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DESIGN AND MANUFACTURE OF BENT AND VARIABLE SECTION TUBES MADE OF FRP COMPOSITE

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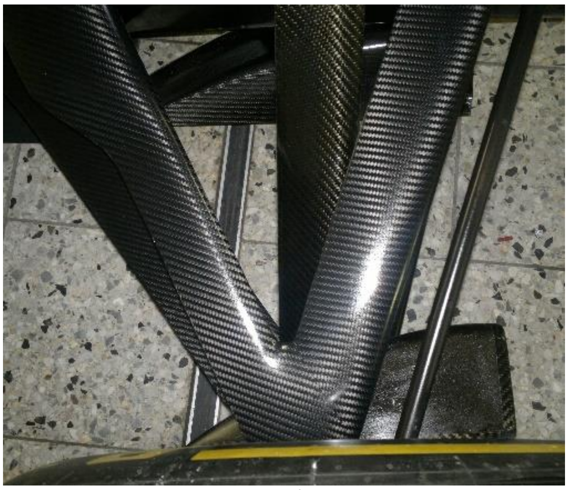
Abstract
Manufacturing of bent composite tubes with variable cross-section is a challenge. The traditional process in composite materials uses retractable mandrels that in case of inflated or bent tubes cannot be applied. The tubular composite elements are often used in high performance bicycles, in the manufacturing of frames, handlebars, saddle pipe supports, etc. This paper presents research on the design of a Mountain Bike (MTB) riser handlebar made of Fiber Reinforced Polymer (FRP). The handlebar is numerically analyzed to estimate the most suitable stacking sequence of Carbon Fiber Reinforced Polymer (CFRP) layers. Depending on the safety standard of bicycle handlebars, a case of longitudinal bending tests was numerically evaluated. Comparing the weight of the CFRP handlebar with the steel handlebar of the same shape, the mass reduction is 5.2 times. The obtained results indicate a two-fold reduction in the weight of the handlebar if it is compared to a handlebar made of aluminum alloys. The research also presents the manufacturing process of the composite mold, and CFRP tubular element. Prepreg CFRP materials are used to manufacture the handlebar, the employed technology being the vacuum bag forming and autoclave curing process.

Keywords:
Fiber Reinforced Polymer, Carbon fiber, Bent tubular part, Numerical analyses, Manufacturing method

1 INTRODUCTION

The manufacture of FRP tubes is influenced by several factors, which leads to the use of certain manufacturing processes. Tubular structures with variable and/or bent sections from these types of materials are obtained through special processes in which the composite material is pressed into a mold, which also determines the outer dimensions of the tubes. Depending on the type of demands to which the composite tube is subjected, the tracking sequence is influenced to obtain reduced masses and the best possible mechanical properties.
The applications of FRP tubes are diverse and they are increasingly used due to the reduction of their mass, special mechanical properties, and resistance to corrosion. They are used in fields such as the aerospace industry, motorsport, automotive, medicine, the chemical and oil industry, fluid transport, construction, sports, and others. Tubular composite structures with a simple geometry have specific manufacturing processes such as filament winding, centrifugal casting or forming on the mandrel/or external mold. Tubes with a complex geometry, bent or with a complex section are obtained by special procedures that are not presented in detail in the specialized literature. The applications of these particular strength and light structures are in high-performance (Fig. 1) fields and that is why the manufacturing companies do not provide this information. As applications of these structures, we can mention suspension arms (Fig 1.a), impact nose cone (Fig. 1.b), pipe for engine air intake system (Fig. 1.c) , the ventilation system for the interior of the Motorsport field, fuselages for aircraft [Sreejith 2021], tanks, structures for wings or empennages, drone's structures frame [Frulla 2008], arms for robots, frames or handlebars for performance bicycles (Fig. 1.d), ski poles, tennis racket tubular structures (columns) for civil constructions [Prabhakar 2019], and many other .
The filament winding process described is a challenging task when high winding angles are required. This study is focused on CFRP simple cone, using rowing material and wet technology. Another interesting approach for CFRP tube manufacturing is depicted by De Nicola and Jang in [De Nicola 2023] [Jiang 2020]. The authors describe a different architecture using lattice tubular structures, grid type used in space applications. Although this technology can apply to both wet layup and prepreg materials, the structures cannot be fully used in the present case where a monolithic structure is needed for the handlebar structure. Tatsuno, et al describe a method for CFRP tube manufacturing using a different method [Tatsuno 2021]. The braid-press forming method implies braiding CFRP

using thermoplastic (PA6) tapes to make a tube, which is consolidated under pressure and heat in the press forming process.



