Science of Sintering, **53** (2021) 127-136

---

https://doi.org/10.2298/SOS2101127S

UDK: 692.533.1; 539.371; 001.572

Numerical Evaluation of the Elastic Properties of Carbon Fiber Reinforced Composite Material at Elevated and Lowered Temperatures

Alteer Taha Saleem[1], Veljko Petrović[1], Aleksandar Grbović[1*)], Jasmina Lozanović Šajić[2], Igor Balać[1]
[1]University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia
[2]University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, Serbia

---

Abstract:
The effect of elevated and lowered temperatures on the elastic properties of carbon fiber-epoxy composite material was studied using multi-phase unit cell (MPUC) numerical model. Evaluation of the elastic properties of carbon fiber-epoxy composite material is based on the finite element method. Obtained results confirmed that elevated and lowered temperature has noticeable influence on elastic properties of carbon fiber-epoxy composite material. As demonstrated, this fact has considerable influence on accurate evaluation of generated thermal stresses in real laminated composite structures, exposed to extremely high or low operating temperatures.

Keywords*: Composite materials; Modulus of elasticity; Shear modulus; Poison's ratio.*

---

1. Introduction

Composite materials are formed by the combination of two or more materials to achieve properties (physical, chemical, etc.) that are superior to those of its constituents. Composite structures have low density, high strength, and high stiffness, and these properties are the reason why the composites are widely used in the aerospace, marine, aviation, and civil engineering industry. The main components of composite materials are fibers (usually carbon) and matrix (usually epoxy). The fibers provide most of the stiffness and strength while the matrix binds the fibers together, providing load transfer between fibers. The matrix, also, protects the fibers from environmental influence.

In real laminated composite structures, stresses generated as a result of external mechanical loads are commonly called *mechanical stresses*. The second source of external loads can be attributed to environmental factors (extreme operating temperatures) resulting in so-called thermal stresses. A typical example is an aircraft, having structural parts made of laminated composite material, exposed to extremely low (below -50 °C) or high temperatures (over 50 °C). These conditions may contribute to the reduction of composite structure strength in two ways. As a first issue, reduction of composite structure strength is attributed to the fact that additional thermal stresses can significantly decrease estimated composite structure strength which is usually determined analytically, using Classical Lamination Theory (CLT). The second issue is associated with the fact that composite lamina strength is determined by

---

*) **Corresponding author:** agrbovic@mas.bg.ac.rs

calculations that involve elastic properties of composite material obtained by laboratory experiments conducted at standard temperature (usually 20 °C). As it is well documented in the literature, elastic properties of the matrix, in some cases, are strongly dependable on temperature changes [1]; therefore, elastic properties of composite material must also depend on temperature changes.

Since operating temperatures could be significantly different from standard laboratory tests temperature, it is clear that exposition of the composite structure to extremely low or high temperatures may lead to a notable change of composite lamina mechanical properties and, consequently, change of lamina strength. Recently, several studies have been carried out regarding the influence of temperature on the mechanical properties of composite materials. In [2] an experimental investigation of the effects of low temperatures on the mechanical, fracture, impact, and dynamic properties of carbon- and E-glass-epoxy composite materials has been conducted. The objective of the study was to quantify the influence of temperatures from 20 °C down to −2 °C on the in-plane (tensile/compressive) and shear material properties, static and dynamic Mode-I fracture characteristics, including impact/residual strength. It was found that nearly all characteristics of the mechanical performance of the laminates are temperature dependent. In [3] authors evaluated the temperature effect on the mechanical properties and damage mechanisms of a Glass/Elium 150 laminate composite. Quasi-static indentation tests have been carried out at different temperatures to highlight the temperature dependency of different parameters of the composite samples, including stiffness. The influence of temperature was analyzed, and it was shown that mechanical properties and the severity of damage were strongly temperature-dependent. The most comprehensive experimental study of the temperature effect on the mechanical properties of composite materials is presented in [4]. The effect of constant and cyclic temperature influences (from -196 °C to 120 °C) on products made of composite materials was observed. The ring samples have been used and the data on the changes in the linear expansion coefficient values, strength, rigidity, and residual deformations with the change of temperature and the number of thermal cycles are given. All above-mentioned studies can be used to evaluate results obtained by numerical evaluations of the elastic properties of carbon fiber reinforced composite material which, surprisingly, cannot be found in the recent literature in the greater number [5].

