BEHAVIOR OF BIKE HANDLEBARS MADE OF BRAIDED CARBON FIBRE

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ABSTRACT:

The mechanical design of a bike handlebar made of carbon fibre is presented. Usually carbon fibre handlebars are constituted by unidirectional (UD) carbon fibre prepreg. That configuration usually leads to a light design of the piece but fragile. The proposed design allows the handlebar to withstand as high efforts as a steel bar could. On the contrary the carbon handlebar presents a weight much lower. This can be achieved thanks to the selected carbon braiding. Design, manufacturing on cheap PolyLactic Acid (PLA) 3D printed moulds, FEM calculation and testing of the developed carbon fibre handlebar are shown in this paper.

Keywords: handlebar, carbon fibre, numerical simulation, test, braiding

1. INTRODUCTION

Handlebars for bikes made of carbon fibre are important components of the bicycle overall structure [1]. Carbon fibre is a popular constitutive material choice for handlebars due to its strength, light weight, and vibration-damping properties. Handlebars made of carbon fibre [2] offer several advantages over traditional aluminium or steel handlebars.

One of the main benefits of carbon fibre handlebars is their weight. Carbon fibre is much lighter than other materials commonly used for handlebars, which can help to reduce the overall weight of the bike [3]. Therefore, the bike is easier to handle and manoeuvre, especially during climbs and other challenging riding tricks or situations.

Another advantage of carbon fibre handlebars is their high stiffness. Carbon fibre is an extremely strong and rigid material, which means that it can resist bending under heavy loads. This can provide a more stable and responsive ride, especially during high-speed descents or aggressive cornering.

Finally, carbon fibre handlebars offer excellent vibration-damping properties. The material can absorb and dissipate vibrations that would otherwise be transferred to the bicyclist hands, arms, and shoulders. This fact implies a reduction of bicyclist fatigue and discomfort during long rides and can improve the overall ride quality.

Altogether, carbon fibre handlebars are a great choice for cyclists looking to optimize their bike performance and ride quality. However, it is important to note that carbon fibre components can be more expensive than those made of traditional materials and may require more careful handling and maintenance to avoid damage or failure.

In this paper, the mechanical design of a carbon handlebar is presented. Usually carbon fibre handlebars are constituted by unidirectional (UD) carbon fibre prepreg. That configuration usually leads to a light design of the piece but fragile. The proposed design allows the handlebar to withstand as high efforts as a steel bar could. That is because of the selected carbon braiding. As far as we are concerned no handlebars are made of braided carbon fibre. A new design based on braided carbon is presented. Braiding is a textile technique which ensure a full fibre continuity throughout the full length of a fabric. That would improve security of users allowing them to come back home in case of crash. The braiding technique will allow the handlebar to behave as a metal piece with the carbon fibre weight advantage. Design, manufacturing on cheap PolyLactic Acid (PLA) 3D printed moulds, FEM calculation and testing of the developed carbon fibre handlebar are shown in this paper.

2. DESIGN

There is an infinite number of possibilities applicable to a new handlebar design, depending on the type of cycling, each one with its corresponding shape, size and weight [4,5]. The handlebar should not be considered as one of the accessories for bicycles, but as a main component of this, since they are the key piece in the bike manoeuvring and cyclist position. It could be highlighted:

● Straight or flat handlebars, common on all-terrain or gravel bikes. It can also be found on mountain bikes. They have high control over the bike, by having a posture wider and higher.

● Dropbar handlebars, with two downward bends extending from the grip zone.

● And bullhorn handlebars, similar to the previous ones, but with the end zones ascenders in place. Both used mainly on road bikes, favouring an aerodynamic and comfortable shape for the cyclist.

● Double height handlebars, they are the most widespread. In these handlebars, the central part lies closest to the bike frame, while the sides are slightly elevated.

The riser bar by and large is a versatile option that offers to bicycle riders the possibility of adapting to different terrains. This is the reason why it is used both in mountain as in city bikes. As a matter of fact, this study focuses on this type of handlebar. Its manufacturing process was developed as the first step.

The handlebar used for this paper is based on a commercial handlebar, shown in Figure 1, of a popular sports store**¡Error! No se encuentra el origen de la referencia.** [5]. It is a MTB/gravel Bicycle Handlebar with the following characteristics:

- Length: 620mm.
- Stem diameter: 25.4mm.
- Diameter at the ends: 22mm.
- Material: steel
- Height: 50mm.
- Back camber angle: 6°
- Top bend angle: 5°
- Weight: 540g. (official). Actual weight is 630g.
- Thickness: 2.25mm (at the ends)

Bearing in mind design, thickness, and weight of some other handlebars commercially available an initial design of 4 layers of braided carbon fibre was considered.

The main reasons for such design are the shown bellow:

- Braided carbon fibre is very well known at University of Zaragoza [6,7]

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- The application of braided carbon fibre would allow the handlebar to behave as a handlebar made of unidirectional (UD) carbon prepreg, but having a substantially better transverse mechanical properties.
- This configuration will allow the handlebar to withstand efforts without a catastrophic failure as unidirectional (UD) carbon pieces use to behave.

