Journal of Chemical Technology and Metallurgy, 61, 5, 2026, 857-864

CANTILEVER BENDING AND COMPRESSION PERFORMANCE OF HYBRID COMPOSITE LOAD - BEARING ARMS FOR UNMANNED AERIAL VEHICLES

Stanislav Slavov[1,2], Rumen K. Krastev[2,3], Vasil Kavardzhikov[2]

[1]*Department of Mathematics, University of Chemical Technology and Metallurgy Sofia 1797, Bulgaria, stanislavslavov@uctm.edu (S.S.)*
[2]*Institute of Mechanics, Bulgarian Academy of Sciences Acad. G. Bonchev St., Bl. 4, Sofia 1113, Bulgaria, stanislavslavov@uctm.edu (S.S.); r_krastev@imbm.bas.bg (R.K.); kavarj@imbm.bas.bg (V.K.)*
[3]*National Centre of Excellence Mechatronics and Clean Technologies Geo Milev Campus, Acad. Georgi Bonchev St., Bl. 29 Sofia 1113, Bulgaria, r_krastev@imbm.bas.bg (R.K.)*

Received 30 May 2026
Accepted 20 July 2026
DOI: 10.59957/jctm.v61.i5.2026.11

ABSTRACT

Lightweight load - bearing arms for unmanned aerial vehicles require high bending capacity, sufficient stiffness and stable local compression response at minimum structural mass. This work evaluates ten hybrid composite arm prototypes combining aluminium tubes, aluminium flat bars, aluminium angles or wooden rods with foam core, flax reinforcement and internal ribs. Cantilever bending tests were carried out at 10.0 mm min^{-1} and 22.0°C, while short composite tube specimens were additionally tested in compression at room temperature. The maximum bending moment ranged from 260 Nm to 587 Nm. The highest bending moment was obtained for the five - aluminium - flat configuration with foam and flax reinforcement, whereas the highest bending stiffness, 63.5 N mm^{-1}, was obtained when the same reinforcement concept also included internal ribs. The compressive strength of the S1 - S10 tube specimens ranged from 14.7 kN to 27.5 kN. The results show that flax/foam hybridisation strongly improves bending load capacity, while ribs mainly improve stiffness and shape stability but must be designed to avoid local stress concentration. The data provide an experimental basis for selecting practical reinforced hybrid composite arms for small UAV airframes.

Keywords: unmanned aerial vehicle structures, hybrid composites, cantilever bending, compression, flax reinforcement, foam core, aluminium ribs, mechanical testing.

INTRODUCTION

Fibre - reinforced polymer composites are widely used in airframe structures because they provide high specific stiffness and strength compared with conventional metallic solutions [1, 2]. In small unmanned aerial vehicles (UAVs), tubular and beam - like arms are subjected to bending from propulsion loads, local crushing close to clamps and load introduction at joints. Increasing wall thickness is usually not an efficient solution; therefore, the structural design must combine laminate hybridisation, core materials and local reinforcements.

Hybrid composite architectures can improve damage tolerance and redistribute local stresses when different fibres or local reinforcement elements are combined within the same load - bearing member [3]. Through - thickness reinforcement and locally implanted elements are known to increase resistance to delamination and load - introduction failure, although they may also introduce manufacturing complexity and local property reductions [4, 5]. Natural fibres such as flax are attractive for lightweight composite structures because of their low density and sustainability, but their mechanical response may exhibit higher scatter than synthetic - fibre laminates and must be verified experimentally [6, 7].

The present study transforms the reinforcement concept for UAV load - bearing composite structures into an experimental comparison of practical arm configurations. Ten prototype arms containing aluminium tubes, aluminium flat bars, aluminium angles or wooden rods, combined with foam, flax reinforcement and ribs, are compared under cantilever bending. In addition, short composite tube specimens are evaluated in compression test. The objective is to identify reinforcement combinations that increase bending moment capacity and stiffness without relying only on laminate thickening.

