YOUNG'S MODULUS OF A CARBON-REINFORCED COMPOSITE AT AN ELEVATED TEMPERATURE

Moduł Younga kompozytu wzmacnianego włóknami węglowymi w podwyższonej temperaturze

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Abstract: Aviation structures are operated under varying environmental conditions, affecting the properties of polymer composites, which are often used to manufacture components for airplanes and helicopters. One of such factors is an operating temperature that changes during a flight in a very wide range. This paper presents the influence of an operating temperature upon composite properties determined during a tensile test. In addition, composites which are intended for the research were post cured during their preparation at different temperatures (in accordance with the recommendations of the resin manufacturer which constitutes a matrix base). The composites consisted of 7 layers of carbon fabric, and matrix of L285 epoxy resin, with a hardener. As a result of the testing it was noted that a change in the operating temperature exerts a significant effect on composite strength properties regardless of the post curing temperature. The materials post cured at higher temperatures were characterized by a greater value of the modulus of elasticity and tensile strength.

Keywords: tensile test, CFRP, *Young's* modulus, static strength

Streszczenie: Konstrukcje lotnicze są eksploatowane w zmiennych warunkach środowiskowych wpływających na właściwości kompozytów polimerowych, z jakich często wykonywane są elementy samolotów i śmigłowców. Jednym z takich czynników jest temperatura użytkowania, zmieniająca się podczas lotu w bardzo szerokim zakresie. W artykule zaprezentowano wpływ temperatury eksploatacji na właściwości kompozytu wyznaczane podczas próby rozciągania. Dodatkowo kompozyty przeznaczone do badań wygrzewano w trakcie przygotowania w różnych temperaturach (zgodnie z zaleceniami producenta żywicy będącej osnową). Kompozyty składały się z 7 warstw tkaniny węglowej przesyconych żywicą epoksydową L285 z utwardzaczem. W wyniku badań zauważono, że zmiana temperatury eksploatacji wywiera istotny wpływ na właściwości wytrzymałościowe kompozytu bez względu na temperaturę wygrzewania. Materiały wygrzewane w wyższych temperaturach cechowała większa wartość współczynnika sprężystości wzdłużnej i wytrzymałości na rozciąganie.

Słowa kluczowe: próba rozciągania, kompozyt ze wzmocnieniem węglowym, moduł *Younga*, wytrzymałość statyczna

Introduction

The search for novel material solutions, enabling the rise of utility performance parameters of products, taking into account the economic and ecological aspects, is one of the main objectives of materials engineering. Composites as construction materials offer the designers a combination of properties not available in traditional materials [1, 13]. Low production costs and high strength made composites extremely common. For this reason, composites are particularly eagerly used by designers of various means of transport [5, 8], where by reducing weight, greater ranges, lower fuel consumption and greater transport possibilities are obtained.

The composites are used in aviation, both in the production of light aircraft e.g. gliders but also in the structures of civil aircraft and military aircraft [3, 11]. During flights many planes take to high altitudes, and as altitude increases, the outside temperature drops. In turn, jet airplanes (especially military ones) and spacecraft achieve high speeds during flight, and their fuselages and other external elements may heat up due to friction [9]. So a lot of aircraft's elements operate at different temperatures that may cause changes in their mechanical properties. Nowadays one of the most frequently used reinforcements in polymer composites used in aviation are carbon fibers [2]. Since the potential change in the mechanical properties of the material along with the temperature of use is a significant problem in aircraft structures, the authors decided to carry out strength tests as a function of different operating temperatures of carbon fibers. Additionally, taking into account the recommendations of the manufacturer of the composite matrix material [6], the influence of the post-curing temperature of the material at the stage of its production on the modulus of elasticity was determined. When designing various structures, including aircraft, the mechanical properties of materials play a very important role. If these properties change during operation, the structure may be damaged or even destroyed. One of the most important material mechanical properties of construction materials is the modulus of elasticity, therefore this physical quantity was analyzed in the research presented in the article.

The test examination was a static tensile test [7]. Each sample from a batch was heated up at a different temperature. During the test, the samples were subjected to a constant temperature, simulating a heightened temperature of operation.

Research methodology

In order to conduct the test, the authors prepared composite panels, which were then used to cut out samples. The composite reinforcement was a carbon-fiber fabric GG 416 P/T, 416 g/m^2 in weight, with a double weave. The laminate consisted of seven layers.