Such initial decision of applying 4 braiding layers must be supported by a FEM [8] analysis of the handlebar that has to be previously carried out.

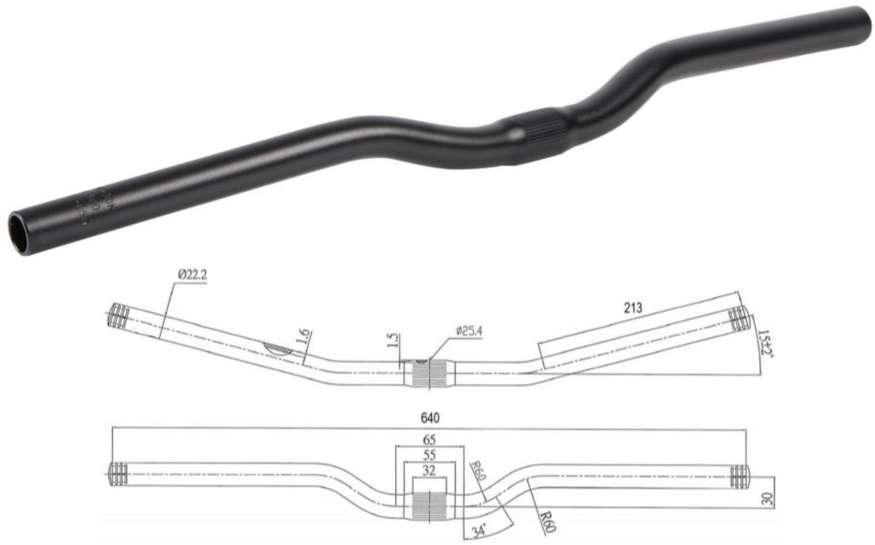

Figure 1. Steel handlebar [5].

3. MATERIALS AND MANUFACTURING

3.1 CARBON FIBRE BRAIDING

Only a carbon fibre material type was used for manufacturing. Material models representing the braided composite materials behaviour were obtained from the test results carried out by the University of Leuven [9] and from backup results carried out in 2023 at University of Zaragoza.

Mechanical and physical properties of the applied braided carbon fibre that are the following:

- Carbon fibre Braid (12K):

Braiding yarns: 12K

Braiding angle +/- 25°

Resin was Greenpoxy33 + SD4770

Fibre volume was measured as a 45%.

Elastic properties and 1st ply failure				
Property	**unit**	**value**	**Property**	**Value**
E_{11}	MPa	76100	X	680
E_{22}	MPa	18100	X’	540
G_{12}	MPa	12700	Y	100

μ	-	0.18	Y’	80
Density	kg/m^3	1560	S_{12}	125

Table 1 Carbon Fibre Reinforced Plastic (CFRP) braiding mechanical properties [9].

Being:

X: tensile strength axis 1.

X’: compressive strength axis 1.

Y: tensile strength axis 2.

Y’: compressive strength axis 2.

S_{12}: interlaminar shear strength.

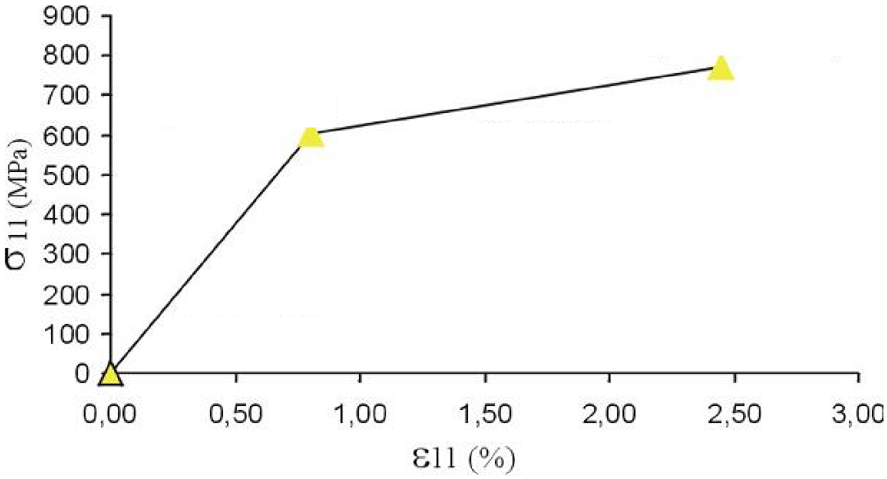

Figure 2. σ_{11} *vs* ε_{11} *behaviour of braiding [9]*

Figure 3.

Braided carbon/epoxy specimens are subjected to ASTM D 3039/D 3039M in order to experimentally measure elastic moduli and tensile and compressive strength in both longitudinal and transversal direction. Five test repetitions were performed in order to obtain the mechanical values in this work as the average of the bunch of samples, achieving a 5% of deviation in terms of stiffness and a 10% of deviation in terms of strength.

Figure 2 shows a first point corresponding to the first ply failure of the braided carbon fibre (680 MPa). However, bearing in mind that applied carbon fibre braiding includes 25º/30º carbon orientation, there is a second section. Therefore, the stress-strain function in longitudinal direction is represented as a bilinear curve model material.