EXPERIMENTAL

Specimen configurations

Ten prototype load - bearing arms were tested. The specimens were labelled 1 - 10 and consisted of a composite outer shell with different internal reinforcement concepts. The internal elements included aluminium tubes with outer diameter 6 mm and 1 mm wall thickness, aluminium flat bars 15 × 2 mm, aluminium angle profiles 10 × 1 mm, 6 mm wooden round rods, polyurethane foam filling, flax reinforcement and internal ribs - adjusted with the profiles shape and printed from PLA+. Representative cross - sections after cutting are shown in Fig. 1. The measured outer diameter, or the equivalent side dimension for square - like sections, its standard deviation and the distance from the force application point to the fractured cross - section are listed in Table 1.

Original drone arm tube

A specimen was cut from carbon fiber drone arm tube and subjected to cantilever bending test. It has 53.8 mm outer diameter and 50 mm internal diameter.

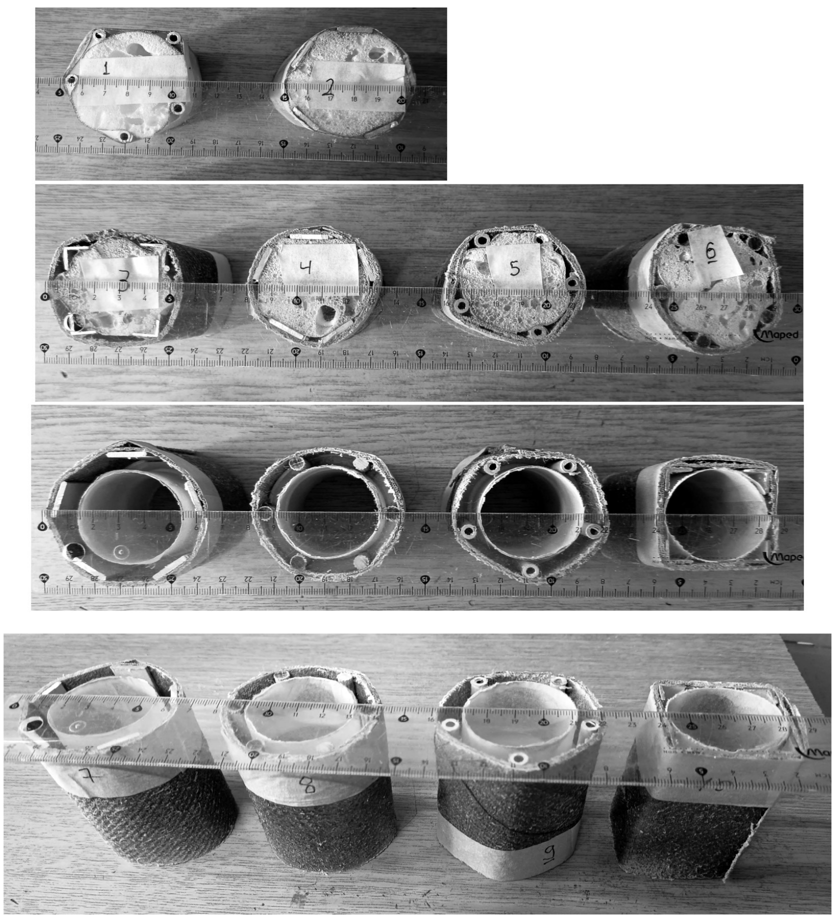

Fig. 1. Representative cross - sections of the tested hybrid composite arm prototypes showing internal aluminium, wooden, foam, flax and rib elements.

The distance from the force to the edge of a cylindrical holder was 414 mm.

Cantilever bending test

Tests were carried out on electric universal testing machine TIRAtest 2300 equipped with 10 kN load cell. The tubular specimens have at one end a cylindrical holder about 100 mm long, cast from epoxy resin. The holder was clamped to the end of a specially designed cantilever beam, Fig. 2, and there is 410 mm distance between the holder edge and the applied force. Deflection was measured using a lever device, an inductive displacement measuring sensor HBM type 1 - WI/5 mm^{-1} and a measuring amplifier HBM model MX840. The specimens were loaded at a prescribed cross - head speed of 10 mm/min, data acquisition frequency was 5.0 Hz and the test temperature was 22°C. The specimen 1 had a 70 mm clamping length, while the remaining specimens were clamped at 100 mm clamping length.

