5, 6], gelation time, heat resistance, mechanical properties, preparation and wettability of the fibers, and everything with regard to price, aiming to implement the product into industry.

The aim of this study was to develop a laminate composite material which may replace a St3S-based steel element in a specific structural application. The steel element in the form of a flat bar with a cross section area in the range of 15x7 mm to 16x9 mm, and support spacing of 250 mm (275 mm overall length), operates under bending stress at ambient temperature close to room temperature. As the composite components, glass fibers in the form of mats and fabrics, and polyester resins were used. Additionally, the glass fiber-reinforced polyester laminate with the best mechanical properties was modified with a woven basalt fiber in order to modify the composite mechanical strength [7, 8]. The mechanical parameters of the samples in the form of bars were determined in three-point bending tests. The studied parameters were: flexural strength and modulus, the maximum bending force and work-to-fracture of the composite samples. The obtained values of the laminate mechanical properties were compared with the mechanical characteristic of the St3S steel.

Commercially available glass fabrics (one, two, three and four-directionally reinforced) mats, and basalt woven fabric were used in the study.

MATERIALS AND TESTS

The following components were used to obtain the laminates:

- medium reactive unsaturated polyester resin (basic characteristics are presented in Table 1),
- E-type glass fibers in the form of fabric (basic characteristics are presented in Table 2),
- woven basalt fibers, grammature 180 g/m^2.

TABLE 1. **Properties of selected polyester resin**
TABELA 1. **Właściwości wybranej żywicy poliestrowej**

Type	Viscosity [mPas]	Geling time [min]	Flexural strength [MPa]	HDT [°C]	Density [g/cm^3]
Orthophtalic	200÷250	14÷24	130	90	1.12

TABLE 2. **Characteristics of selected glass reinforcement**
TABELA 2. **Charakterystyka wybranego zbrojenia z włókna szklanego**

Type	Fber direction	Grammature [g/m^2]	Stitching	Surface preparation	Fiber density [g/cm^3]
Uni-directional fabric	[0°]	1210	polyester	silane	2.6÷2.7
Bi-directional fabric + glass mat	[0°, 90°]	624 300			
Three-directional fabric	[0°, –45°,45°]	831			
Four-directional fabric	[0°, 45°, 90°, –45°]	1198			

Flat, rectangular polyester-glass laminate composites in the form of plates were manufactured using the vacuum-assisted resin transfer molding method. The procedure for manufacturing the composite samples was as follows:

- cutting out layers of glass fabric and placing them one over another on a flat surface parallel to each layer,
- preparation of a mixture of an appropriate amount of polyester resin, together with an accelerator and a hardener,
- vacuum-assisted resin transfer of stacked layers of glass fabric with a mixture prepared at the time corresponding to resin gelation (14÷24 min) at room temperature,
- curing of the laminates at room temperature for about 24÷48 hours.

In total, in the first stage of the procedure six 300x200 mm sheets of polyester-glass laminate were prepared. Depending on the weight of the fabric, the thickness of the laminate samples ranged from 7 to 9 mm. From the above mentioned sheets, samples of a length of 275 mm and cross-section of 15-16x7-9 mm were cut out. A single St3S steel sample in the form of a plate served as the reference material. The samples together with their description are shown in Table 3.

TABLE 3. **Characteristics of samples used in the work**
TABELA 3. **Charakterystyka próbek stosowanych w pracy**

Sample designa-tion	Type of glass fabric	Sample cross-section [mm]	Sample cutting direction
1	1 directional [0°] 1210 g/m^2	16x7	along fabric
2	1 directional [0°] 1210 g/m^2	16x7	across fabric
3	2 directional [0°, 90°] 924 g/m^2	16x9	along fabric
4	3 directional [0°, –45°, 45°] 831 g / m^2	16x7	along fabric
5	3 directional [0°, 45°, 45°] 831 g/m^2	15x7	across fabric
6	4 directional [0°, 45°, 90°, –45°] 1198 g/m^2	16x7	along fabric
7	St3S	16x8	-

The static mechanical properties of the composite and steel samples (flexural strength and modulus) were determined in the three-point bending mode using a universal testing machine Zwick (model 1435) PC controlled by TestXpert (v. 8.1) software, with the strain rate of 10 [mm/min]. The tests were performed using a span-to-thickness ratio of approximately 15 and gauge length of 250 mm. For each type of composite sample, 5 individual measurements were made. The results are presented as mean ±SD.

The glass fabric layers in the composite samples were perpendicularly loaded with flexural force (Fig. 1).

