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COMPOSITES THEORY AND PRACTICE

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FLEXURAL STRENGTH OF HYBRID EPOXY COMPOSITES WITH CARBON FIBER

The paper presents a flexural strength comparison of hybrid epoxy composites with different reinforcing phases and amounts of used fillers. As the reinforcement, carbon fiber was used in mat and fabric forms. As the matrix, an epoxy resin and a mixture of the epoxy resin with a filler in the form of coal fly ash was used. The samples were produced according to the PN-EN ISO 178 standard and bending stress values of the studied composites were determined. The work is a part of studies related to selecting material for the hull of an innovative yacht with a hybrid drive, fueled by renewable energy sources, in the scope of the "RepSail" project in the "Era Net Future Travelling" contest realized at the Maritime University of Szczecin.

Keywords: **epoxy-carbon composites, fly ash, hybrid, flexural strength, carbon fiber**

WYTRZYMAŁOŚĆ NA ZGINANIE EPOKSYDOWYCH KOMPOZYTÓW HYBRYDOWYCH Z WŁÓKNEM WĘGLOWYM

Porównano wytrzymałość na zginanie hybrydowych kompozytów epoksydowych w postaci laminatów różniących się rodzajem fazy zbrojącej oraz ilością użytego napełniacza. Zbrojenie stanowiło włókno węglowe w postaci: maty i tkaniny, osnową była żywica epoksydowa oraz mieszanina żywicy epoksydowej z napełniaczem w postaci popiołu lotnego. Próbki wykonano zgodnie z PN-EN ISO 178, określono wielkości naprężeń zginających dla badanych kompozytów. Praca stanowi części badań, związanych z wyborem materiału do zastosowania na kadłub innowacyjnego jachtu z napędem hybrydowym, zasilanego z odnawialnych źródeł energii, w ramach projektu "RepSail" w "Era Net Future Travelling" konkursu realizowanego w Akademii Morskiej w Szczecinie.

Słowa kluczowe: **kompozyty epoksydowe, hybrydowe, wytrzymałość na zginanie, włókno węglowe, popiół lotny**

INTRODUCTION

The dominating role of coal in the production of electrical energy and heat in Poland creates the necessity for better economic use of fly ash. The storage of coal fly-ash is difficult regarding the location of storage areas and is dangerous to the natural environment [1]. The aluminosilicate chemical composition of fly-ash and its amorphous phase structure makes it an attractive material in the cement industry, road-making industry, civil engineering and agriculture, as well as in advanced ceramic manufacturing technologies. That is why attempts at applying this material in other industries, e.g. transport, are still being made. The search for new materials with better properties than traditional materials used in manufacturing technology has led to the creation of composite materials. In technical applications, polymer matrix composites dominate nowadays [2-5]. By mass fraction, they comprise 90% of the applications of these materials. By appropriate selection of the composite components, which are the matrix and the reinforcing phase, a material with the desired properties can be obtained. Presently, the most widespread polymer composites have a matrix with duroplastics. The most frequently used duroplastics are unsaturated polyester resins, vinylester resins and epoxy resins [6-9]. They are used as a binder when manufacturing layered composites, also known as laminates. Reinforcement in this kind of composites is usually present in the form of glass, aramid (Kevlar), carbon (or graphite) or natural (cellulose, flax) fibers [2-4]. By applying a proper form of reinforcing phase, for example roving, mat or fabric, it is possible to obtain a beneficial stress state during the operation of these materials. The obtained materials are also strong and lightweight. Modifying the composite matrix using a mineral or recyclate filler in the form of dust or particles or short fibers is also very important. It creates the possibilities to obtain new composites with even better qualities, for example with increased flexural strength or elastic strain. That is why studies on such composites were undertaken, with focus on applying coal fly ash as a filler in an epoxy resin reinforced with carbon fibers. The studies were aimed at determining the bending stresses for the examined composites along with determining the effect of coal fly ash on the properties of the tested composites, whose storage poses a threat to the natural environment.