The matrix base was made up of epoxy resin L285 with H285 hardener, in accordance with the manufacturer's recommendations, mixed in 100:40 weight ratio. In order to meet the design requirements during the construction of gliders and motor gliders, resin should be post cured at a temperature of 50–55 °C. If the resin is to be used to build engine aircraft, it should be post cured at a temperature of 80°C. The temperature range in which no significant changes in the properties of the resin are observed is included between -60°C to 50–60 °C without post curing, and between –60°C to 80–100°C for a post cured material.

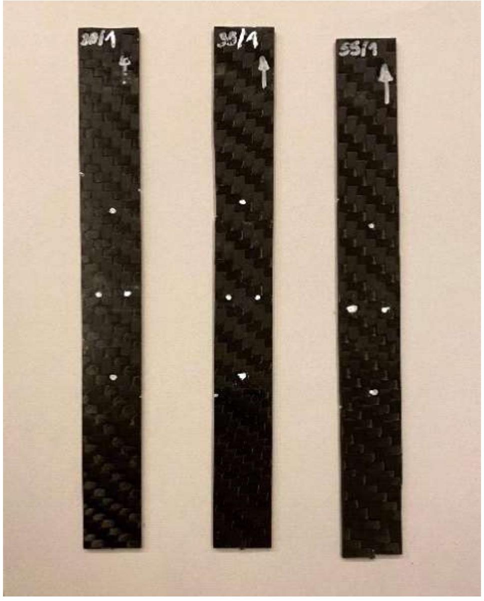

Fig. 1. Test samples

In order to remove any air bubbles from the composition, after mixing the components, the authors removed gas in an ultrasound bath for five minutes. Then the layers were put together and laid down in a hydraulic press. They were exposed to a load of 30 tonnes. The obtained material was used for the preparation of rectangular samples for the tests, sized 280 x 25 x 2.5 mm, in accordance with the EN ISO-527 standard [4]. The samples were cut out by means of the waterjet method.

The prepared sample (Fig. 1) were exposed to the process of post curing in a climatic chamber, manufactured by Weiss WKL 64. Each batch was post cured at a different temperature: 35, 55, 80 and 100°C for 24 hours, respectively.

The tests were conducted by means of the Instron 5982 Testing System with an optical tensometer, additionally equipped with SF-16 resistance furnace. The traverse movement was 2 mm/min during the tests.

In the first stage, the bearing capacity of the prepared samples was determined. For this purpose, a batch of samples, not subjected to post curing, was used. The average bearing load of the examined sample batch amounted to 44 kN. It was decided to continue using tensile load of 25 kN in proper research. In accordance with the adopted methodology, the sample was inserted in a resistance furnace and heated up to a set temperature. It was stabilized at this temperature for 5 min. The loading was increased up to 25 kN (Fig. 2).

Fig. 2. Strength testing machine with a chamber furnace ready for research

Research results

The test results of the composite cured at room temperature prove that along with a temperature increase during an examination, there is an almost linear decrease in the value of *Young's* modulus (Fig. 3).

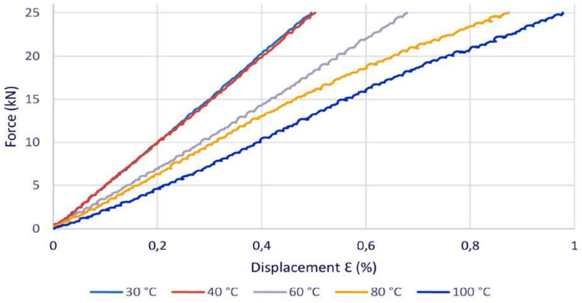

Fig. 3. Tensile test curves of samples cured at room temperature

Table 1. *Young's* modulus values which are dependent upon temperature for the composite cured at room temperature

Temperature (°C)	**30**	**40**	**60**	**80**	**100**
Modulus of elasticity (GPa)	75.45	74.65	62.01	53.62	47.80

The results of the composite cured at room temperature are shown in Table 1. Up to the temperature of 40°C, no change in *Young's* modulus was observed (Fig. 4). However, above this temperature a steady decline in the modulus value is noticeable, by 47.80 GPa for the temperature 100°C.