During the test, after approximately 33 mm of actuator movement, the motion was temporarily

Table 1. Geometry and reinforcement concept of the arm specimens.

Arm No.	Reinforcement concept	Diameter D, mm	L_f, mm
1	five Al tubes, foam	55.3 ± 0.7	410
2	five Al flats	56.3 ± 0.9	330
3	four Al angles + foam + flax	49.1 ± 0.7	355
4	five Al flats + foam + flax	52.1 ± 0.5	422
5	five Al tubes + foam + flax	53.2 ± 1.1	360
6	five wooden rods + foam + flax	54.9 ± 1.5	360
7	five Al flats + ribs + foam + flax	61.4 ± 1.1	400
8	five wooden rods + ribs + foam + flax	59.6 ± 1.0	398
9	five Al tubes + ribs + foam + flax	60.0 ± 1.4	384
10	four Al angles + ribs + foam + flax	50.4 ± 1.9	398

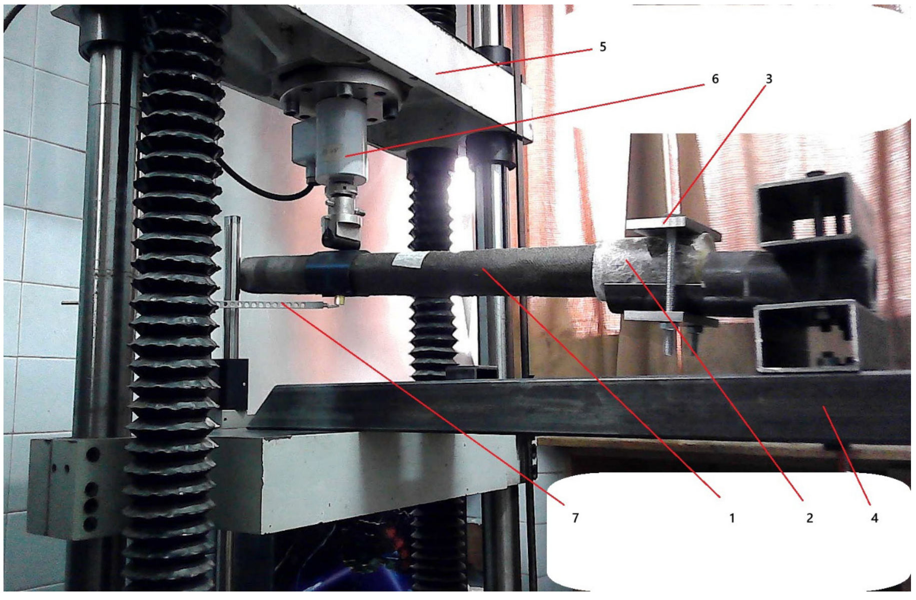

Fig. 2. Bending test arrangement. 1 - specimen, 2 - cylindrical holder, 3 - clamp, 4 - cantilever beam, 5 - movable crosshead, 6 - load cell, 7 - deflection measuring lever device (35 mm stroke).

stopped, and the lever system was adjusted for the next displacement range. The force relaxation observed during this pause was attributed to continuing damage and deformation of the specimen.

The maximum bending moment was calculated according to Eq. (1):

$$M_{max} = F_{max}L_f \quad (1)$$

where F_{max} is the maximum force in N and Lf is the distance from force application point to the fractured cross - section in m. The bending stiffness C was evaluated as the force - deflection slope in the interval 150 - 350 N. Failure generally occurred either by fracture in the tensile zone or by local crushing in the compression zone near the clamped region.