3.2 MOULD MANUFACTURING

The applied mould was made by 3D printing and presents a common shape similar to other handlebars.

It is possible to use 3D printing to create moulds for composites. 3D printing allows the production of intricate and customized moulds quickly and efficiently. These moulds can be used in the fabrication of composite parts by applying the composite materials to the mould and allowing them to cure or solidify. By 3D printing moulds, you have the advantage of designing complex geometries and internal structures that are not really difficult to achieve with traditional mould-making methods but expensive. This flexibility enables the production of lightweight and optimized composite parts. It is important to consider the materials used for 3D printing of the moulds [10,11], as they should be able to withstand the temperatures and pressures involved in the composite manufacturing process. 3D printing moulds for composites can streamline the manufacturing process, reduce costs, and enable the production of experimental or prototype composite parts.

3D printing moulds for composites using PLA (polylactic acid) is a common and accessible method. PLA is a widely used filament material for 3D printing due to its affordability and ease of use. However, it has limitations when it comes to high-temperature applications. When using PLA for composite moulding, it is essential to consider the operating temperature of the composite material and the demoulding process. PLA has a relatively low glass transition temperature (around 65°C), which means it may soften or deform when exposed to higher temperatures. To overcome this limitation, several strategies can be applied. This current mould has been enhanced by covering all of it by a protective coat of epoxy resin instead of gelcoat barrier. That was due to a bad experience with gelcoat. First attempts to cover PLA mould with gelcoat led to delamination of gelcoat from mould. Therefore, an epoxy coat was selected and no further problems raised.

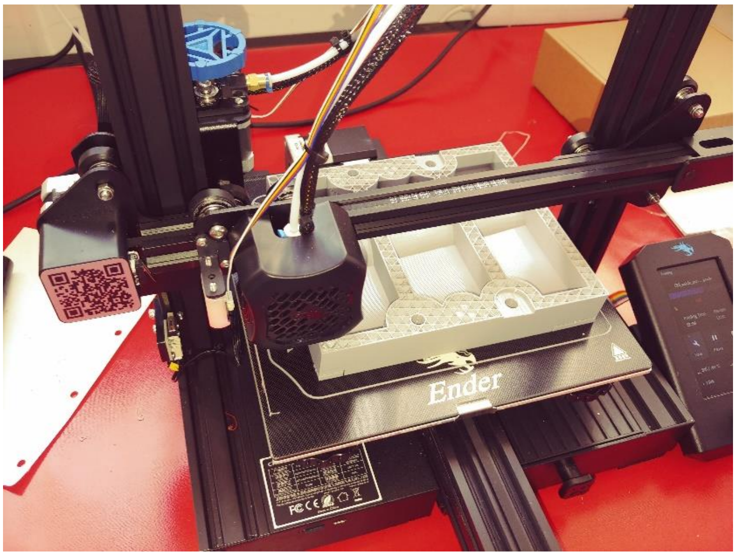

Figure 4. Manufacturing of PLA mould.

Also bottom parts were reinforced with carbon fibre layers and fibreglass, as shown in Figure 5, in order to achieve a relatively high stiffness, specifically taking into account demoulding. Also because of the manufacturing in four parts of each valve of the mould due to length limitations.

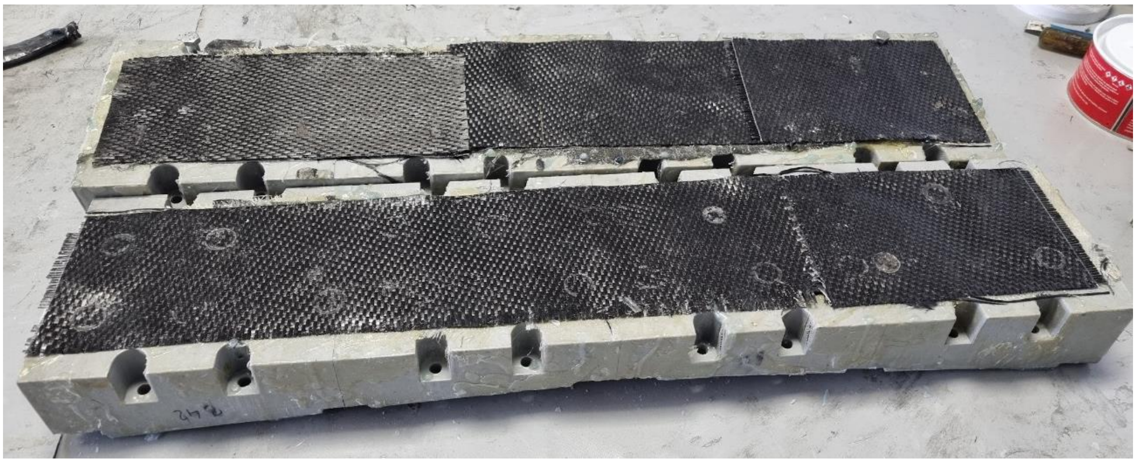

Figure 5. Carbon reinforcement on the bottom part.

