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Identification of mechanical properties of KORDCARBON-CPREG-200-T-3K-EP1-42-A composite

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Abstract. This work is focused on the identification of mechanical properties of a composite from tension, compression and bending tests according to ASTM standards. Selected stiffness and strength parameters were identified. The composite, which was made from KORDCARBON-CPREG-200-T-3K-EP1-42-A prepreg, consists of woven fabric (twill) with carbon fibres and epoxy resin. Some of the parameters were identified using the numerical simulation of the tests in the finite element system Abaqus and using optimization algorithms of Isight software. The whole process of the identification was managed by scripts written in Python software.

1. Introduction

One of the main difficulties in the design of composite structures is the lack of known material parameters. This problem is further exacerbated by utilizing complex material models [1] and complex strength criteria [2, 3]. Woven fabrics are the most widely used types of composite materials. Prepregs are often used, for example, in transport industry, wind energy, sports, etc. [4–6]. This work is motivated by the use of a carbon prepreg for production of a bogie of rail vehicles. Therefore, the KORDCARBON-CPREG-200-T-3K-EP1-42-A composite was analysed in this work. The identification of selected stiffness and strength parameters of this prepreg with woven fabric was performed.

2. Materials

The composite plates were made in autoclave from 8 layers of twill 2/2 weave fabric prepreg KORDCARBON-CPREG-200-T-3K-EP1-42-A. All layers were oriented in the same direction. This prepreg contained carbon fibres (fiber diameter 7 μm) and solvent free epoxy based resin. Specific weight of dry fabric was 205 g m^{-2}.

3. Experiments

3.1. Tensile test

Prismatic specimens were cut using water jet from the composite plate one of the different direction (Θ = 0°, 15°, 30°, 45°, 60°, 70°, 90°). The thickness of the specimens was h = 2.4 mm, the width was w = 25 mm except the specimens with Θ = 0° which had w = 15 mm, the total length of the specimens was l = 250 mm and the gage length was l_g = 50 mm. The specimens were tested in tension in the longitudinal direction. The force - displacement (F - Δl) dependencies were obtained from the tensile test complying with ASTM D 3039 [7]. A uniaxial extensometer was used for measuring the elongation. The stress - strain dependencies were calculated using $\sigma = \frac{F}{w \cdot h}$, $\varepsilon = \frac{\Delta l}{l_g}$. The loading velocity of crosshead was $v_t = 2$ mm min^{-1}.

The effective elastic modulus was identified on the interval of strain $\varepsilon \in \langle 0.1\,\%, 0.3\,\% \rangle$. Tensile strengths (maximum stresses) $\sigma_{\mathrm{max}}^{\mathrm{T}}$ and effective tensile elastic moduli $E_{\mathrm{ef}}^{\mathrm{T}}$ are presented in the table 1 for each tested fiber orientations.

Table 1. Tensile strengths and effective tensile elastic moduli.

specimen ID	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**	**specimen ID**	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**
T_0_01	0	–	51.0	T_90_01	90	–	51.8
T_0_02	0	–	53.7	T_90_02	90	620.5	52.2
T_0_03	0	–	51.4	T_90_03	90	622.8	47.0
T_0_04	0	674.7	52.9	T_90_04	90	619.0	51.1
T_0_05	0	652.5	50.5				
T_0_06	0	644.7	47.1				
mean value (arithmetic)		657.30	51.10			620.77	50.33
standard deviation		12.71	2.10			1.57	2.34
coefficient of variation (%)		2.0	4.2			0.3	4.7
specimen ID	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**	**specimen ID**	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**
T_15_01	15	358.5	27.2	T_75_01	75	307.1	24.8
T_15_02	15	344.8	27.5	T_75_02	75	323.7	25.7
T_15_03	15	349.3	26.4	T_75_03	75	323.9	26.0
mean value (arithmetic)		350.87	27.03			318.23	25.50
standard deviation		5.71	0.47			7.88	0.51
coefficient of variation (%)		1.7	1.8			2.5	2.0
specimen ID	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**	**specimen ID**	**fiber orientation**	$\sigma_{\mathrm{max}}^{\mathrm{T}}$ **(MPa)**	$E_{\mathrm{ef}}^{\mathrm{T}}$ **(GPa)**
T_30_01	30	259.9	14.2	T_60_01	60	253.4	13.4
T_30_02	30	262.2	13.3	T_60_02	60	249.2	13.1
T_30_03	30	256.0	13.2	T_60_03	60	253.0	12.9
mean value (arithmetic)		259.37	13.57			251.87	13.13
standard deviation		2.56	0.45			1.90	0.21
coefficient of variation (%)		1.0	3.4			0.8	1.6