a)

b)

c)

d)

Fig. 1. CFRP tubular applications: a) Formula One suspension arms, b) Formula One impact nose cone, c) Engine ventilation system, d) Bicycle frame

The major difference between the research presented and the one in the current paper is the braiding technique used by authors, materials type, manufacturing procedure which is proper to obtain straight tubes. Regarding numerical analyses for tubular CFRP structures, an approach is given in [Siromani 2014] where a methodology was developed to study the crushing behavior and energy absorption characteristics of CFRP tubes. In the current paper, numerical analyses are focused mainly on bending behavior of the studied structures under normal bending conditions. Using braided CFRP and wet technology, the authors present in [Abad 2024] a study on the manufacture of an MTB bicycle handlebar in a metal mold. The study is focused on the vibration behavior of the bicycle handlebar, being presented the dynamic tests to which it is requested. The tube manufacturing process is like the one presented in [Bere 2014a] and uses an internal pressure of an elastic tube that presses the CFRP layers on the mold wall.
This study presents the design and manufacturing of a novel CFRP handlebar for MTB. Starting from the requests of some performance cyclists, a new shape of the bicycle handlebar was designed.
In addition to the new geometry of the handlebars, certain restrictions were imposed regarding the diameters of the ends and the middle, respectively the length of the tubular element. We also wanted the handlebar to be as light and rigid as possible. The final geometry of the tubular element was analyzed using FEA to identify the limit zones in case of bending stresses.
Based on the previous studies presented in [Bere 2014], the paper presents a new manufacturing technology of the composite mold and the CFRP handlebar.
Several architectural variants of the CFRP layers have been studied so that we have a smaller mass of the tubular element. At the same time, in choosing the final solution, the numerical analysis of the mechanical behavior and especially of the handlebar stiffness was very important. The manufacturing process involved prototyping a polyamide (PA) handlebar with a rapid manufacturing process. Using this prototype, a composite mold was made. The CFRP handlebar prototype was made in this mold according to the initial requirements of the cyclists. Prepreg CFRP materials were used for manufacturing the handlebars, and autoclave curing procedure. This study also contains a numerical analysis of the comparative masses and stiffnesses evaluation of bicycle handlebars made of Al and steel alloys with the same shape as the CFRP prototype.
The study presents several elements of novelty related to the design and manufacturing of an MTB handlebar made of carbon fiber/epoxy. Overall, the novelty lies in the comprehensive and iterative approach to designing a high-performance MTB handlebar, integrating advanced materials (CFRP), computational analysis (FEA), and direct user feedback to create a product that meets specific performance criteria.

2 DESIGN AND MANUFACTURING METHODOLOGY

2.1 Design of the handlebar

The design process started with the specific requirements and feedback from performance cyclists. This approach ensures that the handlebar meets the real-world needs and preferences of high-level users, which can lead to more tailored and optimized performance. A primary objective of the research was to reduce the mass of the tubular element. Achieving a lightweight handlebar without compromising its structural integrity or performance characteristics is a critical innovation in the design process.

Requesting the manufacture of an MTB type handlebar requires the use of special manufacturing techniques. Traditional technologies such as filament winding or spin forming cannot produce such elements because the mandrel cannot be extracted from inside the tube. It has a complex geometry, the middle part has a larger diameter, and the tube is bent. The geometry of the tube is presented in Fig. 2.

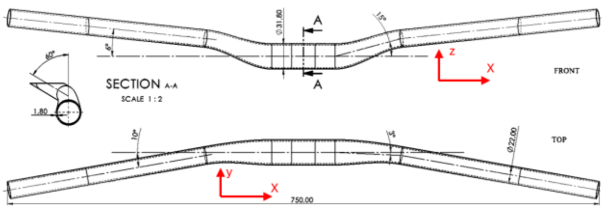


Fig. 2: CAD model of the designed prototype.