The choice between PLA and aluminum moulds depends on the specific requirements of the project. PLA moulds are cost-effective for rapid prototyping and simpler applications, while aluminium moulds are more suitable for high-temperature processes and situations where durability is crucial, despite the higher initial costs and potentially longer construction times. The decision should consider factors such as project budget, expected production volume, mould lifespan, and required precision. Table 2 perfectly summarizes this dilemma between metal mould options and PLA

Material	cost	lead time	durability
Aluminium	2200€	25 days	1500-2500 pieces
PLA by FDM	200€	4 days	25-50 pieces

Table 2 Cost benefit analysis.

3.3 HANDLEBAR MANUFACTURING

To carry out the manufacturing process of a handlebar, first of all, the carbon fibre braiding should be cut using the mould as a reference. All layers should be unrolled in order to put the internal bag for positive pressure compaction. Each layer is wetted out by hand lay-up once the bag is placed. Once all layers are wetted up mould is closed and bag is inflated up to 2 bars. Pressure is critical in order to achieve a good fibre percentage and compaction. Also is a key issue in order to shape correctly mould curves. Pressure bag is made of 80% Rubber - Isobutylene-isoprene rubber (IIR) - Butyl, 20% or 90% IIR. Usually there is no need to use wax or any demold agent and internal bag can be easily taken out.

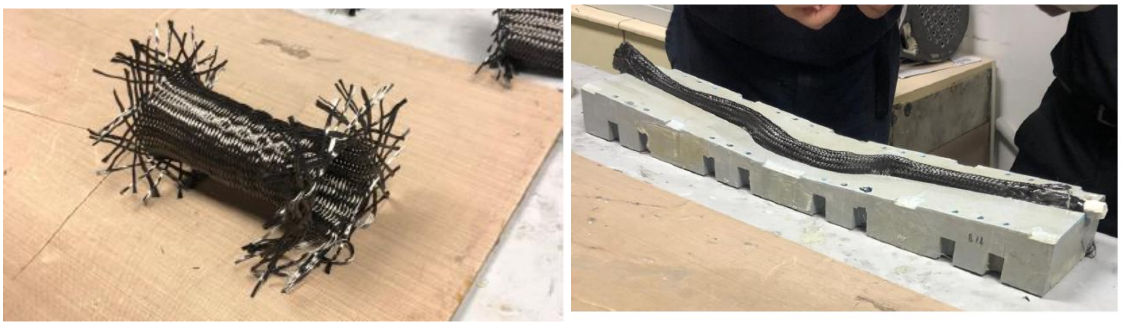

Figure 6. Manufacturing of braided handlebar.

Figure 7. Final handlebar.

Handlebar final piece is quite good in terms of finish and wetting, shown in Figure 7. Problems might raise from low pressure essentially.

4. NUMERICAL MODEL AND FEM CALCULATION

FEM calculation of handle bar was the first step in the development of this project. Firstly, the handlebar design had to fulfil the strength requirement. However, stiffness was not taken into account as an initial target. Two main options [4,5] were considered as the requirement in terms of strength. A target load of 2000-2500N applied at each one the handlebar extremes had to reached previously to first ply failure. That load value for first ply failure was considered high enough, bearing in mind that in combination with bilinear carbon braiding behavior, not showing fragile failure, would allow the bicyclist to come back home without a catastrophic failure [12-14] of the handlebar. Therefore, bike would be fully functional after initial failure even to continue cycling without problems. No matter handle bar should be replaced afterwards. That was the key point for this new design. Typical load cases can be observed in EN 4210-5:2014 [15]. As Blanchard and Sobey [16] consider fatigue testing for their handlebars, the option for the authors was to consider carbon fibre as a fatigue resistant material [17], being the design peak load below 70% of peak load producing first ply failure. It is considered that this statement will ensure a long term behavior [18].

As first approach, Hashin [12,13] damage initiation criteria was selected to model behavior of carbon braiding in terms of failure. This model is not absolutely correct for such simulation but it would give a rough and cheap estimation for the handlebar in terms of strength. A much more complex bilinear model should be needed to model correctly such behavior. FEM calculations have been performed using Abaqus® [5] as core solver and MSC Patran® as preprocessor.

4.1 HASHIN

The applied damage initiation criteria for fibre reinforced composites are based on Theory of Hashin [12,13]. These criteria consider four different damage initiation mechanisms: fibre tension, fibre compression, matrix tension, and matrix compression.