In order to investigate the influence of high and low temperatures on elastic properties of carbon fiber-epoxy composite, which is commonly named *carbon fiber reinforced platics* – CFRP, micro-mechanical analysis should be performed. Micro-mechanical analysis uses the concept of a *representative volume element* (RVE) or sometimes referred as *unit cell.* An RVE is the smallest portion of the composite material that contains all of constituents (part of the fiber and part of the matrix) and, therefore, is considered as representative of the material as a whole. In order to evaluate elastic properties of CFRP, micro-mechanical analysis of RVE has to be done numerically using the finite element method (FEM). This method was successfully used for evaluation of elastic properties and strength of different types of structural materials in the presence of porosity [6-7] and without it [8].

2. Modeling procedure

Single lamina or ply is basic composite product based on continuous fibers (carbon, glass, aramid are the most common) in polymer matrix and usually is produced in the form of thin layers (very thin plates). Elastic properties of the lamina are usually defined according to *principal material directions* - axes 1,2,3 as shown on Fig. 1. The 1-axis is defined to be parallel to the fibers, the 2-axis is defined to lie within the plane of the plate and is perpendicular to the fibers, and the 3- axis is defined to be normal to the plane of the plate.

Note that fibers are arranged symmetrically about the 1-3 and 2-3 planes. For two-dimensional analysis, elastic properties of composite lamina are usually defined through following constants: modulus of elasticity in direction 1 - E_1, modulus of elasticity in direction 2 - E_2, shear modulus in plane 1–2 - G_{12} and major Poissons ratio - ν_{12}, while minor Poissons ratio - ν_{21} is defined through following expression: $\nu_{21} = \nu_{12}\ E_2/\ E_1$. In case of three-dimensional analysis, additional elastic properties are defined through following constants: modulus of elasticity in direction 3 - E_3 ($E_3 = E_2$), shear modulus in plane 2–3 - G_{23}, and Poissons ratio - ν_{23}.

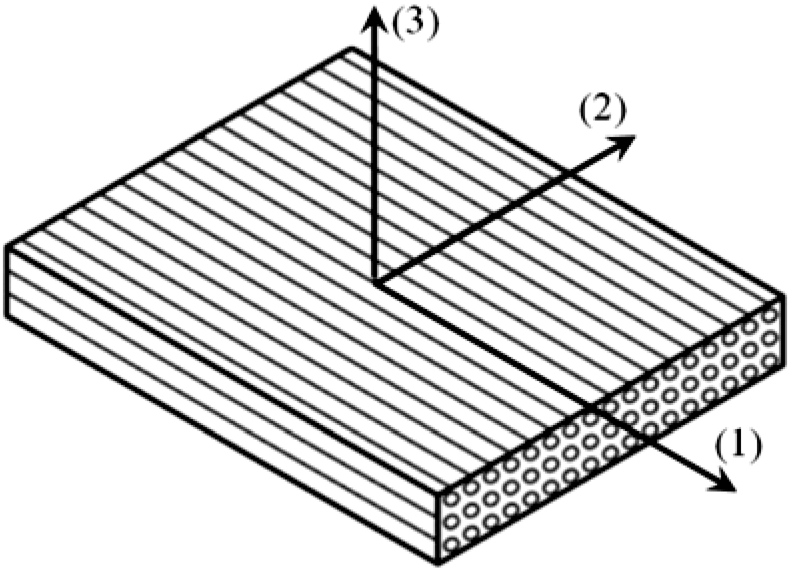

Fig. 1. Single lamina with principal material directions - axes 1,2,3.