The geometric shape of the handlebar starts from the ends with a diameter of 22 mm on a length of 240 mm. This is the part where the handles and brakes are mounted. The tubular element increases its diameter up to the central area, to ø 31.8 mm, where the fixing part of the tubular shaft is. The connection between the central part and the ends is made through a variable complex geometry (from ø 31.8-ø 22) in which the tube rises along the Z axis by 70 mm. At the same time the tube is bent on the X direction by 3° and
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10° (top plane) and on Z axis by 15°, followed by a straight tube swept on the Z direction by 6° on either side (front plane). To design the handlebar prototype CAD software SOLIDWORKS 2021 was used.

2.2 Numerical analysis of the CFRP handlebar

The use of Finite Element (FE) to analyze the final geometry of the tubular element is crucial for identifying areas that need reinforcement or modification. This computational approach ensures that the design is structurally sound and performs well under expected loads.

Simulation has been used to evaluate the strength of the handlebar with different lay-ups of the composite material. We focused on meeting the safety requirements for mountain bikes outlined in the DIN EN 14766:2006 and ISO 4210-2:2023 standards. This standard specifies two key tests for handlebars: a lateral bending test and a torsional security test. ANSYS Workbench software was used to analyses the structural behavior of the CFRP handlebar subject to the first load case. The analysis considered static loading conditions and assumed the material properties followed a linear elastic model. In the FE analyses of the handlebar the mechanical constants were calculated using ANSYS Pre-Post composite module and the materials models available. The elastic constants are presented in Table 1 and represent values provided by the simulation software. A different approach is presented in [Bere 2014] where the FE was used to validate the real tests

Tab. 1: Material constants of CFRP are used in the numerical simulations.

Material constants	Epoxy Carbon Woven Prepreg	Epoxy Carbon UD Prepreg
Young's Modulus X direction (MPa)	61340	1,21e+05
Young's Modulus Y direction (MPa)	61340	8600
Young's Modulus Z direction (MPa)	6900	8600
Poisson's Ratio XY	0,04	0,27
Poisson's Ratio YZ	0,3	0,40
Poisson's Ratio XZ	0,3	0,27

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 two forces of 1000 N each at 50 mm from the free ends of the handlebar. The FE model, meshed with shell elements, has the boundary conditions presented in Fig. 3.

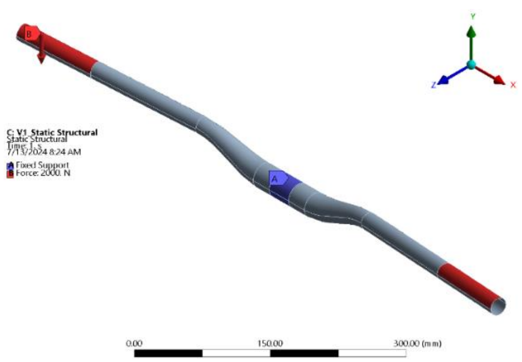
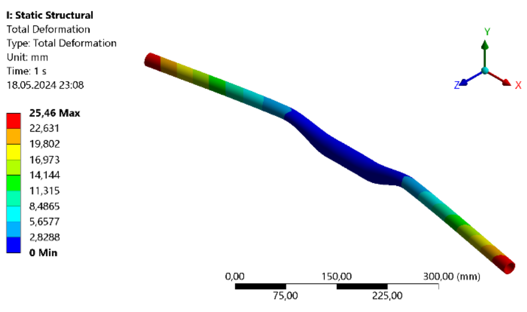


Fig. 3: Boundary conditions applied to the handlebar

Several architectural variants of the carbon fiber reinforced polymer (CFRP) layers were studied. This comprehensive investigation aimed to achieve a lower mass while maintaining or improving the mechanical properties of the handlebar, such as stiffness and strength. The maximum principal stress criterion (Rankine) was used to predict failure in designed composite materials.

The first simulated composite lay-up (V1) is a unidirectional (UD) laminate having four layers of Carbon/Epoxy of 0.45 mm thickness per layer, resulting in a total thickness of 1.8 mm and a mass of 145g. The second variant (V2) is a composite with the following stacking sequence of CFRP fabric type was: $[0/90/0_2/\pm45_2]$, resulting in a thickness of 1.8 mm and a similar mass of 144g. The results of the analyzed variants in terms of total displacements and maximum principal stress are depicted in Fig. 4. Table 2 presents a comparative analysis of the two composite handlebars.