The damage initiation criteria have the following general forms:

$$\frac{1}{X_{\varepsilon T}}\left(\varepsilon_{11}+\frac{\nu_{f12}}{E_{f11}}\cdot m_{\sigma f}\cdot(\sigma_{22}+\sigma_{33})\right)\geq 1 \qquad \text{Ecc. 1}$$

$$\frac{1}{X_{\varepsilon C}}\left(\varepsilon_{11}+\frac{\nu_{f12}}{E_{f11}}\cdot m_{\sigma f}\cdot(\sigma_{22}+\sigma_{33})\right)+(10\cdot\varepsilon_{12})^2\leq -1 \qquad \text{Ecc. 2}$$

$$\frac{1}{{Y_T}^2}(\sigma_{22}+\sigma_{33})^2+\frac{1}{S_T^2}\left(\sigma_{23}^2+(\sigma_{22}\cdot\sigma_{33})\right)+\frac{1}{S^2}\left(\sigma_{12}^2+\sigma_{13}^2\right)\geq 1 \qquad \text{Ecc. 3}$$

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$$\frac{1}{Y_C}\left[\left(\frac{Y_C}{2S_T}\right)^2-1\right](\sigma_{22}+\sigma_{33})+\frac{1}{S_T^2}\left(\sigma_{23}^2+(\sigma_{22}-\sigma_{33})^2\right)+\frac{1}{S^2}\left(\sigma_{12}^2+\sigma_{13}^2\right)\geq 1 \quad \textit{Ecc. 4}$$

The effective stress tensor is used to evaluate the damage initiation criteria. This tensor is computed from:

$$\sigma = E_d \cdot \varepsilon = E_0 \cdot (1-d) \cdot \varepsilon \qquad \textit{Ecc. 5}$$

Damage, *d*, are variables that characterize fibre, matrix, and shear damage, corresponding to the four modes previously discussed, as follows.

Before any damage initiation and evolution occurs the damage operator is equal to the identity matrix. Once damage begins and evolves the damage operator becomes significant. The effective stress is intended to represent the stress acting over the damaged area that could withstands internal forces.

A value of 1.0 or higher for the damage operator shows that the initiation criterion has been fulfilled.

To decrease mesh dependency during material softening, it is possible to introduce a characteristic length into the formulation, so that the constitutive law is expressed as a stress-displacement equation. The positive slope of the stress-displacement curve prior to damage initiation corresponds to linear elastic material behavior; the negative slope after damage initiation is achieved by evolution of the respective damage variables.

4.2 FEM CALCULATION

FEM calculation has been developed in a nonlinear way due to the possible complexity of calculation, given that this calculation encloses large displacements and degradation of material.

Six different sections are needed in order to match braiding orientation [6] on handlebar. Stem and testing supports were modelled together due to the existent nonlinear behavior. That is to say, if stem and supports were neglected, then displacements would be lower than real. On the contrary, extreme sections of handlebar were considered as fully elastic.

Boundary conditions were considered as follows:

- Fixed and vertically displacement restriction on the base of testing support.
- Distributed load at both extremes of handlebar.

Handlebar was divided into two sections, central part and lateral parts. Central part encloses 40% of the straight part of handlebar.

Finally, two options were calculated.

Design 1

4 layers central part 4.2mm thickness

3 layers at the rest of the handlebar length, 3.15mm

Weight: 136 gr

Design 2

5 layers central part 5.25mm thickness

3 layers at the rest of the handlebar length, 3.15mm

Weight: 160 gr

4.3 FEM RESULTS

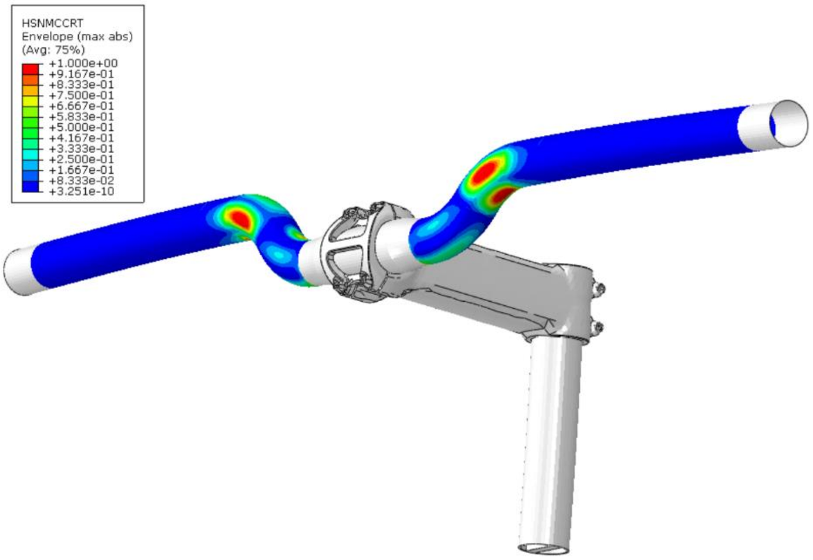


Figure 8. Design 1 before failure Hashin's matrix compressive damage initiation criterion.

Initially, It was expected that central and extreme sections where loads and boundary conditions were applied were not to beconsidered for degradation in order to avoid mathematical stress concentrations. However, once results were plot, it was checked that it was a wrong assumption.

This fact was fully corroborated by testing, given that extreme sections were not damaged under loading brackets and the central part attached to the stem was not damaged at all. A stress concentration can arise in the central part just in case of a high torque on the stem bolts. If torque is beyond 5Nm carbon might fail due to that excessive torque.

FEM results in terms of Force-Displacement for both handlebar designs are quite similar, showing around 2KN of maximum force before first ply failure.