In order to obtain elastic properties of carbon fiber-epoxy composite lamina, a numerical analysis has been performed using Code Aster [9], open source finite element analysis software. RVE of carbon fiber-epoxy composite lamina having 60 % volume fraction of fibers is represented through Multi-Phase Unit Cell (MPUC) model as shown in Fig. 2a. MPUC model is modeled as a 3D continuum using FEM and first-order hexahedral elements. The assumptions for constituents (the fiber and the matrix) are:

(I) the constituents have linear elastic material properties at given temperature,
(II) the fiber is assumed to be a transversely isotropic material, while the matrix is assumed to be an isotropic material,
(III) the fiber and the matrix will not fail at the prescribed loads, and
(IV) the constituents are assumed to be non-porous materials.

Due to the symmetry of the unit cell and the applied loads, as well as adopted isotropic material properties, the models were reduced to one fourth of the unit cell, as shown in Fig. 2b. Dimensions of reduced unit cells presented at Fig. 2b are 5×5×5μm while radius of the fiber is 4,37 μm.

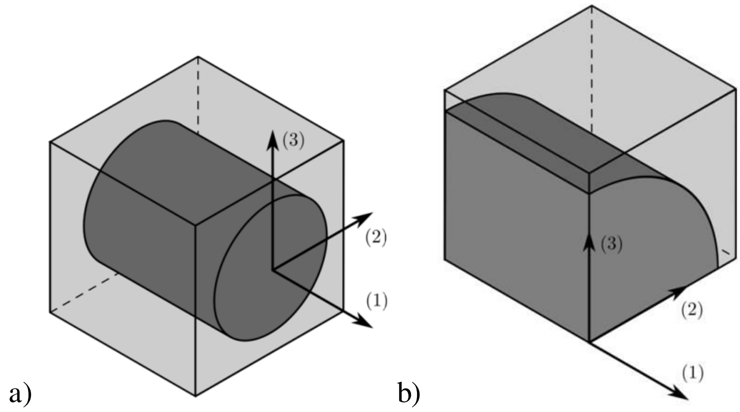

Fig. 2. Representative volume element: MPUC with 60 % of fiber volume fraction (V_f = 0,6) full size MPUC, (b) one fourth of the MPUC.

For carbon fiber, used material properties are assumed to be constant through the full temperature range (from -60 °C to 120 °C) and are presented in Table I.

Tab. I Material properties of used carbon fiber.

Properties	**Carbon Fiber T300**
Longitudinal Young's Modulus E_1 (GPa)	230
Transverse Young's Modulus E_2 (GPa)	15
Longitudinal Shear Modulus G_{12} (GPa)	15
Transverse Shear Modulus G_{23} (GPa)	7
Major Poisson's Ratio ν_{12}	0.2
Transverse Poisson's Ratio ν_{23}	0.07

For epoxy matrix, the modulus of elasticity is temperature-dependent through full temperature range (from -60 °C to 120 °C) and is adopted from the literature [1], as well as the other material properties.

All MPUC models are considered by introducing boundary conditions, which in case of evaluation of modulus of elasticity and Poisson's ratio, constrains the MPUC to remain in its original shape. The MPUC is loaded in compression along principal material directions: 1,2,3 respectively. After loading, the sides of the MPUC remain parallel and orthogonal, but there are changes in length. The local coordinate system aligns with the global one.

Evaluation of shear modulus involved boundary conditions which forced small shear angle in plane 1–2. In this case, despite the MPUC changed its original shape, it is considered that its volume remains the same.

3. Results and Discussion

In order to be easily compared with values at the room temperature (at T = 20 °C), all of obtained results for lamina properties, showed in the next figures, are expressed through their normalized values: $\bar{E}, \bar{G}, \bar{\nu}$.

Values obtained in finite element analysis of lamina's mechanical properties at different temperatures showed that the value of Young's modulus E_1 is not influenced by temperature change (Fig. 3).

On the other hand, values of E_2 and E_3 show notable change with the change of environmental temperature (Fig. 4). With increasing temperature, when the temperature reaches +120 °C, values of E_2 and E_3 decrease by 15 % when compared with room temperature values. When temperature decreases and reaches -60 °C, values of E_2 and E_3 are 18 % higher than at the room temperature.