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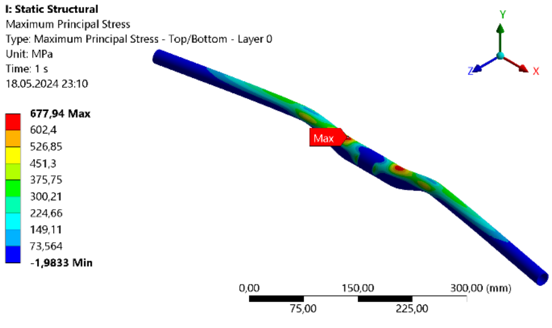

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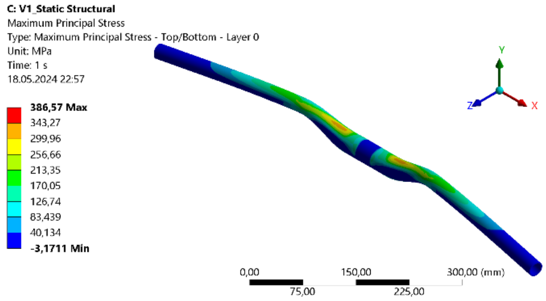

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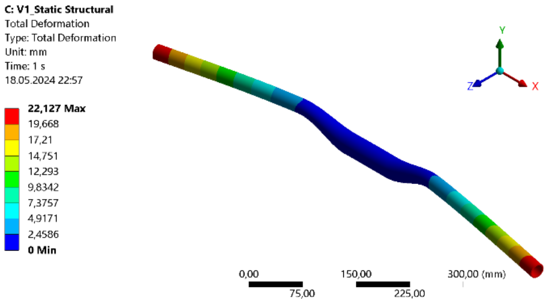


c)

Fig. 4: Numerical simulation of the CFRP handlebar: total displacements V1 (a), V2 (c) and maximum principal stress V1 (b), V2 (d).

It can be noticed that the stress values are under the ultimate tensile strength of the composite materials. The second composite architecture provided a very good strength and an increased stiffness with a similar mass. The layup with different fiber orientations ensures a better mechanical response and should be used to be manufactured and experimentally validated.

Tab. 2: Displacements and stresses for composite handlebars.

Material	Total displacement (mm)	Maximum principal stress (MPa)	Mass (g)
UD CFRP [0_4]	25.46	677.9	145
Fabric CFRP [$0/90/0_2/\pm45_2$]	22.12	386.6	144

Considering the obtained numerical results in terms of stiffness, strength and mass was decided to fabricate a composite handlebar having [$0/90/02/\pm45_2$] as stacking sequence.

2.3 Manufacturing of the CFRP handlebar for MTB bicycle

Initially, using of the CAD model of the handlebar, a prototype was obtained using the Selective Lasser Sintering (SLS) system, through the 3D Sinter Station 2000 machine. A Polyamide (PA) 6 powder was used to obtain the prototype. Due to the working space of the machine, (cylinder by 250X250 mm) the prototype was divided into 4 pieces. After manufacturing the PA handlebar parts, they were assembled, using an epoxy structural adhesive DP 9323 A-B (from 3M Company). To obtain a better roughness of the outer surface, body filler and lack layers were applied, and finally the exterior surface of the PA prototype was sanded and polished.

The next step was to obtain the composite mold. Using the Polyamide prototype of the handlebar a composite mold was made.

The handlebar prototype was fitted with a parting surface applied on the circle section generator that forms the handlebar profile (Fig. 5). Thus, the mold is formed from two half-molds. After assembling the parting surface, the other elements of the mold are mounted for alignment pins and nuts for assembly the two half-molds. They will be integrated into the composite material that will cover both the prototype and the separation plane.

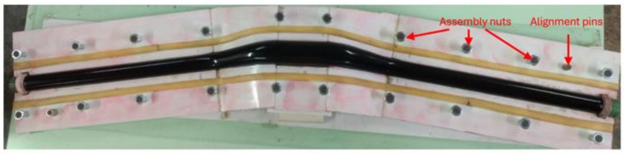


Fig. 5: Parting surface assembly in the mold manufacturing process.

