Design and Analysis of Carbon/epoxy Composite Bicycle Handlebar

PAUL BERE[1], MIRCEA CRISTIAN DUDESCU[2], NICOLAE BALC[1], PETRU BERCE[1], AMALIA MIHAELA IURIAN[3], OVIDIU NEMES[3]*

[1] Technical University of Cluj-Napoca, Faculty of Machine Building, 103-105 Muncii Blv., 400641, Cluj-Napoca, Romania

[2] Technical University of Cluj-Napoca, Faculty of Mechanical Engineering, 103-105 Muncii Blv., 400641, Cluj-Napoca, Romania.

[3] Technical University of Cluj-Napoca, Faculty of Materials and Environmental Engineering, 103-105 Muncii Blv.400641, Cluj-Napoca, Romania.

A simple manufacturing method to obtain bent shape tubes with variable cross-section from fibre reinforced composites with application in high performance handlebars for mountain-bicycles was used. The original procedure is able to assure constant pressure upon the reinforcement material, the result being a compact composite, good quality with an optimum reinforcement degree. Tests and analytical computations, based on classical laminated plate theory delivered the engineering constants that have been used in the finite element simulations of two important safety tests for the handlebar (bending and torsion). The experimental results obtained for lateral bending test (critical test) are in agreement with the finite element simulations.

Keywords: bicycle handlebar, composite parts, mechanical testing, finite element simulation

The fibre reinforced composite (FRC) came successfully in most domains of the global technology. Used in medical, military, performance sports, spatial domains or race cars building, these materials get to be used in our everyday life; even they have contributed significantly to the heightened performance of sports. Manufacturing of reinforced composite bicycle parts (frames, wheels, bar ends, handlebars and seat posts) has been significantly increased in the last decade. From the point of view of obtaining the tubular parts from FRP, the existent technologies mentioned in the literature is the filament winding or pultrusion [1-7].

There are few scientific articles dealing with the analysis of composite tubes as part of a bicycle. Most of the studies [8, 9] are finite element (FE) analyses of the composite bicycle frames. In recent studies Liu and Wu [10] discussed about the fibre direction and stacking sequence design for a bicycle frame made of carbon/epoxy composite laminates. Under torsional, frontal, and vertical loadings, the normal and shear stresses with respect to the principal material coordinate system of each ply have been obtained from the finite element analyses. According to the maximum stress theory and the results of strength-to-stress ratios, optimal stacking sequence under three loading tests has been decided.

The design of tubular parts must account of the material constants obtained on the same geometric shape of the structure. Usually the lay-ups design has influence upon the mechanical characteristics.

The goals of this study were to design, manufacture, characterize and test a bent tubular carbon/epoxy fibre tube with variable section used as a bicycle handlebar. The tubular element made from carbon/epoxy was manufactured in the closed mould using an internal pressure. The two important tests for the handlebar, lateral bending test and torsional security test, provided by the DIN EN 14766:2006 [11] standard were simulated by FE and for the lateral bending an experimental validation have been done. Determination of the apparent material constants corresponding to a single-layer equivalent model was done theoretically based on classical laminated plate theory. To validate the theoretical results in terms of material constants, from the same materials as for the handlebars, laminate plane samples were manufactured by vacuum forming technology and tested in uniaxial tensile test.

Experimental part

Materials and Method

The paper proposed a simple and original method for obtaining bent and variables cross-section tubular parts from carbon fibres composite materials in epoxy matrix. The case of a mountain bike composite handlebar was investigated in order to reduce its weight and to increase the mechanical characteristics.

For the handlebar manufacturing the following materials were used: carbon fibre twill fabric (200 g/m^2, 3K) for carbon look Design, UD longitudinal elastic carbon fibre hose extensible from 20 to 50 mm (HT carbon fibre 9K, 10 ends/cm, flat width, welt 3 ends/cm black double), carbon fibre hose ±45°, to 12-40 mm diameter (96 threads Toray 3K, Weave double-braid), in epoxy resin type L285 and 256 the hardener from Hexion manufacturer. The mixing ratio is 100:40 parts by weight. It was respected the work condition according to the prescription of the resin producer.

The laminate configuration of the tube is in the form of matrix. At the middle of the pipe were laminated two supplementary lay-ups to 300 mm length UD longitudinal elastic carbon fibre hose extensible both the left and right sides from the middle point.

The standard procedure to obtain carbon/epoxy tubular parts consists in using a closed metallic mould (fig. 1) made from aluminium alloy (AU 7075-T6).