Compression test

The composite tube specimens for compression test have the same shape and designation, Fig. 1, however their initial height was approximately 78 - 81 mm and their designation contains "S" in the results section. They were tested at room temperature using a Zwick/Roell testing system in the Laboratory for Mechanical Testing, IMech - BAS/IMSTCHA - BAS. The laboratory protocol specifies ASTM E9 conditions, a preload of 200 N, a loading rate of 0.0002 s^{-1} during elastic slope determination, a yield and crushing loading rate of 0.002 s^{-1} and a linear - regression based method for elastic slope determination [8 - 10].

RESULTS AND DISCUSSION

Cantilever bending response

The bending moment - deflection curves are presented in Fig. 3, and the corresponding maximum values are summarized in Table 2. The fractured cross - section has different distances from the holder edge, which determines the different arms L_f used. Considerable differences between the arm configurations are observed. The maximum bending moment increased from 260.7 Nm for specimen 1 to 587.0 Nm for specimen 4. The five - aluminium - flat configuration with foam and flax reinforcement provided the highest bending moment, whereas specimen 7, which added internal ribs to the five - aluminium - flat/foam/flax concept, provided the highest stiffness.

The influence of foam and flax is most evident

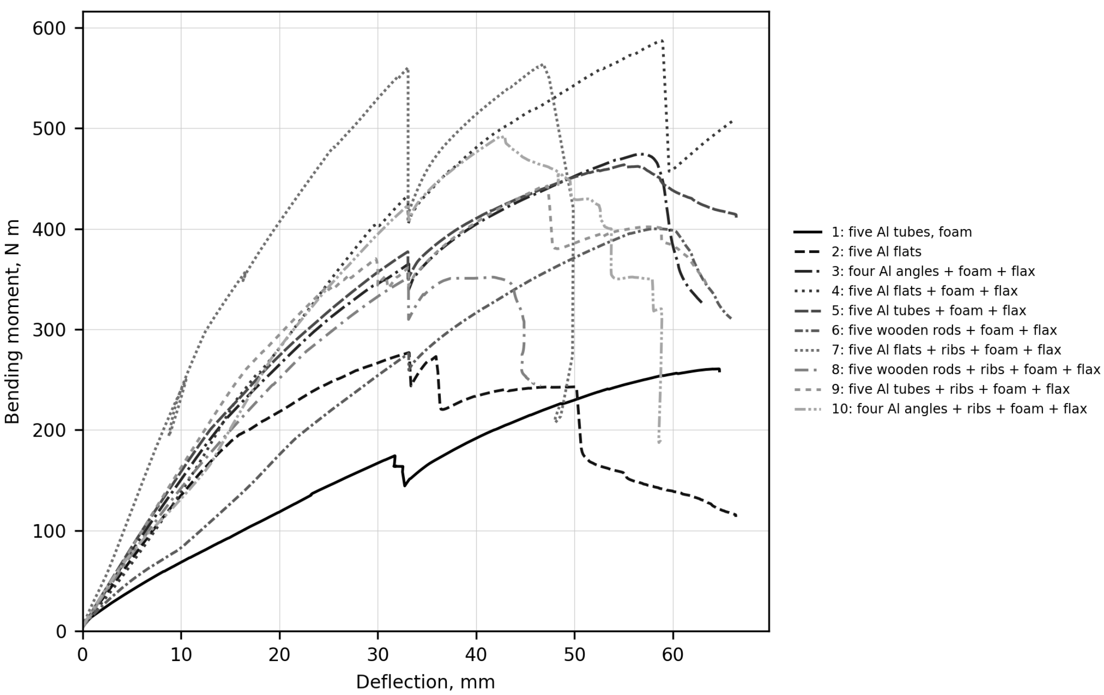

Fig. 3. Bending moment - deflection curves obtained during cantilever tests of the ten arm prototypes.

Table 2. Cantilever bending results of the tested arm specimens.