After assembly of the separation plane, the surface of the prototype and the separation plane were treated with release agent according to the procedure presented in [Bere 2014]. This prevents the composite layers from sticking to the prototype and the parting plane of the mold.

Then two layers of TGL epoxy gelcoat with EPH 573 hardener were applied on the described surface, and layers of FRP for structural consolidation. Successive layers of Glass Fiber (GF) Twill type fabric by 163 g/sq two layers and 300 g/sq eight layers were used. An epoxy L 285 and L286 hardener resin type was used for impregnation of fibers. After curing the process of the GFRP layers the FRP structural material type Epopast 400, green laminating paste were applied.

At the curing process the mold was thermally treated at 100º C during 16 hours in the oven.

The cooling of the mold was done slowly together with the oven. The inner surface of the two molds were sanded and polished. Finally, 10 layers of release agent were applied to the active parts of the mold presented in [Bere 2014].

2.4 Manufacturing of the CFRP prototype

Prepreg CFRP materials were used to manufacture the handlebar. The technology to obtain the tubular structure was forming in a mold, vacuum bag technology, internal pressing with a tubular bag and autoclave curing. The materials used were: CFRP prepreg type GG245TSE-DT121H-42 for Twill layers G300X(T700)-DT121H-37 for biaxial layers and HSC-300-DT806R-33 for UD layers, from Delta Tech S.p.A. Company from Rifoglieto Italy.
The stacking sequence [0_2/0/90/±45_2]. The architecture of the CFRP layers was chosen according to the results of the numerical analysis of the demands on the handlebar imposed by the standards for bicycle elements. The CFRP layers were placed in the mold according to the sequence shown, layer by layer (Fig 6).

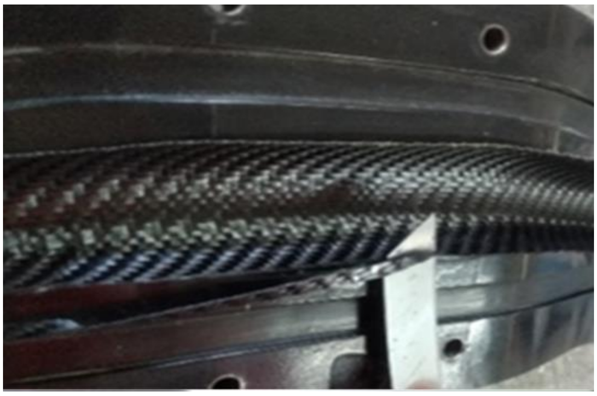


Fig. 6: Applying the CFRP layers in the mold.

Finally, the layers of biaxial material were left longer over the edges of a mold. A tubular foil was placed in the cavity of this half-mold, and the biaxial CFRP edges were bent inside the cavity over the tubular foil. Thus, the two half molds can be closed and the CFRP layers are placed in the mold cavities. The excess biaxial CFRP material is necessary to ensure the connection between the two CFRP sequences placed in the two half-molds.
After applying the CFRP layers and the tubular foil inside the handlebar, the two molds are closed. Their fixing is done with screws. The mold is covered with foil and breeder and then inserted into a vacuum bag that is sealed at the ends. It should be mentioned that the tubular film inside the handlebar must come out of the vacuum bag at the ends. Thus, the pressure from the autoclave can enter through the inside of the tubular foil and press the CFRP layers on the mold walls.

All the system mold and vacuum bag were placed in the autoclave for curing procedure. The autoclave curing steps were. Vacuum applying in all the steps at -0.9 bars. Step 1: Temperature 80º C, Pressure 4 bars for 30 min. Step 2: Temperature 120º C, Pressure 4 bars for 30 min. Step 3: Temperature 120º C, Pressure 4 bar for 180 min. Step 4: Temperature 60º C, Pressure 0 bar for 30 min.
After cooling the mold, the CFRP handlebar was extracted When the tubular element is extracted from the mold, a smooth, glossy surface without pores is observed. Burrs at the ends are removed by mechanical processing.