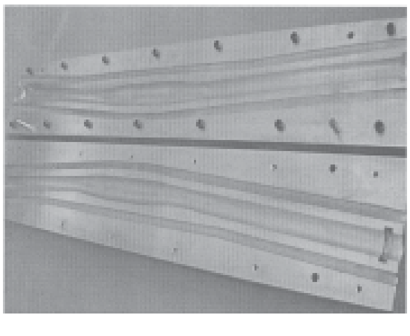

Fig. 1. The metallic mould

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* *email: ovidiu.nemes@sim.utcluj.ro; Tel: +40-(0)724.07.25.98,*

The rigid mandrel was replaced in this case by an elastic tubular element on which an internal pressure is applied. The composite material, in non-polymerization state, was deposited on the elastic element and inserted into the mould. When an internal pressure is applied on the elastic element its volume increased, so the pressing of the composite material to mould wall was realized. The mould is heated through its own plant or in heating room. After polymerization, the elastic element was removed and the composite material tube was released off the mould.

During the manufacturing process the internal pressure in the mould was kept at 6 bar (0.6 MPa) during the polymerization time. Manufacturing technologies of the composite materials usually use vacuum forming at a pressure of - 0.9 bars, equivalent of 9177 kg/m^2. The proposed manufacturing method use a 6 bar pressure equivalent to 61182 kg/m^2, that is almost 6.6 times bigger.

Easy machining is required in the separation plan area to remove the excess of resin from the surface (fig. 2).

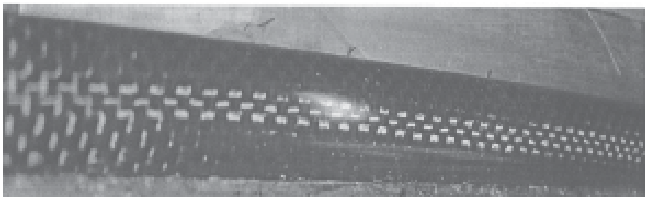

Fig. 2. Resin excess after polymerization

The fibre volume fraction is 67.33% and the final weight is 95 g at 680 mm length. The weight reduction in comparison with an aluminium alloy handlebar with similar dimensions is about 2.6 times and 7.8 times for the case of steel handlebar. The result of the proposed technology is the handlebar shown in figure 3, which actually represents a bent shape tube with variable cross-section made from carbon fibre in epoxy matrix.

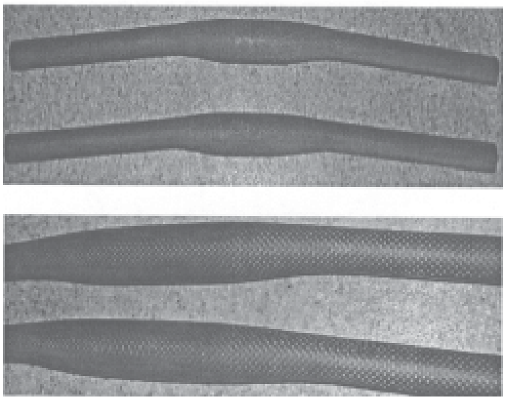

Fig. 3. Carbon fibre handlebars

Through the adopted solutions, this technology allows producing tubular parts calibrated on the outside of the used mould. The reinforced material can be preferentially oriented in the requested direction, keeping its architecture after polymerization. The result is a well compressed composite material with a uniform structure, a high reinforcement degree, and good mechanical characteristics.

Results and discussions

Theoretical and experimental approaches

Knowing the real material parameters plays a key role in a reliable FE simulation of the composite handlebar. The manufactured material is an unsymmetrical (unbalanced) orthotropic laminate, experimental identification of mechanical properties being a complex reverse engineering problem entailing several tests specifically designed for determining a given elastic constant that should be run always serially in order to reliably determine the value of that elastic constant on a statistical basis. Because of anisotropy, non-homogeneity and internal defects of the material, different testing procedures may even result in significantly different values of the same elastic constant [12, 13]. Analytical models and numerical techniques are much simpler than experimental techniques but they are often based on highly idealized conditions that may be openly in contrast with the real behaviour of the material. In the FE simulations the composite laminate has been considered a single-layer equivalent model with orthotropic behaviour characterized by a set of nine engineering constants.