Poisson's ratio $\nu_{12} = 0.11$ was calculated from the tensile test with a biaxial extensometer.

The specimens with orientation 45° were used for the identification of the effective shear modulus G_{ef} from the tensile test complying with standard ASTM D 3518. The biaxial extensometer was used in this test. The effective shear moduli $G_{12\mathrm{ef}}^{\mathrm{S}}$ and the shear strengths $\tau_{\mathrm{max}}^{\mathrm{S}}$ for all of there specimens are presented in table 2.

Table 2. Shear strengths and effective shear moduli.

specimen ID	fiber orientation	σ_{max}^{T} (MPa)	E_{ef}^{T} (GPa)
T_45_01	45	117.8	3.19
T_45_02	45	118.6	3.19
T_45_03	45	117.6	3.17
T_45_04	45	–	3.13
T_45_05	45	–	3.16
T_45_06	45	–	3.16
mean value (arithmetic)		118.10	3.167
standard deviation		0.36	0.03
coefficient of variation (%)		0.3	0.7

The comparison of the stress - strain dependencies for all specimens is shown in figure 1. Good agreement between curves of equivalent specimens (0° – 90°, 15° – 75°, 30° – 60°) is obvious.

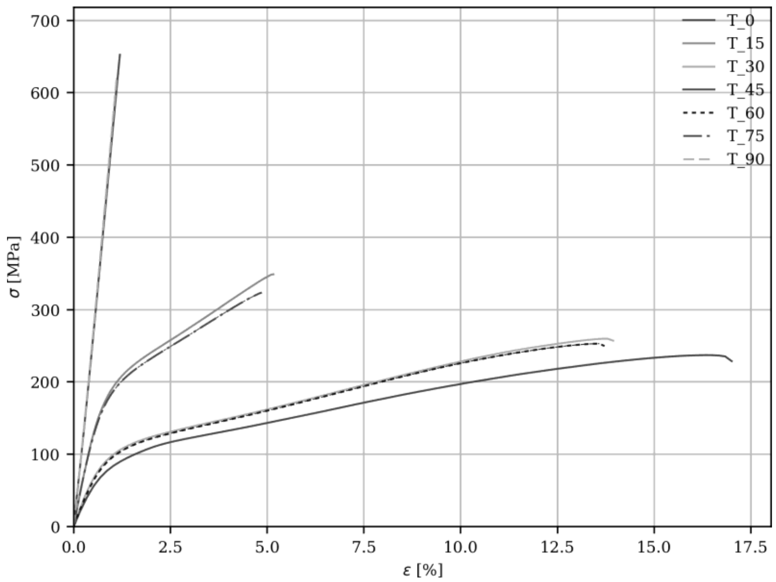

Figure 1. Stress - strain dependencies, tensile test.

3.2. Compression test

Two types of specimens (figures 2 and 3) were cut using water jet from the composite plate. Specimens were tested in compression in the longitudinal direction. The loading velocity was v_c = 1 mm min^{-1}. The effective compression elastic moduli (specimen type CM) were obtained from the compression test complying with standard ASTM D 695 [8] in the interval of strain $\varepsilon \in \langle 0.15\ \%, 0.25\ \% \rangle$. The effective compression elastic moduli E_{ef}^{C} are presented in table 3.