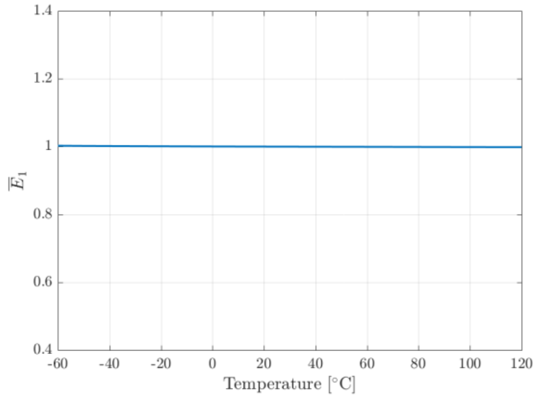

Fig. 3. Change of normalized E_1 within temperature range.

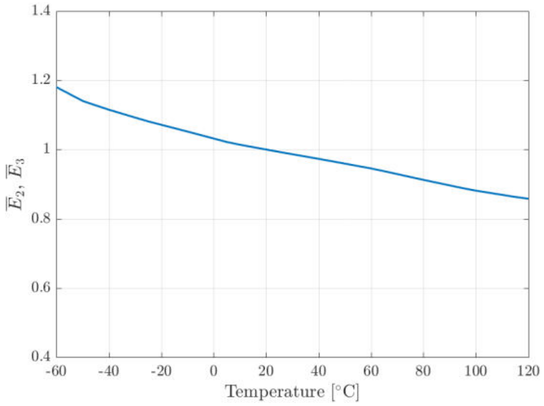

Fig. 4. Change of normalized E_2 and E_3 within temperature range.

Shear moduli slightly change when the temperature is decreasing (at -60 °C values of G_{12}, G_{13} and G_{23} are higher by approximately 1 %), whereas with an increasing temperature, changes of shear moduli are negligible up to 120 °C (Figs 5 and 6).

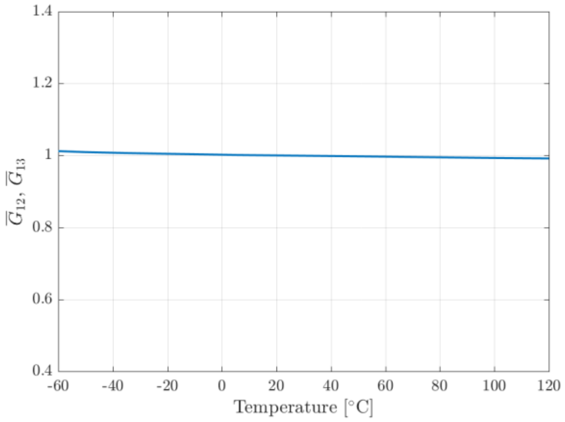

Fig. 5. Change of normalized G_{12} and G_{13} within temperature range.

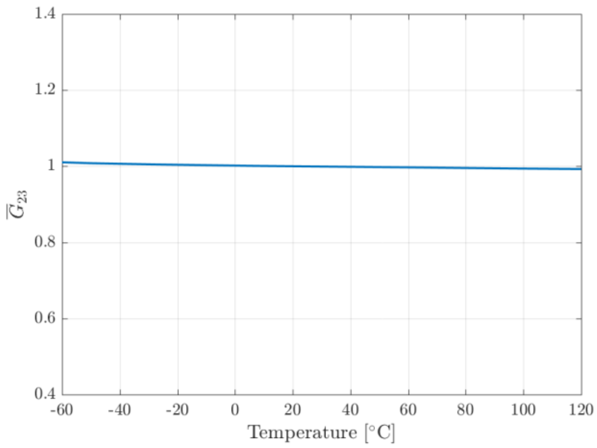

Fig. 6. Change of normalized G_{23} within temperature range.

Changes of values of Poisson's ratios ν_{12} and ν_{13} are negligible within temperature range (Fig. 7), but ν_{23} experiences change by approximately +4 % when temperature reaches +120 °C, and -7 % when temperature is -60 °C (Fig. 8).