RESEARCH MATERIAL

To manufacture the layered composites used for this paper, the following materials were used as the reinforcement:

- **carbon mat** - CF270 - carbon 300 g/m^2 from the Suretexcomp company (with cut roving, Fig. 1)
- **carbon fabric** - CF072 - carbon 300 g/m^2 of plain type: 1/1 weave, from the Suretexcomp company (with continuous roving, made as a result of interleaving skeins of fiber as in plain weave, Fig. 2)
- and as the matrix:
- **epoxy resin** - Epidian 5 with the commercially available curing agent (Z1)
- **mineral filler** - EJ III/ Min fly ash (of particle size up to 15 μm), F-class. In F-class ashes the portion of the three most important oxides: silicon (SiO_2), iron (Fe_2O_3) and aluminum (Al_2O_3) is above 70% and the portion of CaO is less than 5%. These ashes are known as low-calciferous ashes [1].

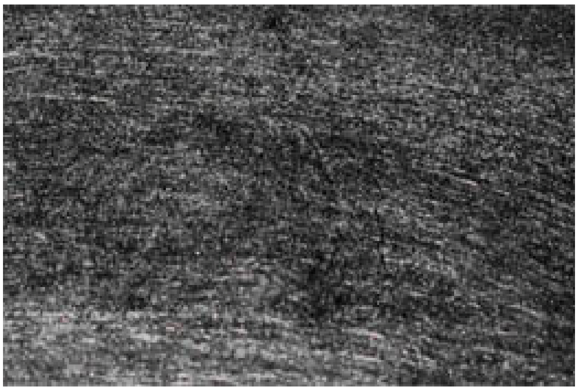

Fig. 1. CF270 - carbon 300 g/m^2 from Suretexcomp company - cut roving, no magnification

Rys. 1. CF270 - carbon 300 g/m^2 firmy Suretexcomp - wykonana z rovingu ciętego

The composition of the composites subjected to the studies are shown in Table 1.

For the studies, laminates with arrangements of 3, 6, 9, 12, 15 and 18 layers were manufactured by manual saturation (using a brush) of the material fragments with Epidian 5 epoxy resin with Z1 curing agent, using 1:10 mass proportions. For the M3-M8 materials (according to Table 1), coal fly ash EJ III/Min was added to the epoxy resin as a filler, in amounts of 10, 20 or 30%. Then, a number of samples was cut from the prepared laminates, in accordance with PN-EN ISO 178. For each type of material, five identical samples were prepared in order to verify the results.

Fig. 2. CF072 - carbon 300 g/m^2 of plain type: 1/1 weave, from Suretexcomp company - continuous roving, plain weave, no magnification

Rys. 2. CF072 - carbon 300 g/m^2 typu plain: splot 1/1 firmy Suretexcomp - wykonana z rovingu ciągłego, powstający w wyniku przeplatania ze sobą pasm włókna według splotu płóciennego

TABLE 1. **Composition of hybrid composites**
TABELA 1. **Skład kompozytów hybrydowych**

Material ID	**Matrix**	**Reinforcement**
M1	Epoxy resin	carbon fabric
M2	Epoxy resin	carbon mat
M3	Epoxy resin + 10% filler – fly ash	carbon fabric
M4	Epoxy resin + 10% filler – fly ash	carbon mat
M5	Epoxy resin + 20% filler – fly ash	carbon fabric
M6	Epoxy resin + 20% filler – fly ash	carbon mat
M7	Epoxy resin + 30% filler – fly ash	carbon fabric
M8	Epoxy resin + 30% filler – fly ash	carbon mat

METHODOLOGY OF STUDIES

The samples made from the composite materials of the compositions presented in Table 1 were subjected to tests to determine their flexural strength. Three point bending was assumed as the load scheme, in accordance with the standard (Fig. 3). The test was conducted until the sample was destroyed (fractured). On the basis of the tests, the maximal failure loads and bending stresses were determined.