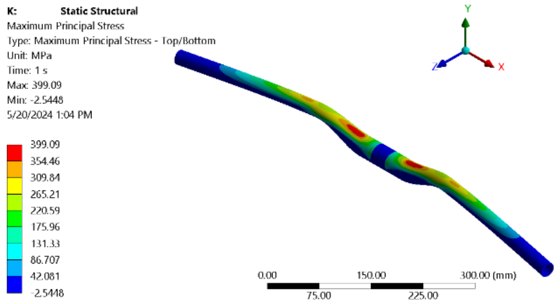
3 RESULTS AND DISCUSSION

The design of the MTB handlebar with a geometry imposed by performance cyclists led to the obtaining of complex shapes made through the CAD program. The CAD model was modified so that the middle of the surface needed for the FE numerical analysis of the standard demands on the handlebar were generated. Following the analysis carried out, an architectural version of the CFRP layers was To compare the mechanical response of the composite handlebars with similar models having the same thickness but manufactured from steel and aluminum alloy two additional simulations were run. The material constants are presented in Table 3.

Tab. 3: Material constants of metallic handlebars.

Material constants	Structural steel	Aluminum alloy
Young's Modulus (MPa)	200000	71000
Poisson's Ratio	0,3	0.33

The FE results on metallic handlebars with a thickness of 1.8 mm are presented in Table 4 and the stress distribution in Figure 7.



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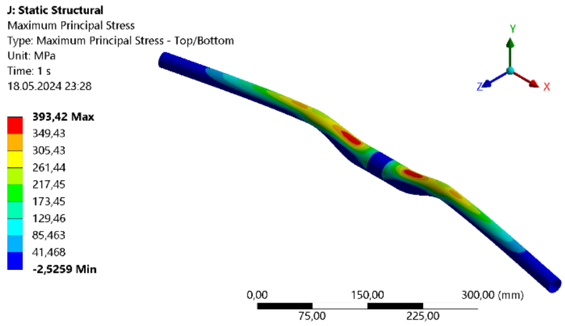


b)

Fig. 7: Principal stresses corresponding to identical loading force in: (a) aluminum alloy handlebar and (b) steel handlebar.

Is important to mention that the loading values were kept identical with the CFRP handlebar. Having the mass considerably higher it can be noticed that the strength requirements are not fulfilled for aluminum handlebar considering the tensile strength of aluminum alloy 310 MPa or exceeds the yield stress in case of steel handlebar (yield strength of 250 MPa and 460 MPa ultimate tensile strength).

The composite handlebar has a higher strength than metallic ones with the same wall thickness. For metallic variants an increased wall thickness is mandatory to ensure stress values under the material's limits.

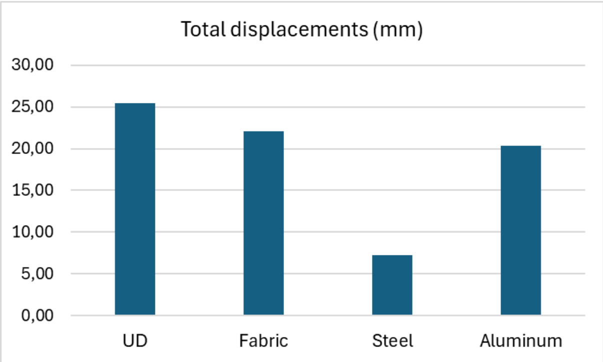
Tab. 4: Displacements and stresses for metallic handlebars.

Material	Total displacement (mm)	Maximum principal stress (MPa)	Mass (g)

Steel	7.26	393.4	764
Aluminum alloy	20.33	399.1	269

Decreasing the stress level can be achieved by increasing the wall thickness of the tubular handlebar which leads to a mass increase.

Fig. 8 presents the variation of total displacements (stiffness) and maximum principal stress for the investigated handlebars having different materials. The results support the manufacturing decision and composite layup.



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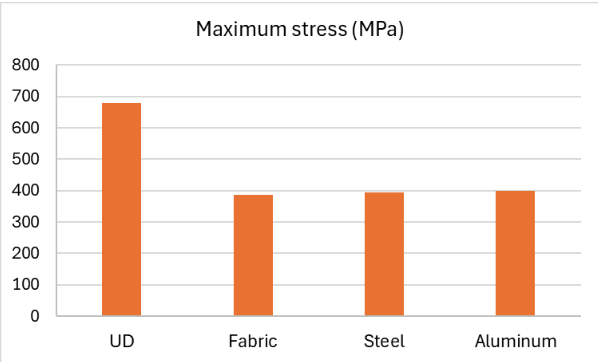

b)

Fig. 8: Comparative results between handlebars manufactured by different materials (a) total displacement, (d) maximum principal stress.