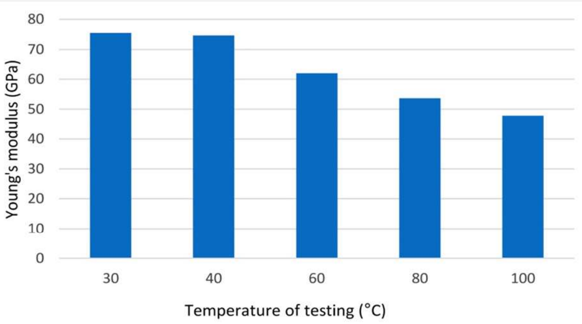

Fig. 4. *Young's* modulus of the composite hardened at ambient temperature

Increasing the temperature of testing composites post cured at 35°C, similar to a non-post cured composite, causes an almost linear decrease in *Young's* modulus (Fig. 5, 6). It seems that values close to the value of the modulus of elasticity during an examination at 30°C and 40°C may be due to a slight increase in temperature. They do not entail changes in the structure of the composite matrix base. At higher research temperatures, there was a decline in *Young's* modulus to a value of 51.91 GPa for the temperature 100°C (Table 2), i.e. by 28%.

Table 2. *Young's* modulus values which are dependent on a temperature for the composite post cured at 35°C

Temperature (°C)	**30**	**40**	**60**	**80**	**100**
***Young's* modulus (GPa)**	72.81	71.02	62.38	58.08	51.91

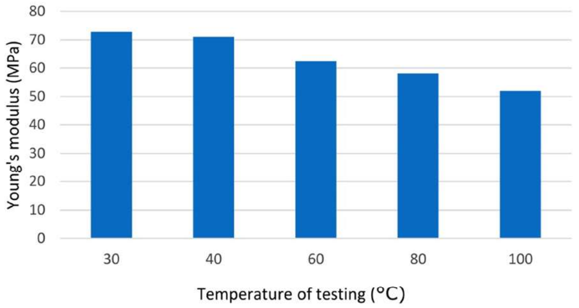

Fig. 5. *Young's* modulus of composite post cured at 35°C

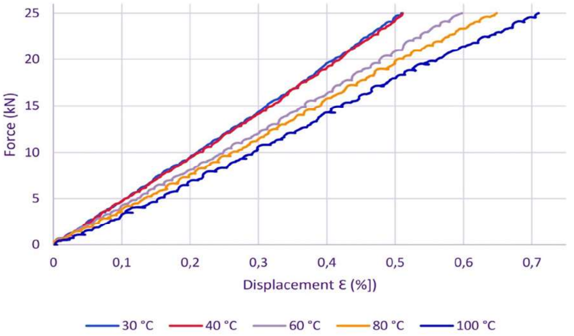

Fig. 6. Tensile test graph of samples post cured at 35°C

The examinations of the samples post cured at 55°C show a drop in *Young's* modulus along with increasing the examination temperature. *Young's* modulus changes in a linear manner, from 76 to 63.18 GPa (Fig. 7), yet its drop is lower than for samples post cured at a lower temperature.

Table 3. *Young's* modulus values which are dependent on temperature research for the composite post cured at 55°C

Temperature (°C)	**30**	**40**	**60**	**80**	**100**
***Young's* modulus (GPa)**	76.49	76.8	73.67	69.39	63.18

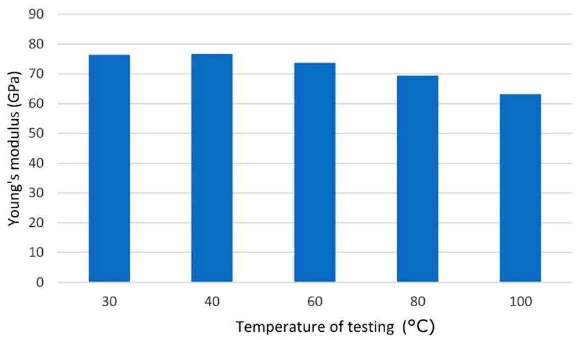

Fig. 7. *Young's* modulus of samples post cured at 55°C

The examination carried out for the samples post cured at 80°C demonstrates that the elasticity modulus initially rose at 40°C, and then, at a further temperature rise, its value was lowered. The highest value of *Young's* modulus equalled 72.3 GPa (for the research temperature of 40°C), and the lowest was 59.61 GPa (for the research temperature of 100°C) (Fig. 8).