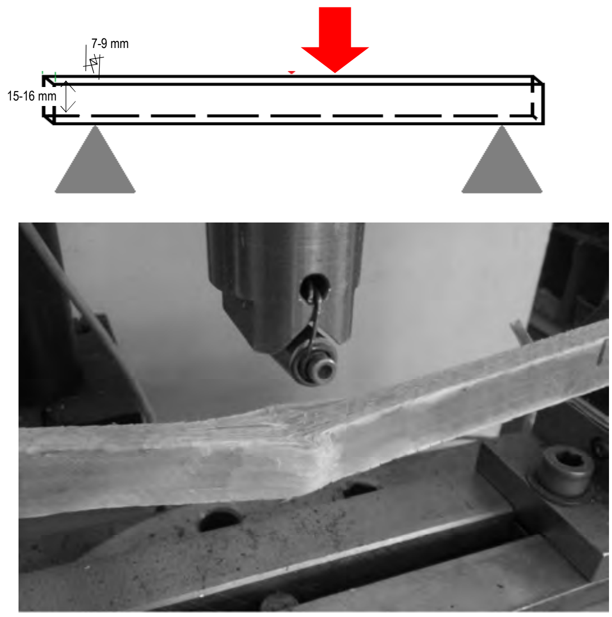

Fig. 1. Scheme of sample loading in three-point bending mode
Rys. 1. Schemat obciążania próbki w próbie trójpunktowego zginania

RESULTS AND DISCUSSION

Based on the St3S steel characteristics of force-deflection (Fig. 2) in a static three-point bending test as reference, analysis of the relevant mechanical parameters of the material was performed. In the further part of the study, the results of the crucial mechanical properties of the composite materials were compared with those of the St3S steel accordingly.

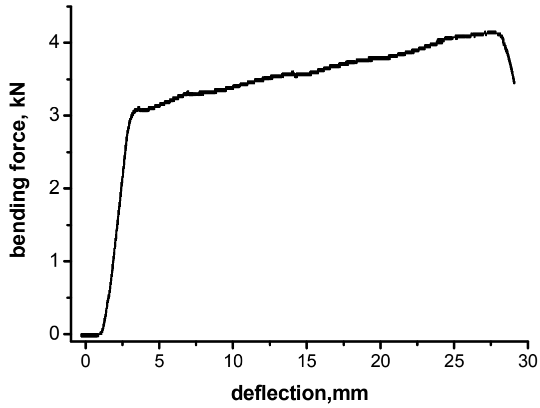

Fig. 2. Characteristics of St3S steel sample force-deflection
Rys. 2. Charakterystyka siła-ugięcie próbki stalowej St3SC

On the basis of the mechanical bending test, the following St3S steel parameters were determined:

- Flexural modulus, E = 165 GPa
- Yield point corresponding to the force value of 2.8 kN, Re = 429 MPa
- Maximum force F_{max} = 4.2 kN

Taking into account these parameters with respect to the material characteristics, the yield stress was considered to be a crucial value as it indicates the point at which deformation of the material is irreversible. Therefore, the St3S steel yield stress amounting to 429 MPa (for flexural force of 2.8 kN) was chosen as a reference point for the strength of the composite materials since this is the point at which the materials undergo irreversible deformation and lose their functionality.

The study performed in the flexural test of the composite materials allows one to determine the influence of the glass fiber reinforcements in a composite matrix on the mechanical parameters of the resulting polyester-glass laminates (Fig. 3).

Based on the results, it can be seen that the laminate composite sample made of unidirectional fabric (sample No. 1) has the highest flexural modulus. In contrast, the highest flexural strength was displayed by the composites reinforced with glass fibers in the form of three- and four-directional fabrics (sample No. 4 and sample No. 6 respectively). The differences in the strength between the samples amount to several percent. Due to the fact that the flexural strength is a more important parameter for the analysis in the study than the flexural modulus, as well as taking into account the price of glass fabric, sample No. 4 was selected for further modification with the use of basalt fibers to form a hybrid reinforcement of the polyester matrix. At the stage of laminate manufacture, fabrics made from basalt fiber with a weight content in the laminate of approximately 8÷10% were added to the stacked glass fabric, simultaneously the same amount of glass fabric (about 8÷10%) was removed so that the total weight of the laminate before and after modification would be the same and equal to 7÷9 mm in thickness.