Arm no.	F_{max}, N	M_{max}, Nm	Deflection at Fmax, mm	C, N mm^{-1}
1	636	260.7	64.7	12.4
2	839	276.9	66.4	39.8
3	1337	474.5	63.2	41.1
4	1391	587.0	66.2	33.7
5	1288	463.7	66.5	42.8
6	1111	400.0	66.0	20.1
7	1410	563.9	49.9	63.5
8	884	351.9	46.6	33.6
9	1152	442.5	63.5	42.1
10	1236	492.1	58.9	27.4

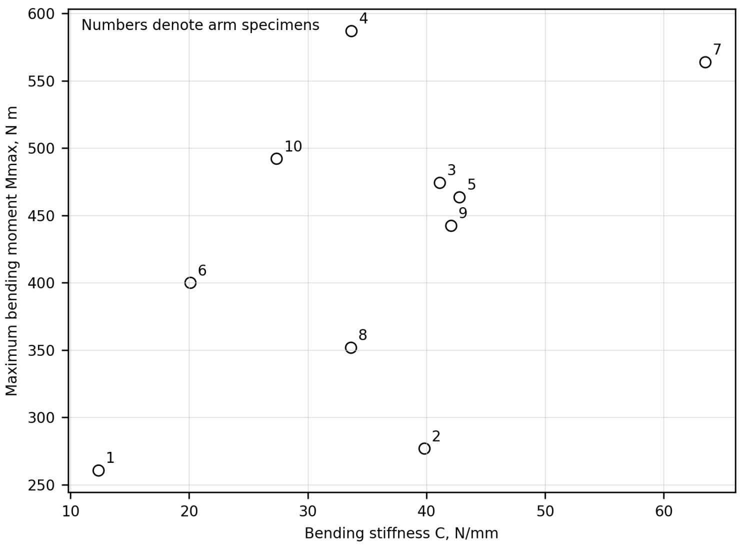

Fig. 4. Strength - stiffness map based on maximum bending moment and bending stiffness C.

when specimens with the aluminium - tube concept are compared. The specimen with five aluminium tubes and foam reached 260.7 Nm maximum bending moment and 12.4 N mm^{-1} stiffness. Adding flax reinforcement and foam increased the maximum bending moment to 463.7 N m and the stiffness to 42.8 N mm^{-1}. This corresponds to increases of approximately 77.8 % in bending moment and 246 % in stiffness. The related rib - reinforced aluminium - tube specimen retained high stiffness, 42.1 N mm^{-1}, with a maximum moment of 442.5 N m.

The strength - stiffness map in Fig. 3 shows that maximum bending moment and stiffness do not always increase simultaneously. Specimen 4 had the highest moment but a moderate stiffness of 33.7 N mm^{-1}. Specimen 7 had a slightly lower moment, 563.9 N m, but the highest stiffness, 63.5 N mm^{-1}. This indicates that ribs improve section stability and stiffness; however, the rib geometry and local bonding must be optimised to prevent stress concentration or premature local damage. Similar behaviour was observed for the wooden - rod family, where ribs increased stiffness from 20.1 N mm^{-1} to 33.6 N mm^{-1} but reduced the maximum moment from 400.0 N m to 351.9 N m (Fig. 4).

Cantilever bending of the original drone arm

The obtained diagram is shown in Fig. 5. By applying a well - known model for cantilever bending of a homogeneous tube, 215 MPa bending strength of the pipe material and 32 GPa elastic modulus were determined. As can be seen, the bending resistance of the original tube (835 N m) is higher than that of the prototype tubes (260 to 587 N m).

Compression behaviour

The compression results of specimens S1 - S10 are listed in Table 3, and the compressive strength distribution is shown in Fig. 6. The load is represented by the maximum compressive force because the samples are different and inhomogeneous.

The highest compressive strengths were measured for S4 and S8, 27.5 kN and 27.2 kN, respectively. The lowest strength, 14.7 kN, was measured for S1. Because the specimen height was consistent, with a coefficient of variation of only 1.1 %, the strength scatter is mainly attributed to internal architecture and local defects rather than to specimen length. These results confirm that compression and cantilever bending must be considered together when selecting a UAV arm concept. A configuration that maximizes bending moment can still require additional local reinforcement near compression - critical support or joint zones.