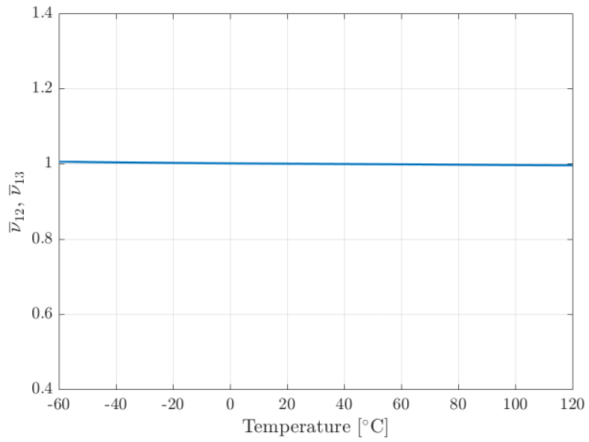

Fig. 7. Change of normalized ν_{12} and ν_{13} within temperature range.

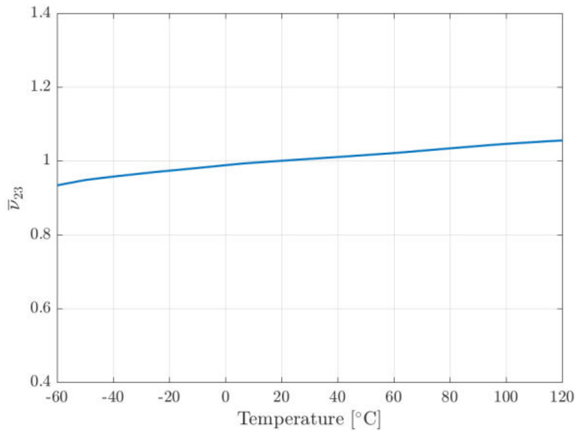

Fig. 8. Change of normalized ν_{23} within temperature range.

In order to quantify the influence of temperature dependent elastic properties on generated thermal stresses, a simple case of an unconstrained carbon fiber-epoxy [0/90/90]s symmetric laminated plate (6×6 mm) is considered (Fig. 9).

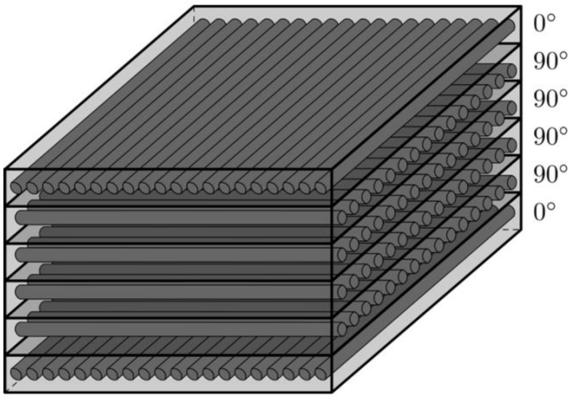

Fig. 9. Symmetrical laminate with 6 plies (laminas) - [0/90/90]s.

Symmetrical lay-ups are widely used in the industry nowadays since geometrical and material symmetry help to avoid thermal twisting of parts as they cool down after curing. In considered laminate, the thickness of each lamina is 0.2 mm. The plate is thermally loaded by different temperature changes, in range from $\Delta T = -80\ ^{o}C$ (which simulate that laminate is exposed to temperature of -60 °C) to $\Delta T = +100\ ^{o}C$ (which simulate that laminate is exposed to temperature of +120 °C). The size of the numerically modeled plate is assumed to be large enough so that the free-edges effects are negligible at the symmetry plane of the plate. Since there are no other external loads, such as external forces and moments, the plate is considered to be stress free at standard (room) temperature of 20 °C. Due to the fact that in directions 1 and 2 each lamina has different coefficients of thermal expansion, applied temperature changes induced thermal loads which consequently generated thermal stresses. These thermal stresses have been determined numerically using open source software Code Aster [9]. Values of obtained stresses in direction 1 (σ_1) and in direction 2 (σ_2), in lamina oriented at 0^0, are shown in Figs 10 and 11.