5. MECHANICAL TESTING OF HANDLEBARS

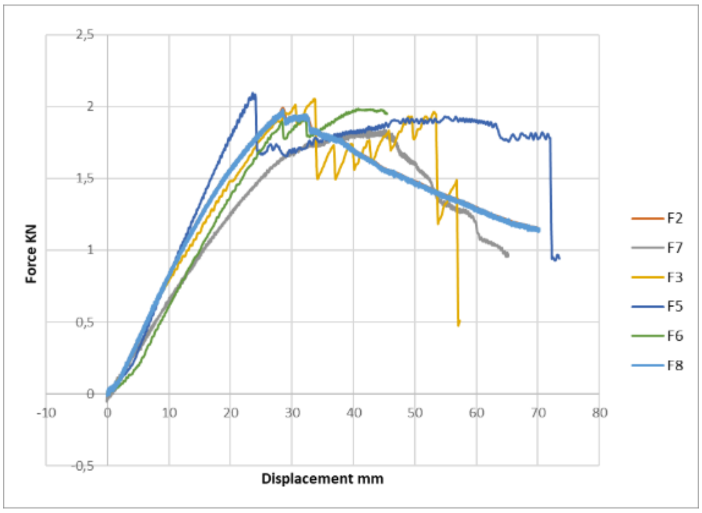
A stem with appropriate tooling was manufactured in order to perform testing. Handlebars were attached to the stem with 5Nm torque and fixed by means of hydraulic clamps. As shown in Figure 9 an Instron 8032 testing machine was used. Figure 9 shows the three point testing arrangement for the handlebar.

Figure 9. Testing setup.

2.5mm/min velocity was applied to the samples as far as complete failure was reached.

In addition to presenting the results for both designs, this article includes a comparison with a similar handlebar manufactured from unidirectional carbon fibre (UD). The commercial handlebar in question weighs approximately 130 grams, a weight closely resembling the handlebars discussed in this article. The primary distinctions lie in the angles of the sides and the length of the central part.

5.1 BRAIDING TESTING RESULTS



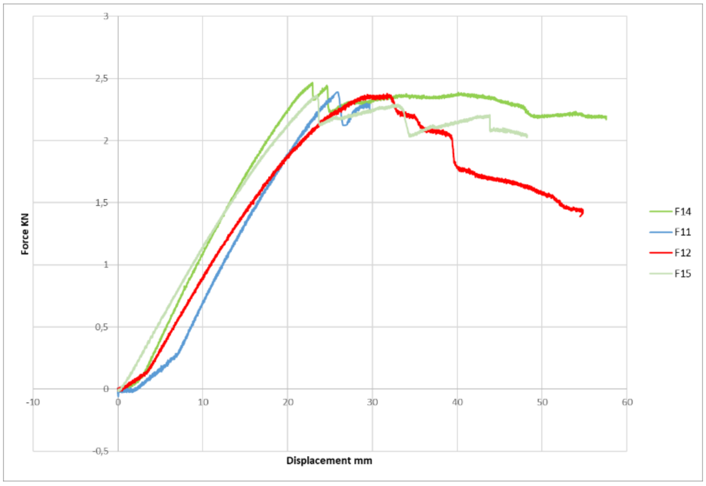


Figure 10. Option 1 and option 2 Testing Force-Displacement curves.

Ten samples were manufactured following the design 1 specification, and five for design 2.

Six out of the ten design 1 handlebar samples and four out of the five design 2 handlebar were tested. Some of them were reserved for further testing and actual evaluation on bicycle.

Both designs behave in a similar manner. First ply failure leads to a peak around 2KN and 2.5 KN for design 1 and 2 respectively. Once the maximum peak is reached handlebar continues withstanding load as far as final failure. Design 1 and 2 use to fail in the curve shown in Figure 13. Secondary failures use to occur in the symmetric curve. Once both fail handlebar continues to withstand load as far as all layers fail. Design 1 use to fail catastrophically in the laminate joint of zone1 and zone2, whereas design 2 does not fail in such part and testing is stopped due to time issue. Sample F11 behave in the same way but data record stopped at 30mm.

5.2 UD-BRAIDING TESTING RESULTS

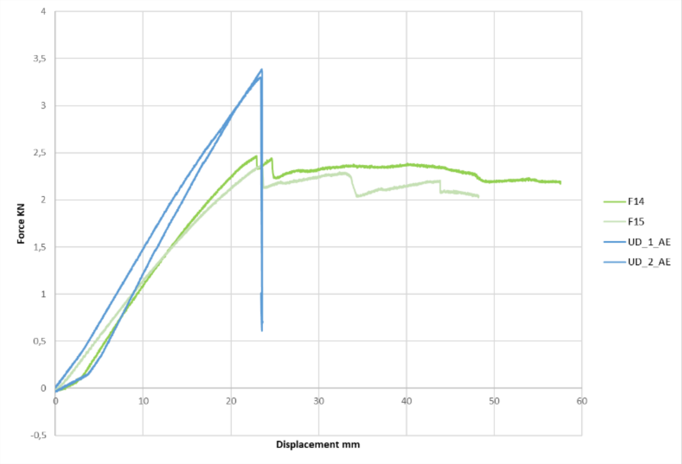


Figure 11. UD vs braiding testing.