Calculation of the material constants was done using a theoretically based on classical laminated plate theory software, for performing simple calculations, called The Laminator ver. 3.7. [14]. Based on single ply material proprieties and layup (stacking sequence) the software calculates the apparent laminate stiffness properties, Poisson and shear coupling coefficients and A, B, D stiffness matrices of the laminate. Table 1 shows the input data which are the material properties of individual plies according to the producer. Bi-directional ply was considered for calculation as two uni-directional layers having the half of thickness and orientation +45° and -45° respectively.

Apparent values of the material constants, corresponding to the single-layer equivalent model, obtained using the above presented stacking sequence is listed in table 2, where the subscript 1 denotes the fibre axes of the second ply.

Table 1

PLY MATERIAL PROPRIETIES OF CARBON/ EPOXY COMPOSITE

Layer / Mat_ID	*Material description*	E_1 *[GPa]*	E_2 *[GPa]*	G_{12} *[GPa]*	ν_{12}	*Ply angle [°]*	*Thickness [mm]*
1	2x2 Twill Weave	53.6	55.2	2.85	0.042	0	0.25
2	UD	181	10.3	7.17	0.28	0	1
3	UD	181	10.3	7.17	0.28	+45	0.5
3	UD	181	10.3	7.17	0.28	-45	0.5

Table 2

APPARENT MATERIAL CONSTANTS FOR THE SINGLE-LAYER EQUIVALENT MODEL

Young's modulus [GPa]		
E_1	E_2	E_3
67.7	24.61	24.61
Poissons's ratio		
ν_{12}	ν_{13}	ν_{23}
0.657	0.239	0.239
Shear modulus [GPa]		
G_{12}	G_{13}	G_{23}
11.32	9.93	9.93

Using the Cartesian coordinate 1-2-3, the constitutive equation of the orthotropic material such as the manufactured laminate is of the form [15]:

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \tau_{23}\\ \tau_{31}\\ \tau_{12}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{23}\\ \gamma_{31}\\ \gamma_{12}\end{bmatrix} \qquad (1)$$

In a condensed form the eq. (1) can be written:

$$\{\sigma\} = [C]\{\varepsilon\} \qquad (2)$$

where {σ}, {ε} and [C] are the stress, strain and stiffness matrix, respectively. The inverse of matrix [C] is a symmetrical matrix called the compliance matrix [S], which has in case of orthotropic material nine independent material constants as follows:

$$[S]=[C]^{-1}=\begin{bmatrix}\frac{1}{E_1} & \frac{-\upsilon_{21}}{E_2} & \frac{-\upsilon_{31}}{E_3} & 0 & 0 & 0\\ \frac{-\upsilon_{12}}{E_1} & \frac{1}{E_2} & \frac{-\upsilon_{32}}{E_3} & 0 & 0 & 0\\ \frac{-\upsilon_{13}}{E_1} & \frac{-\upsilon_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}\end{bmatrix} \qquad (3)$$

To validate the theoretical results, from the same materials as for the handlebars, laminate plates were manufactured by vacuum forming technology. Stacking sequence and reinforcement degree were kept the same. Five specimens in fibbers and in perpendicular directions with respect to the second ply (called in the following longitudinal and transverse sample) were manufactured from each plate and subject to uniaxial tensile tests on an INSTRON 8862 tensile test machine. The samples dimensions and test procedure were compliant DIN EN ISO 527-4 and DIN EN ISO 527-5 standards related unidirectional and multidirectional fibre - reinforced plastic composites [16-17]. The ends of the specimens were additionally reinforced with 2 mm thick, 20x35 mm tabs in order to avoid the slippage and breakage of specimens at clamping. The reinforcement tabs were made from glass woven fabric/epoxy resin reinforced composite and were fixed on the specimens with a structural epoxy glue type Scotch-Weld DP9323 A-B. Prepared specimens were loaded to break (fig. 4a), the strain values being acquired with a bi-axial extensometer. Figure 4b shown the strain-stress curves of the two types of tested specimens.

a

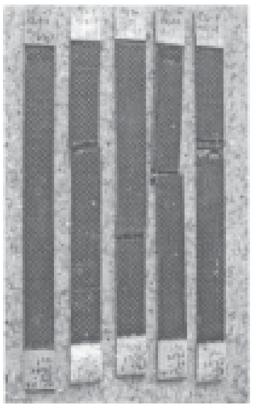

Fig. 4. Specimen tensile testing: a) Carbon/epoxy composite specimens after failure