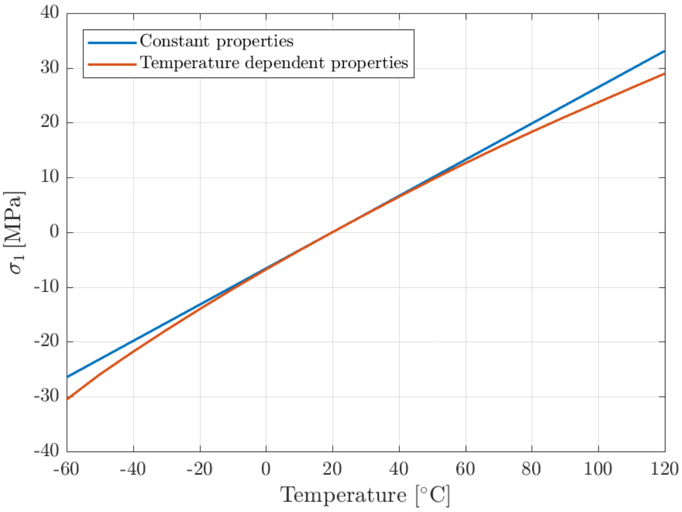

Fig. 10. Variation of σ_1 with temperature change (values in lamina oriented at 0°).

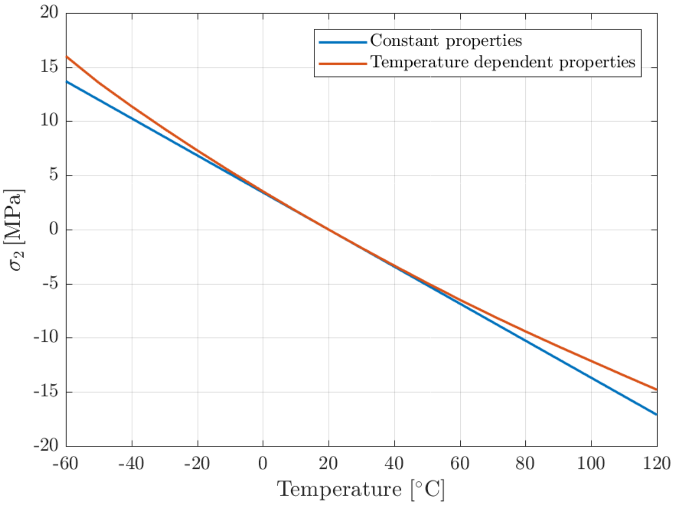

Fig. 11. Variation of σ_2 with temperature change (values in lamina oriented at 0°).

Figs 10 and 11 show that in case of lamina's temperature-dependent elastic properties values of stresses: σ_1 and σ_2 are different than the values of those stresses calculated with constant material properties (at T = 20 °C). As presented in Figs 10 and 11, these differences are not small and must not be ignored. At -60 °C differences between these stresses is 15.4 % for stress σ_1 and 16.9 % for stress σ_2, while at +120 °C these differences are: 14.3 % for stress σ_1 and 15.6 % for stress σ_2.