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The commercial UD handlebars exhibit failure closer to the center and reach higher load values. However, these elevated values are not pertinent in the context of comparing them to the braided handlebar. The objective of this comparison is to highlight the inherently fragile behavior of the UD handlebar. Only two handlebars are depicted in the figure to provide a clear representation of their behavior. Samples F14 and F15 are compared against the commercial UD handlebars UD_1_AE and UD_2_AE and shown in Figure 11.

6. NUMERICAL-TESTING CORRELATION ANALYSIS

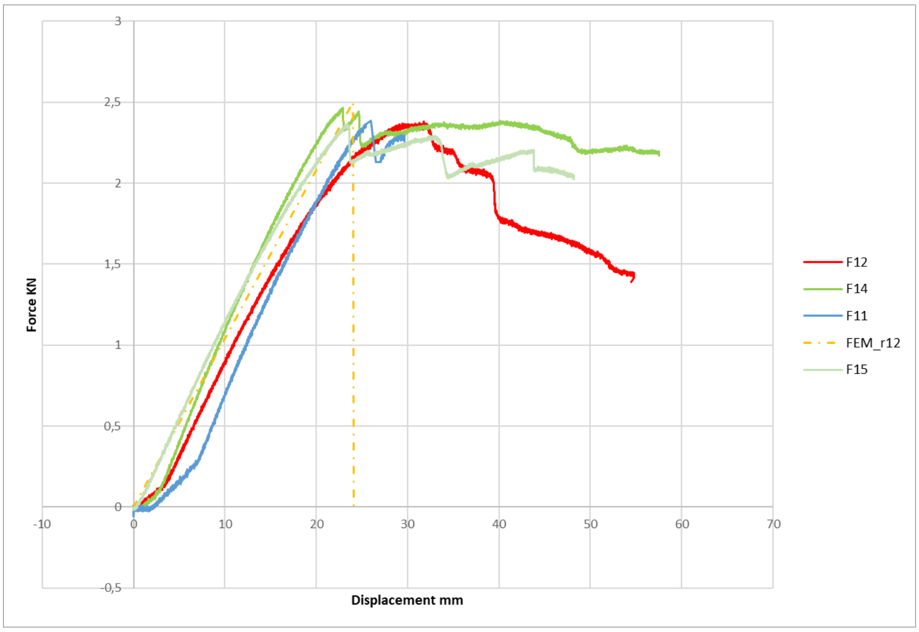

Figure 12. Design 2 Comparison numerical – experimental.

Correlation between experimental and numerical results in terms of Force-Displacement curves for both design 1 and 2 is very high until first ply failure takes place. Later on, once first ply failure has taken place, Hashin Law cannot represent correctly a damage model in the braided carbon. Therefore, it does not make sense to expect an accurate Force – Displacement curve obtained numerically. Thus, mechanical behavior from that moment is only representative when it is experimentally obtained.

Figure 13. Strain gauges.

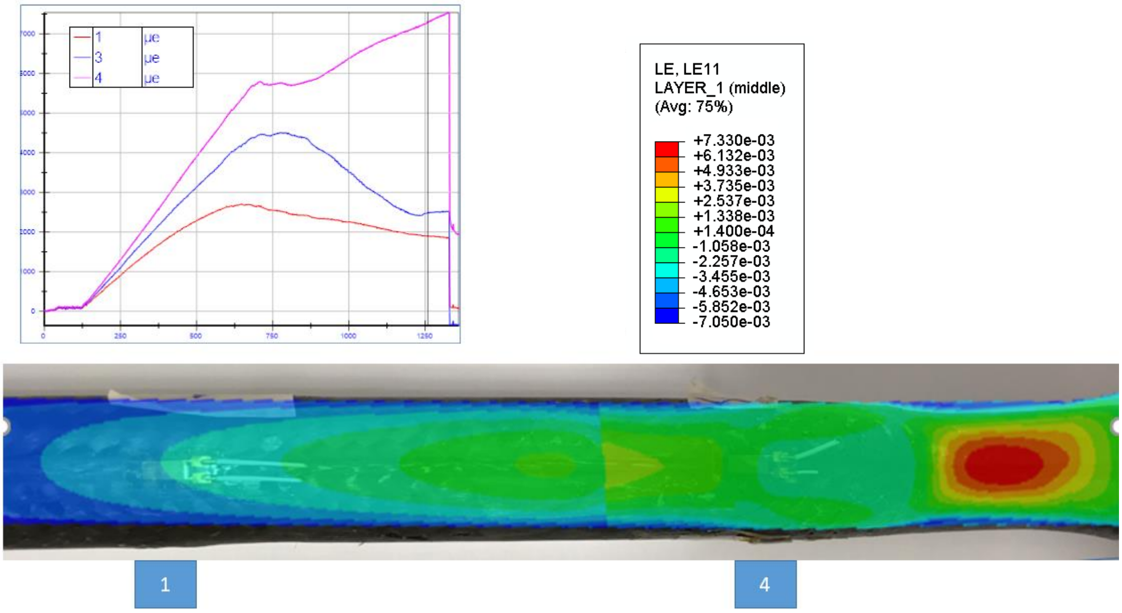

Figure 14. Engineering Strain along local 1 direction obtained by FEM and strain gauges.

