ENHANCING MECHANICAL PROPERTIES AND CONDUCTIVITY OF CFRP USING CARBON NANOTUBES

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Composites are widely used in aerospace offering the engineer a possibility to create lightweight parts suitable for exact loading conditions: polymer matrix composites are used for mechanically loaded aircraft structures, ceramic matrix composites applied for engine parts can withstanding high temperature and corrosive environment, etc. However aerospace demands specific properties: the skins should be electrically conductive to ensure that high-voltage impact during lightning strike would not damage the aircraft. Metal structures do not require any additional solutions due to good electrical conductivity but in CFRP designs the engineers need to use special techniques which however modify only the surface of CFRP making the production technology more complicated. The enhancing of the bulk properties of CFRP is a promising way to improve both electrical conductivity and thermal one, which is also quite important.

Naturally carbon fibers are conductors but the epoxy is an insulator. The carbon fiber/epoxy composite due to high anisotropy demonstrate insufficient electrical conductivity, which can be improved by additives establishing cross-links between the layers of carbon: carbon nanofibers, carbon nanotubes or graphene. Such materials have affinity with carbon fiber fabrics and epoxy binder resulting in high adhesion thus CFRPs can be upgraded to hybrid composites with great electrical and thermal conductivity along with high mechanical properties.

The aim of the present work is to investigate the electrical properties and fracture behavior of hybrid carbon fiber reinforced polymers modified with single-wall carbon nanotubes (SWCNT). The resistivity of both modified and non-modified CFRP specimens were measured. The mechanical behavior of CFRP was evaluated via three point bending tests and static tension.

The specimens were produced using carbon fabrics, VATI basalt fabrics with densities of 200 g/m^2 both and epoxy binder resulting in a 2.1 mm thick 12-ply orthotropic laminate. The basalt layers allow avoiding the contact between neighboring carbon fiber layers and helping to investigate directly the effect of modification by CNTs. Hand lay-up with hot pressing using Gotech 7014-R (pressure 0.48 MPa, heating of plates to 60 °C, 12 hours) was used to fabricate blanks which were cut into specimens using milling machine. The SWCNTs by OCSiAl were used to modify CFRP and were added into epoxy. In order to obtain a uniform distribution and deagglomeration the mixture was subjected to ultrasonication during 20 min. Then modified epoxy was manually mixed with hardener. The specimens were tested using Instron 5582 universal testing machine. Quasi static tension was performed at the rate of 1.5 mm/min with gage length of 70 mm. Three-point bending was conducted with the span of 60 mm at 10 mm/min rate. Three specimens were tested for each CNT content and testing method.

In order to perform conductivity measurement the CFRP and epoxy the specimens were coated with silver conductive paint. The epoxy specimens were tested only in one configuration: between the ends of cylindrical specimen. While for CFRP specimens there were 3 configurations: in-plane surface measurement, out-of-plane diagonal and out-of-plane through thickness. For each CNTs content the conductivity measurements were conducted for 3 epoxy and 2 CFRP samples.

The failure mode of all specimens was lateral crack at the grip. Table 1 presents the summarized results of tensile tests. Ultimate strength and modulus are not significantly affected by addition of CNTs. The result is agreed with theoretical assumptions: tensile strength and modulus depends mainly on the longitude oriented fibers while the impact of a binder is small.

In bending tests the strength and stiffness of matrix greatly influences the final properties of CFRP/SWCNT hybrid composites. The shearing stresses occurring in interlayers of bended specimen are held by binder. Thus modification of matrix should improve flexural properties.

Table 1 - Results of mechanical testing

Specimen	**CNT, wt.%**	**UTS, MPa**	**Strain at fracture, %**	**Modulus, GPa**	**Flexural strength, MPa**	**Fracture deflection, mm**	**Flexural modulus, GPa**
CNT-0	0	601.7±18.8	6.9±0.6	9.81±0.25	493.1±1.7	2.9±0.05	48.1±1.01
CNT-1	0.1	590.8±13.5	6.6±0.2	9.84±0.18	510.4±59	3.1±0.2	49.4±1.57
CNT-2	0.2	583.5±17.2	6.4±0.1	9.58±0.36	585.1±58	3.4±0.4	52.3±1.13
CNT-3	0.3	604.6±15.3	6.3±0.3	9.71±0.23	604.9±29	3.3±0.3	55.9±2.16

Table 1 present the results of 3-point bending test. It can be seen that both flexural strength and modulus were increased by 23% and 16% correspondingly for 0.3 wt.% of SWCNT. The modification increases the flexural strength of hybrid composite, but the scatter is quite high for CNT-1 and CNT-2. Flexural modulus with increase of CNTs demonstrates a uniform growth with average scatter. The increase of flexure properties is attributed to higher shear strength of binder and adhesion between the layers after modification.

The results of conductivity measurements are presented in Table 2. Non-modified epoxy has very low electrical conductivity: less than 10^{-7} S/m. The addition of 0.1% of CNTs increases its conductivity to 0.012 S/m. Larger CNTs content results in nonlinear drastic rise of conductivity to 0.063 S/m for specimen CNT-3. The scatter for CNT-1 is about 6% while for CNT-2 – 27%. The results demonstrate the possibility of enhancing the conductivity of materials using CNTs: the dielectric epoxy after modification acquired conductive properties.

The in-plane conductivity of CFRP depends only on the surface fiber layer thus in-plane conductivity demonstrates slight increase with addition of CNTs however the CNT-0 specimen is conductive as well: 564 S/m. Quite identical results of out-of-plane through thickness and diagonal measurements along with null conductivity for CNT-0 are showing that the final electrical conductivity of hybrid CFRP in out-of-plane mode is dictated by epoxy matrix. Thus an addition of CNTs enhances conductivity in final hybrid CFRP even if it was zero. Table 4 shows electrical properties for modified and non-modified specimens measured in three directions.

Table 2 - Electrical conductivity of the specimens

Specimen	**Electrical conductivity, S/m**			
	epoxy specimen	CFRP in-plane surface	CFRP out-of-plane diagonal	CFRP out-of-plane thickness
CNT-0	$<10^{-7}$	564±319	$<10^{-5}$	$<10^{-5}$
CNT-1	0.012±0.0007 (±6%)	514±252	6.8±1.5	7±1.18
CNT-2	0.03±0.0083 (±27%)	702±228	16.1±1.5	16.3±1.02
CNT-3	0.063±0.0025 (±4%)	865±184	65.3±11.1	66.2±9.9

The investigation of CFRP modified by SWCNT was performed. The experiments were focused on the evaluation of electrical conductivity and mechanical properties. It has been shown that tensile properties are less affected by addition of SWCNT while flexural were improved. Addition of 0.3 wt.% SWCNTs results in improvement of flexural strength and modulus on 22% and 16% correspondingly. Electrical conductivity after the addition of SWCNT raised both for epoxy and CFRP. The effect of CNTs on CFRP conductivity is much higher for out-of-plane path provided by interlayer connections in epoxy binder while in-plane conductivity determined by carbon fibers and therefore it shows an ambiguous increase with large scatter. Addition 0.3 wt.% of SWCNT increases out-of-plane conductivity up to ~66 S/m while unmodified CFRP was dielectric. The proposed method for producing of hybrid composites has good potential and future research is to be linked to the development of reliable and inexpensive preparation and mixing technique and investigation of fatigue properties which are important for industrial application.

Acknowledgements

This work was performed with support of Fundamental Research Program III.23 of the State Academies of Sciences for 2013-2020 and RF President Council Grant for leading research schools NSh-5875.2018.8.