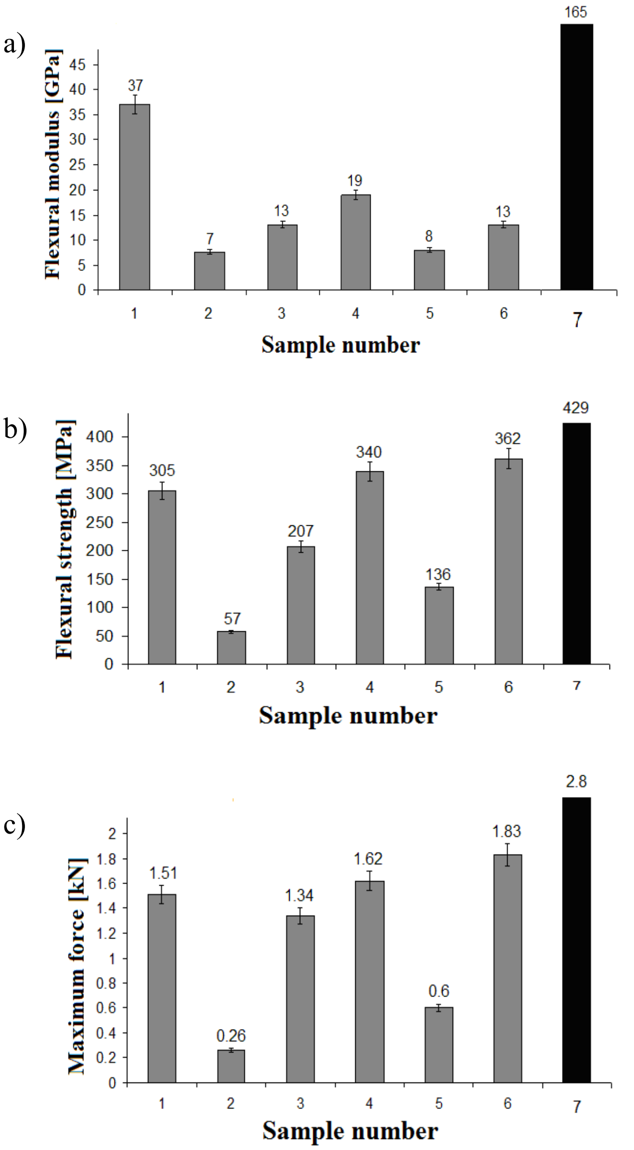

Fig. 3. Mechanical properties of polyester-glass laminates and St3S steel: a) flexural modulus, b) flexural strength, c) force

Rys. 3. Właściwości mechaniczne kompozytu poliester-włókno szklane i stali St3S: a) moduł przy zginaniu, b) wytrzymałość przy zginaniu, c) maksimum siły

Such a modified structure of sample No. 4 was subjected to vacuum polyester resin transfer molding as the remaining samples. A sample of a 15x9 mm cross-section and length of 275 mm was cut out of the laminate. The results of the mechanical tests in the three-point bending mode of sample No. 4 before and after modification (hybrid reinforcement) as well as the reference sample (No. 7) are presented in Figure 4. In addition, Figure 5 shows the characteristics of the force-displacement of sample No. 4.

Comparing the mechanical strength (tensile strength) of the basalt fiber and E-glass which amount to 3000÷3500 MPa and 1500 MPa respectively, a conclusion can be drawn about the purpose of using basalt fiber and its benefits. Furthermore, the additional modifications of the laminate composite with basalt woven fabric carried out in the study, shown in Figure 4, indicate an improvement of the mechanical properties of the hybrid laminate composite (sample No. 4) by more than 20%. The flexural modulus of the modified samples was the only parameter that hardly changed since it fluctuated around a similar value as in the case of the unmodified sample. Further improvement of the flexural modulus of the laminate composite can be achieved by changing the type of fibrous reinforcement i.e., by the use of a uni-directional fabric instead of a multi-directional one.