Table 4. Dependence between *Young's* modulus values and research temperature for the composite post cured at 80°C

Temperature (°C)	30	40	60	80	100
***Young's* modulus (GPa)**	68.55	72.3	68.41	66.66	59.61

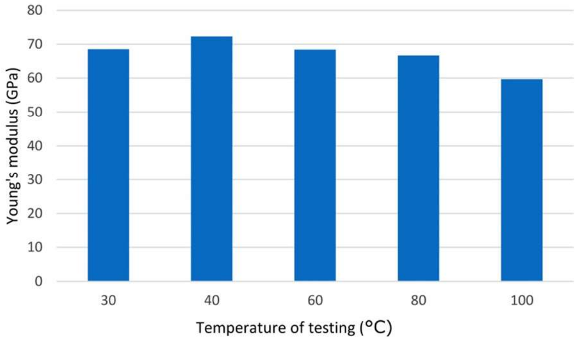

Fig. 8. *Young's* modulus of samples post cured at 80°C

No significant differences of *Young's* modulus were observed for samples post cured at 100°C during tests conducted at 30, 60, 80°C (Fig. 9). During a test at a temperature of 40°C, the value of *Young's* modulus exceeded 6%, whereas at 100°C it was over 8 % lower than *Young's* modulus, determined at 30°C. The changes can also be observed on a graph displaying a static tensile test of the sample (Fig. 10).

Table 5. Dependence between *Young's* modulus values and research temperature for the composite post cured at 100°C

Temperature (°C)	30	40	60	80	100
Young's modulus (GPa)	83.95	89.60	84.71	81.47	76.86

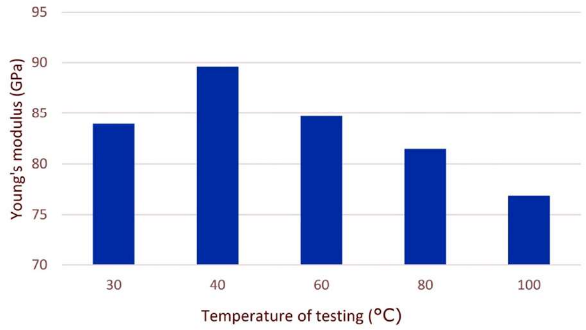

Fig.9. *Young's* modulus of samples post cured at 100°C

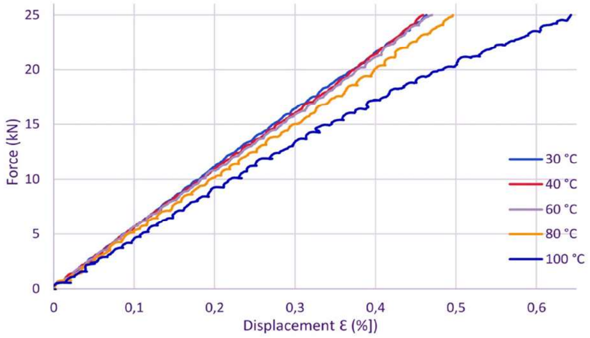

Fig. 10. Graph of a tensile test of samples post cured at 100°C was

Young's modulus value depended on temperatures, in which the composite was post cured (Fig. 11). Batch samples post cured at 100°C are characterized by the highest value of *Young's* modulus, regardless of the test temperature. Batch samples which were post cured at ambient temperature and at a temperature of 35°C are characterized by similar values (the differences do not exceed 5 GPa). The most stable value of *Young's* modulus is characterized by samples post cured at 55°C (changing the value is approximately 10 GPa for the whole range of the research temperatures). On the other hand, the biggest changes were observed for the material cured at room temperature.

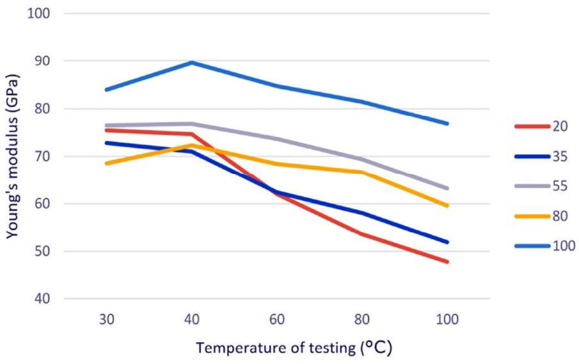

Fig. 11. *Young's* modulus in a function of temperature for all batches

After the tests were carried out in the thermal chamber, all the samples underwent full tensile tests. Examples of stress-strain curves after temperature testing are shown in Fig. 12. The highest bearing capacity (approximately 47 kN) was observed in samples post cured at 55°C and 80°C. It needs to be noted that these are the temperatures recommended by the resin manufacturer. The sample post cured at 80°C was also characterized by the highest value of relative deformation during the destruction - the lowest deformation during destruction demonstrated the sample post cured at 100°C, in which the highest value of *Young's* modulus is visible.