The compression strengths (specimen type CS) were obtained from the compression test complying with standard ASTM D 3410 [9]. Compression strengths σ_{max}^{C} are presented in table 4.

The results show that the effective elastic modulus in compression was higher than in tension by 16 %. The compressive strength in the longitudinal direction was lower than the tensile strength in the longitudinal direction by 37 %.

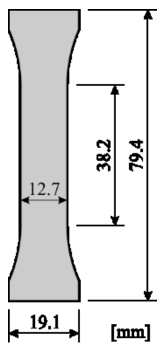

Figure 2. Specimen type CM.

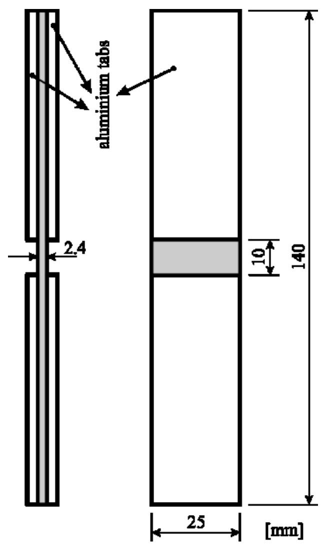

Figure 3. Specimen type CS.

Table 3. Effective compression moduli.

specimen ID	fiber orientation	E_{ef}^{C} (GPa)	specimen ID	fiber orientation	E_{ef}^{C} (GPa)
CM_0_01	0	59.7	CM_90_01	90	55.6
CM_0_02	0	59.2	CM_90_02	90	57.1
CM_0_03	0	59.0	CM_90_03	90	58.1
mean value (arithmetic)		59.30			56.93
standard deviation		0.30			1.03
coefficient of variation (%)		0.5			1.8

Table 4. Compression strength.

specimen ID	fiber orientation	σ_{max}^{C} (MPa)	specimen ID	fiber orientation	σ_{max}^{C} (MPa)
CS_0_01	0	530.2	CS_90_01	90	414.8
CS_0_02	0	434.7	CS_90_02	90	469.4
CS_0_03	0	481.1	CS_90_03	90	489.0
CS_0_04	0	487.3	CS_90_04	90	434.1
CS_0_05	0	455.8	CS_90_05	90	512.2
CS_0_06	0	433.7	CS_90_06	90	390.2
CS_0_07	0	534.4			
mean value (arithmetic)		479.60			451.52
standard deviation		38.39			42.47
coefficient of variation (%)		8.0			9.4

3.3. Bending test

Prismatic specimens (width w = 12.8 mm, thickness h = 2.4 mm, and total length l = 60 mm) were tested in the 4-point bending test complying with standard ASTM D 6272 [10]. The support span was l_s = 40 mm and the load span was l_l = 20 mm. The loading velocity was v_b = 1 mm min^{-1}.

The effective bending elastic moduli E_{ef}^{B} and maximum bending stresses are presented in table 5. The effective bending elastic modulus was higher than the elastic modulus in tension by 68 %. The bending strength was higher than the tensile strength by 80 %.

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Table 5. Effective bending moduli and maximum bending stresses.

specimen ID	**fiber orientation**	σ^{B}_{max} **(MPa)**	E^{B}_{ef} **(GPa)**	**specimen ID**	**fiber orientation**	σ^{B}_{max} **(MPa)**	E^{B}_{ef} **(GPa)**
B_0_01	0	1194.2	89.5	B_90_01	90	1194.1	79.6
B_0_02	0	1182.0	82.0	B_90_02	90	1185.4	91.4
B_0_03	0	1164.2	85.1	B_90_03	90	1139.2	78.3
B_0_04	0	1180.9	81.8	B_90_04	90	1191.5	90.7
B_0_05	0	1174.4	91.4	B_90_05	90	1191.7	79.5
B_0_06	0	1179.9	84.3	B_90_06	90	1153.0	76.2
mean value (arithmetic)		1179.27	85.68			1175.82	82.62
standard deviation		8.99	3.61			21.55	6.08
coefficient of variation (%)		0.8	4.3			1.9	7.4