For Design 1 strain gauges were placed on a handlebar. 4 strain gages were attached. Results for gages 1 and 4 are shown in Figure 11. FEM plot is over plotted on an actual picture of handlebar in Figure 14.

Correlation between numerical and testing results in terms of engineering strain at the points were gages were applied is very high, bearing in mind that midpoint of the curve should be considered. It corresponds to first ply failure.

7. CONCLUSIONS

The mechanical design of a carbon handlebar is presented.

The proposed design allows the handlebar to withstand as high efforts as a steel bar could, thanks to the selected braided carbon fibre. Additionally, extremely cost-effective moulds made of PolyLactic Acid (PLA) by 3D printing technique are shown.

Usually, carbon fibre handlebars are made of unidirectional (UD) carbon fibre prepreg, resulting in a quite light but fragile piece.

This new handlebar design, demonstrates its ability to withstand forces comparable to those of a steel bar.

The mechanical behaviour of this new handlebar design ensures that final user can at least come back home in case of a failure. Weight is almost the same as unidirectional carbon fibre handlebars but its behavior allows a safer cycling.

8. AUTHOR CONTRIBUTION

J Cuartero wrote the main manuscript text and performed design, manufacturing and FEM. D Ranz participate on testing and manufacturing. A Poniecka participate on future development and wrote some text. All authors reviewed the manuscript.

9. COMPETING INTEREST

I declare that the authors have no competing interests, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

REFERENCES

[1] P BERE, M CRISTIAN, et al. Design and Analysis of Carbon/epoxy Composite Bicycle Handlebar. Materiale Plastice June 2014.

[2] Bere P; Nemes O, Dudescu M. Design and Analysis of Carbon/Epoxy Composite Tubular Parts. June 2013. Advanced Engineering Forum 8-9:207-214. DOI:10.4028/www.scientific.net/AEF.8-9.207

[3] Ranz D, Ochoa M, et al DISEÑO DE MANILLAR DE BICICLETA CON ALTA ABSORCIÓN DE VIBRACIONES UTILIZANDO COMPOSITES NATURALES. DYNA 2024 Vol 99

[4] https://beast-components.de/

[5] https://www.decathlon.es/es/p/manillar-bicicleta-trekking-diametro-25-4-mm-longitud-640-mm-acero-negro/_/R-p-339493?mc=8739576

[6] Miravete A, JM Bielsa, A Chiminelli et al. “3D mesomechanical analysis of three-axial braided composite materials” *Composites Science and Technology* Vol 66(15) 2006, 10.1016/j.compscitech.2006.02.015

[7] Castejon L, A Miravete, J Cuartero ““Analytical formulation of 0,+-45 Braided composites and its application in Crashworthiness simulation” MECHANICS OF COMPOSITE MATERIALS AND STRUCTURES, Volume 8, number 3, July-September 2001. 10.1080/10759410118129

[8] “Abaqus User´s Manual” Version 6.14, Hibbit, Karlsson & Sorensen Inc.

[9] Carrera M, Cuartero J, Miravete A et al. Crash Behaviour of a Carbon Fibre Floor Panel. International Journal of Vehicle Design, 44, 2007

[10] Miralbes, R.; Cuartero, J.; Ranz, D et al. Numerical simulations of gyroid structures under compressive loads. Mechanics of advanced materials and structures 2023, DOI:10.1080/15376494.2023.2192712

[11] Ranz D; Cuartero J; et al.. Experimental and numerical study of the influence of manufacturing parameters on the interlayer behavior of 3D printing materials with and without reinforcement fibres. DYNA 2023. DOI:10.6036/10625

[12] Hashin Z, “Failure Criteria for Unidirectional Fibre Composites,” *Journal of Applied Mechanics*, vol. 47, pp. 329–334, 1980.

[13] Hashin Z, and A Rotem, “A Fatigue Criterion for Fibre-Reinforced Materials” Journal of Composite Materials, vol. 7, pp. 448–464, 1973.

[14] Davila C, Camanho P, Rose C, “Failure criteria for FRP Laminates” Journal of Composite Materials, vol. 39, no 4, 2005, 10.1177/0021998305046452.

[15] EN 4210-5:2014 Ciclos. Requisitos de seguridad para bicicletas. Parte5: Métodos de ensayo de la dirección.

[16] JM Blanchard, AJ Sobey, Comparative design of E-glass and flax structures based on reliability, Composite Structures, Volume 225, 2019, 111037

[17] Revuelta, Cuartero, Miravete, Clemente. A new approach to fatigue analysis in composites based on residual strength degradation. Composite Structures Volume 48, Issues 1–3, January–March 2000, Pages 183-186

[18] Jitendra S. Tate a, Ajit D. Kelkar. Stiffness degradation model for biaxial braided composites under fatigue loading. Composites: Part B 39 (2008) 548–555

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