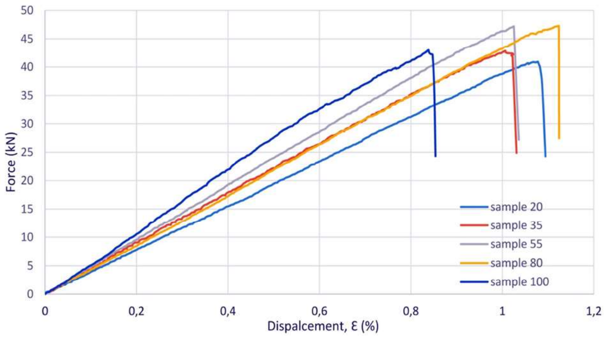

Fig. 12. Tensile test curves of selected samples after temperature tests

Conclusions

Based on the analysis of the results of the conducted research, the following conclusions were formulated:

1. The tests carried out have shown that the temperature change has a significant impact on the strength properties of the composite. Both the post-curing process and the thermal conditions of the exploited composite affect its strength.
2. Post-curing at higher temperatures increases the modulus of elasticity, which is important in aircraft structures [10, 12]. The highest value of this coefficient, regardless of the test temperature, has a composite hardened at a temperature of 100°C, which shows that when recommending the value of the post-curing temperature, the manufacturer was not guided solely by the value of Young's modulus.
3. The majority of the examined composites were characterized by the highest value of the modulus of elasticity during the tests at 40°C, the process of post curing the sample increases the tensile strength of the examined composites, after the entire testing cycle, the samples post cured at 55°C (recommended for gliders) and at 80°C (recommended for engine aircraft) had the highest bearing capacity.

References

[1] Alabtah F., Mahdi E., Eliyan F. 2021. The Use of Fiber Reinforced Polymeric Composites in Pipelines: A Review. Composite Structures. 276. 114595. 10.1016/j.compstruct.2021.114595.

[2] Banisaukas J., Shioleno M., Levan Ch., Rawal S., Silverman E., Watts R. 2005. Carbon Fiber Composites for Spacecraft Thermal Management Opportunities. AIP Conference Proceedings. 746. 10-21. 10.1063/1.1867113.

[3] Gay D. 2015. Composite materials: Design and applications. 3rd ed. CRC Press/Taylor & Francis Group.

[4] ISO 527-1:2019 Plastics — Determination of tensile properties.

[5] Koštial P., Koštialová-Jančíková Z., Ružiak I., Gajtanska, M. 2020. "Case Study of Chosen Sandwich-Structured Composite Materials for Means of Transport". Coatings 10: 750. https://doi.org/10.3390/coatings10080750.

[6] Laminating Resin MGS L285; Hexion Speciality Chemicals GmbH: Stuttgart, Germany. 2016. Available online: https://m.aircraftspruce.com/catalog/pdf/mgs285tech.pdf.

[7] Lomov, S.V., Ivanov, D., Truong, T.C., Verpoest, I., Baudry, F., Vanden Bosche, K., Xie, H. 2008. Experimental methodology of study of damage initiation and development in textile composites in uniaxial tensile test. Composites Science and Technology 68(12): 2340–2349. https://doi.org/10.1016/j.compscitech.2007.07.005.

[8] Mistry P., Johnson M., Galappaththi U. 2021. "Selection and ranking of rail vehicle components for optimal lightweighting using composite materials". Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 235(3):390–402. doi:10.1177/0954409720925685.

[9] Reznik S. 2018. Thermal regimes of space composite structures. Part I, MATEC Web of Conferences 194, 01048, https://doi.org/10.1051/matecconf/201819401048.

[10] Scheuring, J.N., Grandt, A F. 1997. "Mechanical Properties of Aircraft Materials Subjected to Long Periods of Service Usage". J. Eng. Mater. Technol. 119(4): 380–386, https://doi.org/10.1115/1.2812273. [11] Swornowski P. 2010. „Kompozyty węglowe i szklane we współczesnym lotnictwie". Mechanik 1: 44–50.

[12] Szczeciński S. 2009. „Zagadnienia napędów lotniczych". Prace Instytutu Lotnictwa 4 (199).

[13] Tunali A. 2013. "Advanced Composite Applications in the Construction Industry". Polymers and Polymer Composites 21(3):195–198. doi:10.1177/096739111302100313.

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