4. Numerical model of tensile test

Numerical simulation of the tensile tests was created in the finite element system *Abaqus*. Hexahedral elements with 8 nodes were used in parametrically created model. The loading was controlled by the displacement of the crosshead. Transverse isotropic material model was used in the numerical analysis.

The identification of the effective tensile modulus and the effective shear modulus was performed based on the numerical simulation and optimization algorithms included in *Isight* software. By means of these optimization algorithms, the following function was minimized:

$$R = \sum_{i=1}^{n}[1 - \frac{F_{\mathrm{num}}(u_i,\Theta)}{F_{\mathrm{exp}}(u_i,\Theta)},$$

where n is the number of values included in the calculation across all test samples, u_i is the magnitude of the corresponding kinematic load and Θ represents the fiber orientation of the individual specimens, where F_{exp} is the force from the experiment, F_{num} is the force from the numerical simulation. The whole process of the identification was managed by scripts written in *Python* software. In case of the numerical simulation, experimental data were limited by change of the slope 5 %.

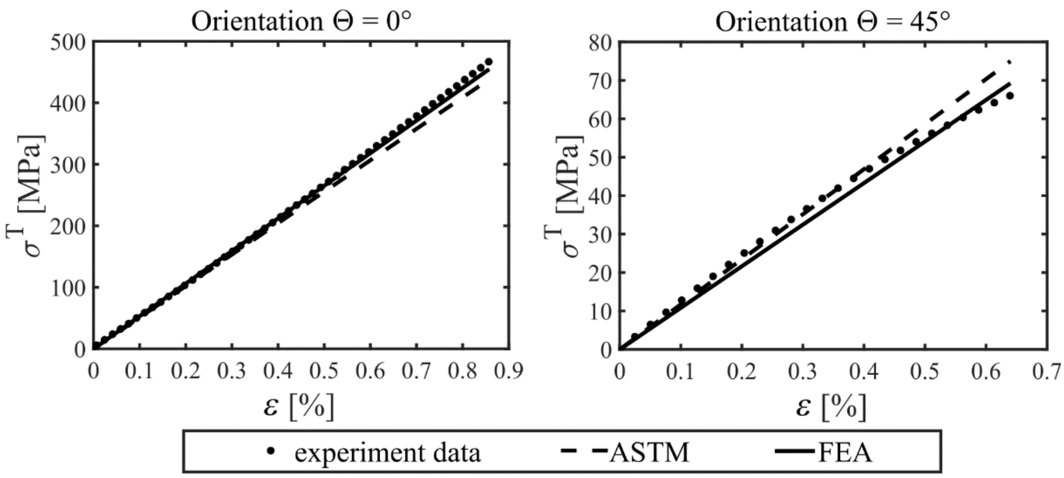

Figure 4. Comparison of numerical simulation and experimental results.

5. Conclusion

The mechanical properties of a carbon woven fabric composite were identified by means of tension, compression, and bending tests. The tests were carried out according to ASTM standards.

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The effective elastic modulus in tension was the lowest. The elastic effective modulus in compression was higher than in tension by 16 %. The elastic modulus in bending was higher than the elastic modulus in tension by 68 %. The lowest strength was the compressive strength in the longitudinal direction. This strength was lower than the tensile strength in the longitudinal direction by 37 %. The bending strength was higher than the tensile strength in the longitudinal direction by 80 %.

The tensile elastic properties identified based on the numerical simulation and the optimization algorithms gave better agreement over the whole linear region of the tensile curve.

6. References

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