Overall, the best performance balance was achieved

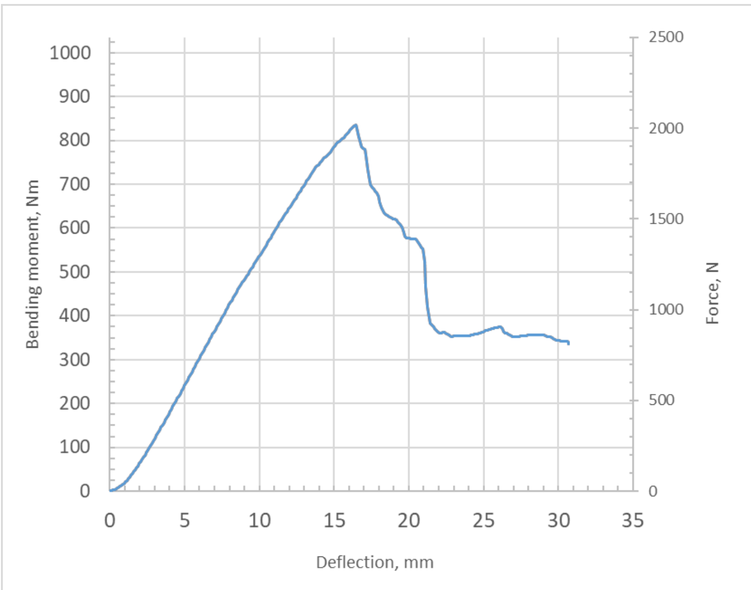

Fig. 5. Loading capacity of an original drone arm.

Table 3. Compression response of short composite tube specimens S1 - S10.

Specimen	Rigidity, kN mm^{-1}	Yield strength (0.2 %), kN	Compressive strength, kN	h, mm
S1	8.9	13.7	14.7	78.5
S2	27.0	15.3	16.8	78.5
S3	20.0	16.4	17.5	78.5
S4	26.0	26.5	27.5	79.0
S5	18.0	25.9	26.0	79.0
S6	9.4	24.8	25.0	79.5
S7	20.0	15.9	21.2	78.0
S8	16.0	23.8	27.2	78.0
S9	12.0	23.5	23.7	81.0
S10	11.0	17.3	17.3	79.0

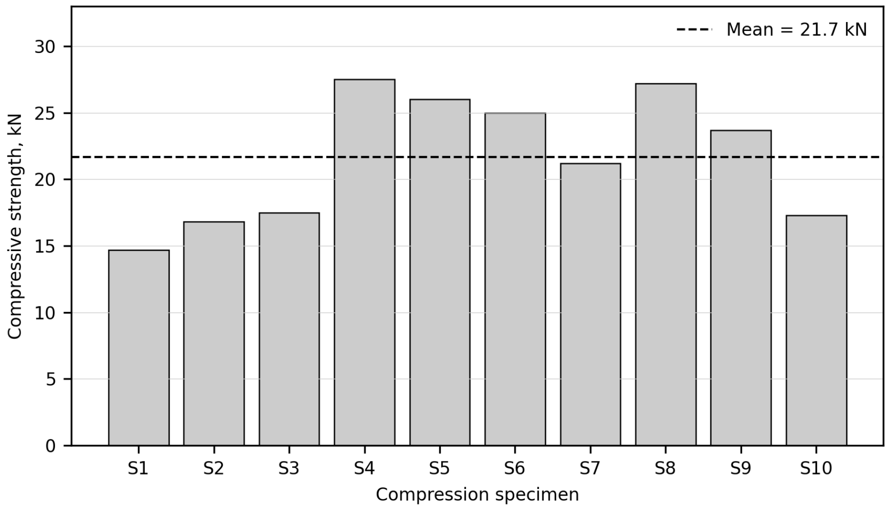

Fig. 6. Compressive strength of S1 - S10 composite tube specimens; dashed line denotes the average value.

by the configurations that combined aluminium flat or tubular elements with foam and flax reinforcement. Ribs were effective for increasing stiffness and delaying ovalisation, especially in the five - aluminium - flat family. Nevertheless, rib location and bonding should be treated as design variables, because the ribbed configurations did not universally increase peak bending moment. A mass - normalised analysis could not be performed because specimen mass was not recorded in the available experimental data; this is a necessary step for final UAV structural optimisation.