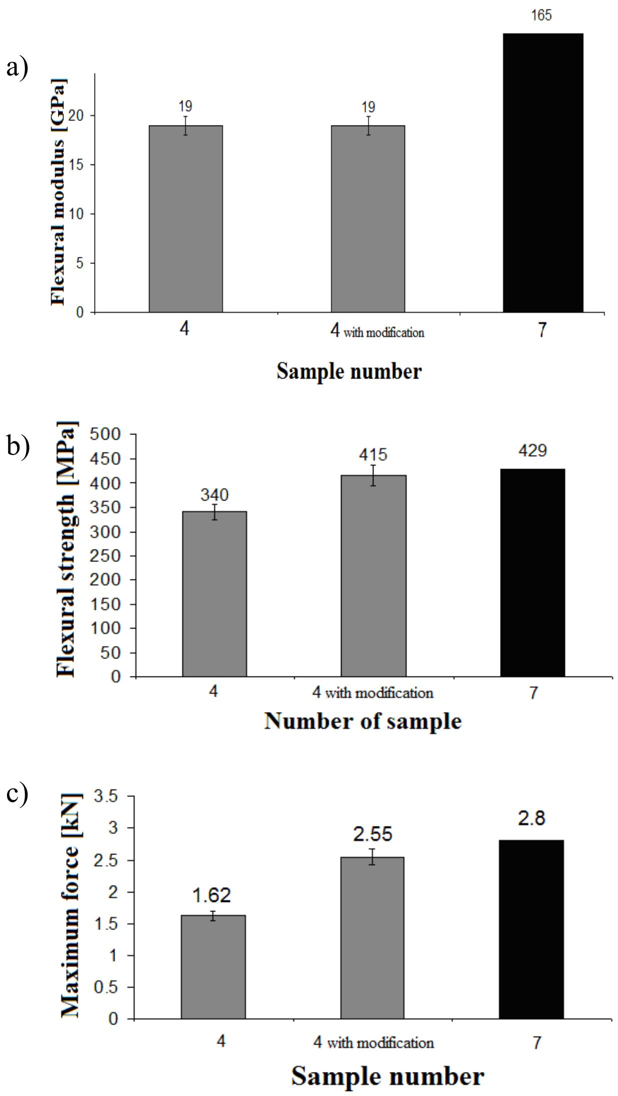

Fig. 4. Comparison of polyester-glass laminate composites (with and without modification) and St3S steel mechanical properties: a) flexural modulus, b) flexural strength, c) maximum of force

Rys. 4. Porównanie właściwości mechanicznych kompozytów poliester-włókno szklane (modyfikowane i niemodyfikowane) i stali St3S: a) moduł przy zginaniu, b) wytrzymałość przy zginaniu, c) maksimum siły

Figure 5 illustrates a sample graph of flexural force as a function of deflection for both the tested laminate composites. The hybrid laminate composite containing basalt woven fabric has a clearly higher work-fracture (related to the cross section area unit), which amounts to 200 J·m^{-2}, in comparison with the unmodified laminate samples 80 J·m^{-2}.

a)
b)

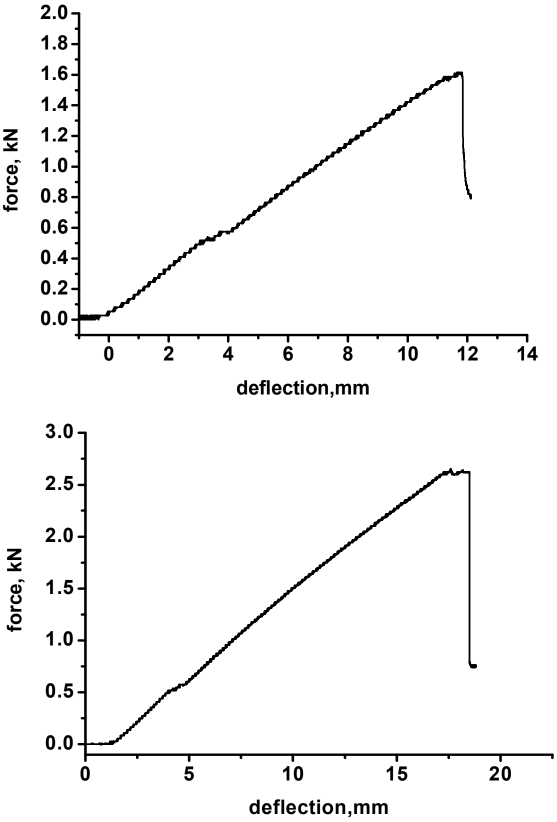

Fig. 5. Characteristics of laminate composite force-deflection: a) glass fiber-reinforced polyester without modification, b) hybrid glass-basalt fiber reinforced polyester

Rys. 5. Charakterystyki siła-ugięcie kompozytów laminatowych: a) poliester wzmocniony włóknem szklanym bez modyfikacji, b) poliester wzmocniony hybrydowym wzmocnieniem szklano--bazaltowym

CONCLUSIONS

The study aimed at comparing the possibility of using polymer laminates as materials which may compete with steel with respect to its mechanical properties. The following conclusions can be drawn:

- the best results of flexural strength and work up to fracture are obtained for the laminate composites reinforced with the three-directional and four--directional glass fabrics modification of the glass fiber laminate structure using basalt fibers allows one to improve the flexural strength of the laminate in comparison to the glass fiber laminate composite
- the laminate composites made on the basis of hybrid glass-basalt fabrics have similar values of flexural strength (415 MPa) compared to the value determined for the yield stress of St3S steel (429 MPa).

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