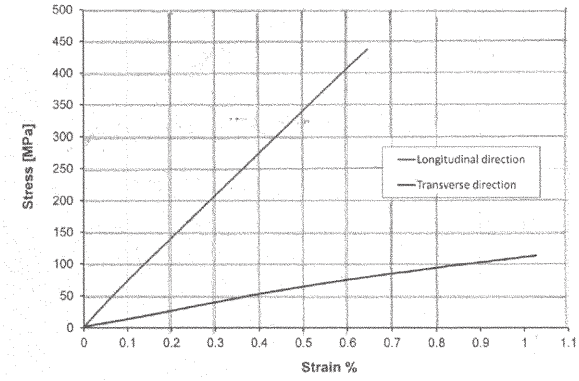

Fig. 4. Specimen tensile testing: b) Strain-stress diagram of longitudinal and transverse samples

The experimentally obtained results (mean values) are presented in table 3 and it can be noticed the good agreement with the above presented theoretical ones.

Table 3
EXPERIMENTAL MATERIAL PROPRIETIES OF CARBON/EPOXY LAMINATE.

E_1 [GPa]	E_2 [GPa]	ν_{12}	ν_{23}	σ_{u1} [MPa]	σ_{u2} [MPa]
63.1	20.91	0.659	0.261	456.4	99.5

The morphology of the structure was investigated using scanning electron microscopy (SEM) type Quanta 200 3D DUAL BEAM. The analysis of microstructure in the fracture area of the carbon/epoxy handlebar indicate monofilaments of carbon fibre, simultaneously grouped and broken (fig. 5).

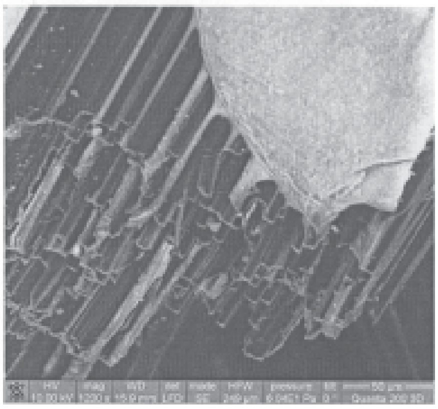

Fig. 5. Fracture area microstructure of carbon/epoxy handlebar

The particles of epoxy resin glued on the carbon monofilament indicate that connection between carbon and epoxy matrix was correct. It appears a good impregnating matrix and a good compatibility between filaments and matrix. No individual monofilaments were observed, tensile request being taken over by groups of filaments that have acted together. No defects were observed in the composite structure or the microstructure of carbon/epoxy handlebar that indicate a compact, impregnating and good pressed material.

Finite element simulation

The DIN EN 14766:2006 [11] standard provides the safety requirements and test methods for mountain-bicycles. There are two important tests for the handlebar, one called lateral bending test and one torsional security test. The finite element method and ANSYS Workbench [18] software was used to analyse the structural behaviour of the composite handlebar subject to the load cases requested by the standard. Static structural analysis and

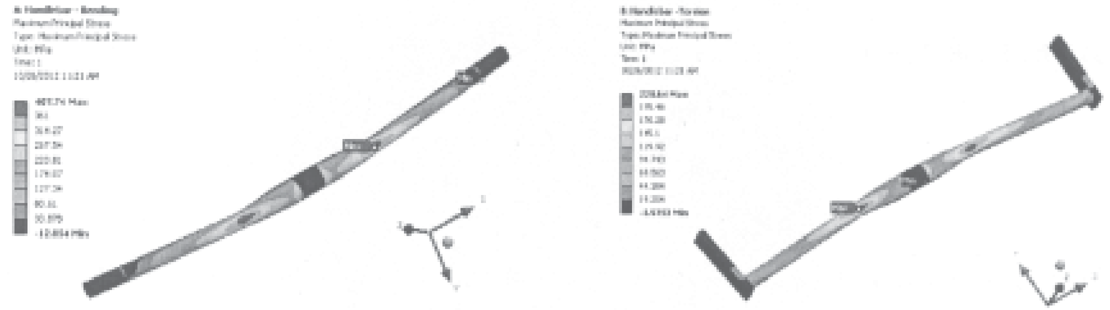

Fig. 6. Maximum principal stress distribution in the handlebar: a) lateral bending test; b) torsional security test