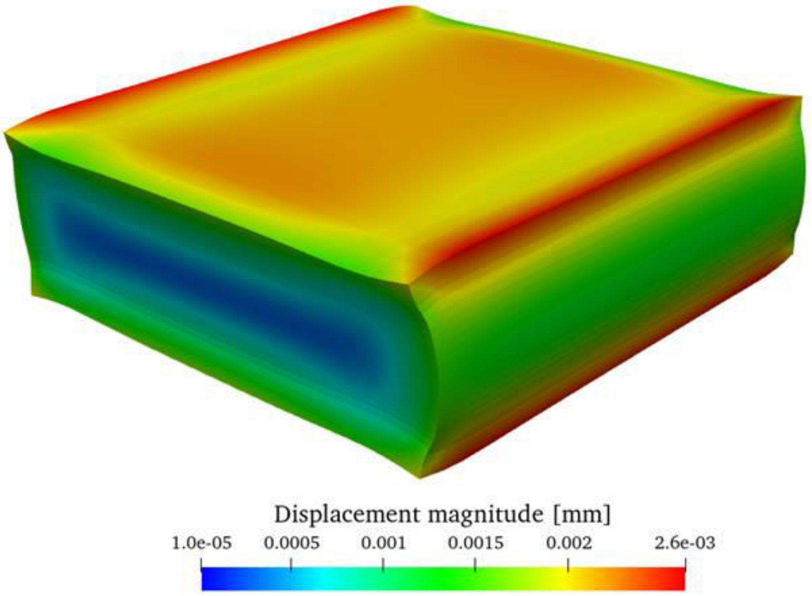

Fig. 12. Displacement field in lamina (0°) at 120 °C (scale factor 100).

Finally, Fig. 12 shows non-homogenous displacement field of laminate exposed at temperature of +120 °C (ΔT=100 °C). As can be seen, since laminate is anisotropic material, a displacement is not uniform (as can be expected in case of isotropic plate).

Obtained results clearly indicate that in case when lamina properties are temperature dependent, those ones must be considered in composite design process if such composite structure is going to be exposed to considerable temperature changes – extreme operating temperatures.

4. Conclusion

The effect of elevated and lowered temperatures on the elastic properties of carbon fiber-epoxy composite lamina was studied using multi-phase unit cell (MPUC) numerical model. Obtained results confirmed that elevated and lowered temperature has noticeable influence on some elastic properties of carbon fiber-epoxy composite lamina. The following elastic properties of carbon fiber-epoxy composite lamina appear to be considerably temperature-dependent: transverse moduli of elasticity E_2 and E_3. As shown on sample of thermally loaded composite plate, this fact may have significant influence on accurate evaluation of generated thermal stresses in real laminated composite structures, exposed to extremely high or low operating temperatures.

Acknowledgments

This investigation was supported by by Ministry for Education, Science and Technological Development, Grant Number: 451-03-68/2020-14/200105.

5. References

1. S. Deng, M. Hou, L. Ye, Polymer Testing 26 (2007) 803.
2. J. Leblanc, P. Cavallaro, A. Shukla, International Journal of Lightweight Materials and Manufacture, DOI:10.1016/j.ijlmm.2020.05.002 Corpus ID: 219509879, (2020).
3. L. Cadieu, J. B. Kopp, J. Jumel, J. Bega, C. Froustey, Journal of Composite Materials, 54 (2020) 2271.
4. V. P. Nikolaev, E.V. MyshenkovaV. S. Pichugin, Inorganic Materials 50 (2014) 1511.
5. S. Liu, J. Fu, J. Yang, H. Feng, Journal of Civil Engineering 24, (2020) pages 3875-3883.
6. E. Abdulrazag, I. Balać, K. Čolić, A. Grbović, M. Milovančević, M. Jelić, Sci Sint 51 (2019) 153.
7. M. Higaeg, I. Balać, A. Grbović, M. Milovančević, M. Jelić, Sci Sint 51 (2019) 459.
8. Balac, K. Colic, M. Milovancevic, P. Uskokovic, M. Zrilic, FME Transactions, 40 (2012) 81.
9. Électricité de France, Code_Aster, Analysis of Structures and Thermomechanics for Studies & Research, 1987-2020.

Сажетак: *Утицај повишене и снижене температуре на карактеристике еластичности композитне ламине- угљенично влакно у епокси смоли, анализиран је применом multi-phase unit cell - MPUC нумеричког модела. Одређивање карактеристика екастичности је спроведено применом методе коначних елемената. Добијени резултати су потврдили да постоји приметан утицај повишене и снижене температуре на карактеристике еластичности композитне ламине- угљенично влакно у епокси смоли. Ова чињеница може значајно допринети нетачности приликом* *израчунавања генерисаних термичких напона код реалних ламинатних композитних конструкција које су изложене екстремно високим или ниским радним температурама.*

Кључне речи*: композитни материјали, модул еластичности, модул смицања, поасонов однос.*