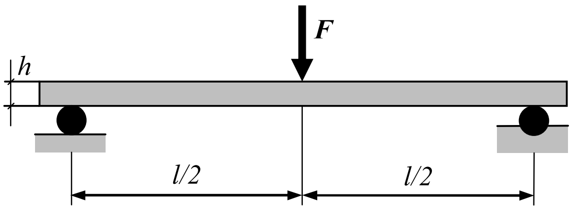

Fig. 3. Scheme of sample loading method and location of force F in three point bending test [10]

Rys. 3. Schemat sposobu obciążenia próbki i miejsce przyłożenia siły F w próbie zginania tzw. „trzypunktowego” [10]

The bending theory developed for homogeneous and isotropic materials can be used to evaluate inhomogeneous and strongly anisotropic materials. It is also widely accepted for composite studies [5-8]. Using the experimental data described above, the flexural strength of the studied hybrid composites was determined, as the greatest value of σ_f stress, using the following equation [6]:

$$\sigma_f = \frac{3Fl}{2bh^2} \quad (1)$$

where: σ_f - bending stress [MPa], F - applied force [N], l - support distance [mm], b - sample width [mm], h - sample thickness [mm].

STUDY RESULTS

In the standard, samples of the length/height ratio l/h = 16 are used. The average values of height (h) corresponding to the number of layers of the reinforcing material in the laminates are shown in Table 2. This condition ensures that failure through normal stresses related to the bending moment will occur before layer separation as a result of the shearing stress [6-11].

TABLE 2. **Average thickness of samples, corresponding to number of reinforcing layers in laminate**
TABELA 2. **Uśredniona grubość próbek odpowiadająca ilości warstw zbrojenia w laminacie**

Reinforcement form	Number of reinforcement layers in laminate (pcs.)	Average sample height *h* [mm]
Carbon mat	3	2.4
	6	5.1
	9	7.4
	12	9.8
	15	12.2
	18	14.5
Carbon fabric	3	1.5
	6	3.3
	9	4.7
	12	6.2
	15	7.6
	18	9.1

In Figure 4, the values of applied force F occurring at sample failure are presented, depending on the number of layers in the examined laminates. On the basis of this force and Equation (1), the bending stresses were determined, as shown in Figures 5 and 6.

Figure 5 presents the values of bending stresses σ_f for the laminates with reinforcement in form of carbon mat, depending on the number of reinforcement layers and the amount of filler. Analysis of Figure 5 allows the authors to conclude that the greatest flexural strength is exhibited by the laminate with the matrix modified by adding 10% mineral filler-fly ash. In the case of this material (M4), an approximate 16% increase in strength can be observed in comparison to a composite without the addition of fly ash. Increasing the modifying filler to 20% leads to a 2% strength drop in comparison with the non-modified composite. A further increase in the fly ash portion in the composite causes a rapid decrease in the flexural strength, even up to 30% (for the M8 composite), in comparison with the non-modified composite. It is most probably caused by a certain part of hard inclusions in the fly ash filler (SiO_2 - hardness of 7 on the Mohs scale, Fe_2O_3 - hardness of 6 on the Mohs scale and Al_2O_3 - hardness of 9 on the Mohs scale), which cause a decrease in composite elasticity. Moreover, the decrease in the strength of the M8 material is also caused by the manufacturing process itself as the 30% portion of filler causes a significant increase in matrix density, making the saturation process difficult to perform. As results from the diagram, the bending stresses also grow with an increase in the number of reinforcement layers in the laminate, but only up to 15 layers - then it starts dropping.

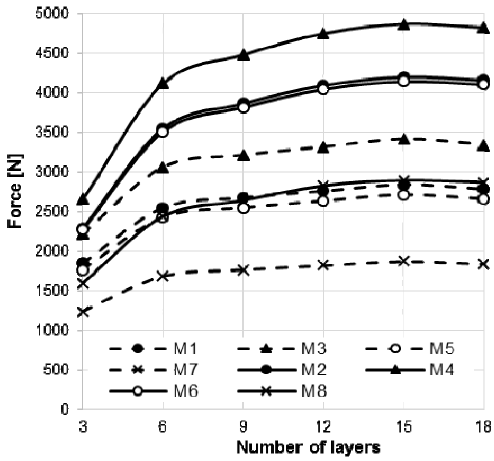

Fig. 4. Dependence of bending F force on number of layers for examined laminates (material *IDs* according to Table 1)