CONCLUSIONS

- Ten hybrid composite arm concepts for UAV load - bearing structures were evaluated by cantilever bending and supplemented by compression testing of short tube specimens.
- The highest maximum bending moment, 587.0 N m, was obtained for the specimen with five aluminium flat bars, foam and flax reinforcement.
- The highest bending stiffness, 63.5 N mm^{-1}, was obtained for the specimen with five aluminium flat bars, ribs, foam and flax reinforcement.
- For the aluminium - tube family, the addition of foam and flax increased the maximum bending moment from 260.7 N m to 463.7 N m and the stiffness from 12.4 N mm^{-1} to 42.8 N mm^{-1}.
- The S1 - S10 compression specimens showed an average compressive strength of 21.7 kN. Composite specimens containing aluminium flats and tubes have good compressive strength.
- Future work should include specimen mass, fatigue spectra, environmental conditioning and standardized composite flexural tests to obtain UAV - specific strength - to - weight allowable.

Acknowledgements

This publication was created with the financial support of the European Union – Next Generation EU, under Contract No. BG-RRP-2.011-0029-C03 "Development of Innovative Materials with Environmental Focus, Used for the Manufacture of Parts of Unmanned Aerial Systems (Drones) with Applications in Transport". „The entire responsibility for the content of the document lies with the INSTITUTE OF MECHANICS and under no circumstances can it be assumed that this document reflects the official position of the European Union and the Bulgarian Academy of Sciences.

Research equipment of the project № BG16RFPR002-1.014-0006 "National Centre of Excellence Mechatronics and Clean Technologies" was used for experimental work financially supported by European Regional Development Fund under "Research Innovation and Digitization for Smart Transformation" program 2021 - 2027.

Authors' contributions

S.S.: Conceptualisation, methodology, writing original draft, specimen preparation; R.K.: Bending and compressive tests, compressive specimen preparation, data analysis; V.K.: Writing and validation.

REFERENCES

1. C. Soutis, Fibre reinforced composites in aircraft construction, Prog. Aerosp. Sci., 41, 2005, 143 - 151.
2. A. Baker, S. Dutton, D. Kelly, Composite Materials for Aircraft Structures, 2nd ed., Reston, AIAA, 2004.
3. G. Dell'Anno, D.D.R. Cartié, I.K. Partridge, A. Rezai, Exploring mechanical property balance in carbon/glass hybrid composites, Compos. Sci. Technol., 67, 2007, 268-276.
4. A.P. Mouritz, Review of z - pinned composite laminates, Compos. Part A Appl. Sci. Manuf., 38, 2007, 2383-2397.
5. A.P. Mouritz, B.N. Cox, A mechanistic approach to the properties of stitched laminates, Compos. Part A Appl. Sci. Manuf., 41, 2010, 709-728.
6. K.L. Pickering, M.G. Aruan Efendy, T.M. Le, A review of recent developments in natural fibre composites and their mechanical performance, Compos. Part A Appl. Sci. Manuf., 83, 2016, 98-112.
7. O. Faruk, A.K. Bledzki, H.P. Fink, M. Sain, Biocomposites reinforced with natural fibers: 2000 - 2010, Prog. Polym. Sci., 37, 2012, 1552-1596.
8. ASTM E9 - 19, Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature, ASTM International, West Conshohocken, PA, USA, 2019.
9. S. Akbarpour, S. Hallström, Enhancing the performance of bolted joints in composites by use of patched steel or titanium inserts, Compos. Struct., 275, 2021, 114464.
10. L.J. Hart - Smith, Adhesive - bonded double - lap joints, NASA CR - 112236, NASA, Washington, DC, USA, 1973.