For the manufacture of the CFRP handlebar, a composite mold was made, which reduced both the manufacturing time and its cost price.

The use of prepreg CFRP materials makes the transition from classic dirty technologies (wet technology) to clean technologies friendly to the environment. At the same time the weight fraction ratio of CFRP is established by the manufacturer and has a uniform distribution in the material. For the manufacture of the MTB bicycle handlebar from CFRP, a technology with internal pressing with a tubular element was used. The curing process in the autoclave resulted in obtaining a compact composite material well pressed at temperature. The obtained MTB handlebar (Fig. 9) has a pressed structure and on the surface the porosity is not presented. The surface of the tube perfectly copies the polished surface of the mold

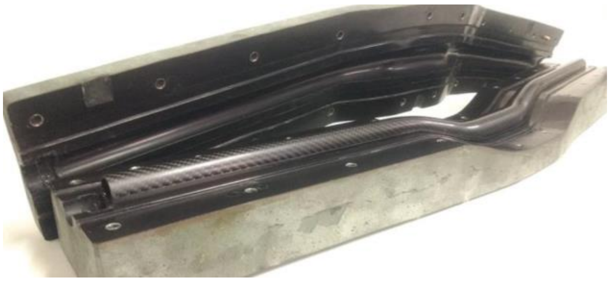

Fig. 9: The obtained CFRP handlebar and the composite mold.

From the point of view of the weight of the obtained handlebar, it has 145 g at a length of 750 mm. Through the CDA model of the designed handlebar, a simulation was made to compare this type of handlebar made of CFRP with other handlebars made of steel or Al alloy. In the case of the steel handlebar, the resulting weight was 764 g, and in the case of the Al alloy, the weight was 269 g. The mass reduction is significant in the conditions of maintaining the same wall thickness in the case of aluminum alloy. If we compare the CFRP with steel handlebar the mass reduction is 5,2 times. Can be mentioned that displacement in the steel tubular parts is 2.8 times lower.

The results of the numerical simulations led to the highlighting of problem areas for different requests. They are especially noticeable in areas where the segments change their angle with respect to the longitudinal axis. These areas can be reinforced internally with additional layers. Due to the complex requirements that can appear in this type of cycling competition, a safety coefficient can be considered so that the tubular element does not break during shocks due to potholes or rough terrain.

4 CONCLUSIONS

This paper presents the design and fabrication methodology of a new CFRP MTB handlebar for performance. The novelty of this study is the detailed presentation of the fabrication methodology of both the mold and the CFRP handlebar, which has not yet been published. The manufacturing process includes the detailed steps and materials used to obtain a bent tubular element with variable sections. Classic tube manufacturing technologies do not allow obtaining such structures.

The results of this study lead to the following conclusions:

- Prepreg CFRP materials were used and applied in a composite mold to obtain the composite handlebar. They were pressed by vacuum bagging technology and autoclave curing. There is no information in the specialized literature about composite molds that are used for high temperature curing of autoclave technologies.
- The CAD model of the designed handlebar was numerically analyzed for bending requirements as per the standard for such elements. Using FEA to evaluate the mass and stiffness of the handlebar, a comparative study was simulated between a steel handlebar, one made of aluminum alloy, and one made of CFRP.
- In the case of the CFRP handlebar, the mass reduction is 85.5% compared to the aluminum alloy one. Comparing the two handlebars, we observe the same deformation values.
- Evaluating comparatively the CFRP handlebar with the steel one, the mass reduction is 526.8%. In the case of the steel handlebar, the deformations are 3 times lower, this being the most rigid but also having a greater mass.
- For the CFRP handlebar, two variants of layer distribution were studied. The first variant noted V1 with

unidirectional layers were investigated, and the second with layers arranged at different angles of the fibers, compared to the longitudinal axis of the tubular structure. In the case of the first UD version of the layers, there was an increase in displacements by 3 mm compared to the second version, under the conditions that the handlebar mass remains constant at 145 g.

Future research will complete the study with experimental determinations related to the mechanical properties of the proposed material, and the tubular elements obtained in the composite mold. Validation of analytically obtained results with experimentally obtained values is considered.

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