Rys. 4. Zależność siły zginającej F od ilości warstw dla badanych laminatów (ID materiałów zgodnie z tabelą 1)

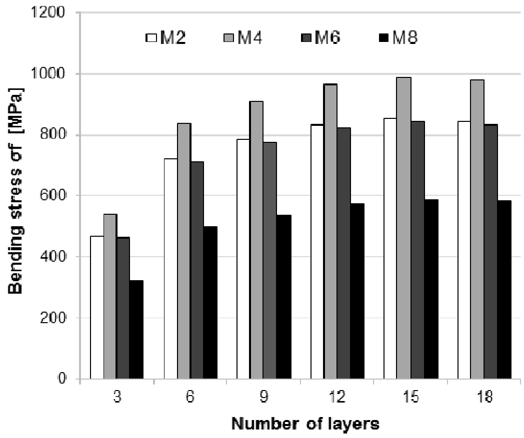

Fig. 5. Comparison of bending stresses for laminates with reinforcement in form of mats (material IDs according to Table 1)

Rys. 5. Porównanie naprężeń zginających dla laminatów ze zbrojeniem w postaci maty (ID materiałów zgodnie z tabelą 1)

Figure 6 presents the value of bending stresses σ_f for the laminates with reinforcement in the form of carbon fabric depending on the number of reinforcement layers and used filler. Analogically as in the case of the carbon mat, it can be stated that the greatest strength is presented by the laminate with the matrix modified by adding 10% mineral fly ash filler. However, in the case of this composite (M3), a 20% increase in the strength can be observed in comparison with the non-modified composite. For the material reinforced with the fabric it is 4% more than for the same material reinforced with carbon mat.

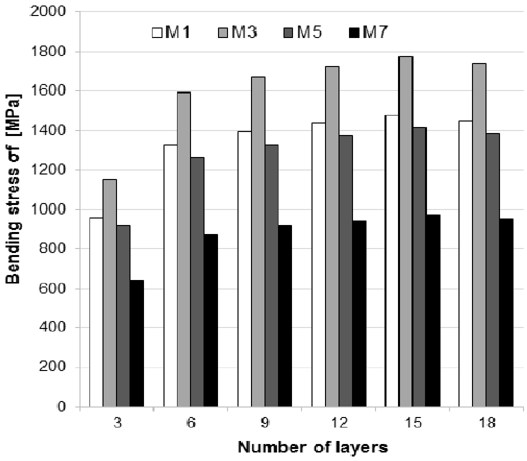

Fig. 6. Comparison of bending stresses for laminates with reinforcement in form of fabric (material IDs according to Table 1)

Rys. 6. Porównanie naprężeń zginających dla laminatów ze zbrojeniem w postaci tkaniny (ID materiałów zgodnie z tabelą 1)

Increasing the portion of filler to 20% causes an approx. 5% drop in the bending strength, in comparison with a non-modified composite. A further increase in the fly ash portion in the composite causes again a very rapid decrease in the flexural strength, even up to 33% (for composite M7) in comparison with the non-modified composite.

CONCLUSION

The conducted studies allow the authors to conclude that the greatest flexural strength is exhibited by the composites in which the reinforcement was in the form of a fabric. It is related to the more beneficial stress state in the material due to the ordered fiber arrangement than in the case of the carbon mat. It was also found that the number of layers in the laminate influences the flexural strength, the highest value of bending stress σ_f was achieved in the case of the 15-layer laminates (in both cases of the examined reinforcement types). From the performed tests, it can be concluded that the flexural strength of the hybrid composites is greater than in comparison with the non-modified composites. It was also found that adding 10% mineral filler in the form of coal fly ash increases the flexural strength by 15÷20%. However, increasing the filler amount to above 20% causes a drop in the flexural bending in comparison with non-modified composites. The application of fly ash may significantly contribute to environmental protection through their use, for example, as a filler in laminates used for manufacturing of the hull of a boat. Nevertheless, this statement requires further material studies and will be presented in further publications by the authors. The determined values will be the basis for further studies of the presented hybrid composites.

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