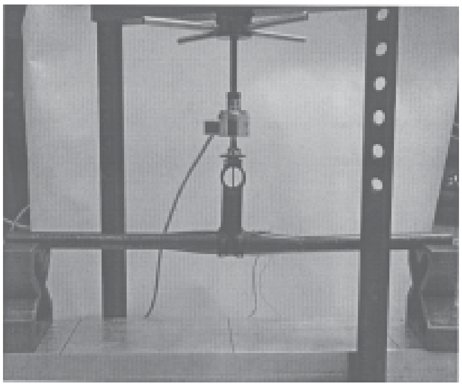

Fig. 7. Experimental set-up for handlebar lateral bending test

linear elastic proprieties were considered in this study. In the FE analyses of the handlebar the mechanical constants of orthotropic, single-layer equivalent model presented in table 2 were used. Lateral bending test presumes a static test of the handlebar-stem assembly that is permanently connected with the grips portion of the handlebar in a plane perpendicular to the stem axis. The assembly is loaded with a force of 1000 N at a distance of 50 mm from the free end of the handlebar. This force will be maintained for 1 min. The torsional security test presumes clamping of the handlebar stem securely in a fixture to the minimum insertion depth and with its axis vertical and applying a torque of 80 Nm about the centre-line of the stem-clamp. The torque is divided equally by vertically, downward forces applied to both sides of the handlebar. In figure 6 it is shown the maximum principal stress distribution of the lateral bending test (a) and torsion test (b).

The FE results confirm that the carbon/epoxy composite handlebar undergoes maximum stress values of 407.7 MPa in case of lateral bending and 220.6 MPa for the torsion test. Analysing the maximum principal stress, its direction coinciding with the direction 1 (fibres direction of the second ply), the maximum values are under the ultimate stress experimentally measured of 456.4 MPa. Maximum deflection for the lateral bending test was 11.5 mm.

Mechanical characterization

The epoxy/composite handlebar manufactured with the described technology was tested for the critical load case called lateral bending test. As presented in the simulations the torsion test produce lower stress value than the bending tests. When tested at lateral bending, there shall be no cracking or fracture of the handlebar, stem or clamp-bolt and the permanent set measured at the point of application of the test force shall not exceed 15 mm. Experimental set-up that reproduce the bending test requirements is shown in figure 7. The handlebar is simply supported and connected by clamping with a commercial aluminium stem coupled to a loading frame through a force transducer (HBM-U2B-10KN). Strain at outer surface near the clamping area was measured by a strain gauge (Vishay C2A-06-125LW-120).

Performing the test it could be noticed that the handlebar fulfil the safety requirements, being enough strength to undergo the total applied force of 2000 N. Increasing the force till failure it could be noticed that around 2100 N some fibres broke, the ultimate force being 2230 N. Broken area coincides with that obtained in the FE simulation.

The maximum loading force obtained in the experimental analysis in case of lateral bending test validates the numerical simulation and in the same time the material proprieties determined both analytically and also by the tensile test. Measured strain values were also much closed with those from the numerical simulation. The safety factor is small, the ultimate force being close to the standard requirement.

Conclusions

The proposed method allows manufacturing of the bent shape tubes with variable cross-section from fibre reinforced composites. The original procedure by using an inner pressurized elastic mandrel is able to assure constant pressure upon the reinforcement material, the result being a compact composite, well pressed with an optimum reinforcement degree related the materials used. Traditional methods that use a rigid mandrel manufacturing of bent tubes with variable cross-section as the presented handlebar could not be possible due to the fact that the mandrel cannot be released from the composite tube. The obtained handlebar has a significantly reduced weight (95 g) in comparison with aluminium alloy handlebar with the same dimensions (~250 g). Morphologic analyses revealed a good connection and compatibility between carbon and epoxy matrix. The procedure is relatively simple to put in practice and the costs are reduced.

The materials constants, experimentally obtained, an unsymmetrical orthotropic laminate, are in good agreement with the theoretical results based on the classical laminated plate theory that considered the composite material as a single-layer equivalent orthotropic model.

The FE results of the two important tests for the handlebar, requested by the safety requirements and test methods standard of mountain-bicycles, lateral bending test and torsional security test confirm that the carbon/epoxy composite handlebar undergoes maximum principal stresses of 407.7 MPa in case of lateral bending and 220.6 MPa for the torsion test. Analysing the maximum principal stress values, its direction coinciding with the fibres direction of the second ply, the maximum value was under the ultimate stress experimentally measured. Performing the lateral bending test on the manufactured handlebar test it could be noticed that the handlebar fulfil the safety requirements, being enough strength to undergo the total applied force of 2000 N. The maximum loading force obtained in the experimental analysis has validated the numerical simulation and, in the same time, the material proprieties were determined by both analytical and experimental way. The safety coefficient is small, reason why, according to the designer options, the handlebar can be strengthened by additional plies inner placed in the maximum stressed area.

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