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The use of sustainable composites for the manufacturing of electric cars[☆]

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ABSTRACT

The current work presents a material characterization for bio composites used for automotive industrial applications. The mechanical properties are utilized in the design of components of an electric micro-car for the green innovation of automotive industry. The composite material is homogenized as equivalent orthotropic medium and its mechanical properties verified through laboratory testing. Finally a finite element model of some composite parts are analyzed by considering classical materials and innovative bio-composites. The comparison shows the valuable structural performances of the natural-based composites with respect to classical ones both in terms of cost, economical impact and mechanical performances.

1. Introduction

Industry nowadays is trying to take advantage of renewable resources and simultaneously to use recyclable materials or materials which have a smaller global footprint. All this in order to fight against climate change. Therefore, competencies have to be radically increased in the field of bio-polymer technologies [1]. Natural fibers can be impregnated both with thermoplastic and thermosetting matrices, becoming a valid alternative to carbon/glass fibres and aluminium [2], which instead requires a lot of electricity for its production, but they are also extensively used in recent research works for they high structural performances. With a view to continuous innovation aimed at eco-sustainability, the present industrial research intends to obtain solutions that allow to achieve higher technological performance, paying particular attention to the environment. The low cost of the material and the fact that especially the developing Countries are the largest producers of many of these fibres are determining a growing interest in these bio-materials that are gradually more and more largely applied also in aerospace and automotive industries.

Bio-composites or Natural Fibre Composites (NFCs) are not a recent invention, as they were studied and applied in the industry since the beginning of the 20th century [3]. In England during the Second World War, owing to the lack of aluminium, a special fibre based on reinforced linen was used with a phenol-formaldehyde resin (Gordon-Aerolite) for the production of the plies of the fuselage of the Spitfire military aircraft. In 1941 Henry Ford had already produced a prototype using a composite based on hemp fibres but, unfortunately, that model never entered in production in consequence of economic limitations and difficult relations in the international commercial context of the Second World War. In the 1950s, the first standard-built passenger car, produced with natural wool or cotton fibre reinforcements, was the Trabant, designed in then East Germany (DDR), and produced from 1964 until the fall of the Berlin wall. During the Cold War the Trabant was the usual means of transport for families living beyond the Iron Curtain, under the Warsaw Pact and with a five-year stability plan. Today NFCs are used in the automotive sector, especially in order to save weight: we can now save up to 34% of the individual parts. The Lotus Eco Elise, presented at the end of 2008, weighed 32 kg less than the standard car thanks to bio-sustainable materials. Furthermore, Mercedes-Benz is also expanding the use of bio-compounds in its series production of the E class.

All vegetable fibres have an extremely complex molecular structure formed by a multiplicity of bio-polymers (lignin, crystalline cellulose, pectin, etc.) and a nano-structured architecture which gives these fibres mechanical properties usefully used as reinforcements in the transport sector and green mobility. Among all the most employed natural fibers are hemp, cotton and linen. They are majorly selected for their high tensile strength and breaking deformation; low thermal, electrical and acoustic conductivity; electromagnetic transparency; low energy for production; biodegradable and recyclable, finally extracted from re-

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newable sources. Challenges in the adhesives sector, on sustainable and eco-friendly chemicals that enable bio-derived adhesives, recycling and debonding, and surface treatment approaches involved in the adhesive application process, was discussed in [4].

Many bio-composite materials use recycled materials [5] or fibres derived from fast-growing plants such as hemp (Cannabis sativa) [6] or flax (Linum usitatissimum) [7]. They can therefore be recycled in a simple way or designed to be very quickly biodegradable. They also greatly reduce the need of products derived from the petrochemical industry or in any case from fossil fuels, with a relative lack of climate-altering CO_2, as they generally use natural binders and also favour the use of locally sourced products, reducing the cost of transport. Lastly, they can grant an increase in social well-being, becoming massively used in the production of urban electric vehicles because they are light and ecological. Bio-composites find different types of applications in the automotive field such as [8]: body-shell of micro-cars; e-bikes; full-electric vehicles (FEV); automobile interiors; frame structural elements.

In recent years, the use of flax fibres as reinforcement in composites has gained popularity due to an increasing requirement for developing sustainable materials [9]. Flax fibres are cost-effective and offer specific mechanical properties comparable to those of glass fibres [10–12]. Composites made of flax fibres with thermoplastic, thermoset, and biodegradable matrices have exhibited good mechanical properties [13,14]. Among all flax fibers have been recently used in natural-based composites with bio- (polypropylene, polylactic acid) or epoxy-based resins [15]. Flax is not only employed in the form of unidirectional reinforcing fiber [16] but also as woven reinforcing phase [17]. It is remarked that woven composites have a more complex micro-mechanical behaviour as unidirectional fiber reinforced composites [18]. Development and characterization of bioactive woven flax-based composites have been discussed in [19]. Failure prediction of sandwich panels based on flax fibres reinforced epoxy bio-composites has been also investigated in [20] as well as impact [21]. As far as failure is concerned, fracture toughness of flax woven composites have also been analyzed [22,23]. It has been proven that flax-based composites can be used to form complex shaped components via sheet forming process [24,25] which is the most used industrial technique for forming of body parts in automotive industry and others. In this work, the application of some of these composites will be considered with an application to automotive sector.

Other researchers investigated bio-composites made of different natural fibers such as jute [26], hemp [27–30] and kenaf [31,32] or hybrid bio-composites such as jute/rubber [33] and hemp/straw [34]. Another hybridization such as carbon/hemp hybrid bio-composites have been presented in [35]. Other examples of bio-based composites are discussed in [36] for a PLA/hemp composite which is completely biodegradable. It is also important to be remark that bio-composites can be fabricated with bio-based and regular epoxy resins [37], however, in this work regular epoxy is utilized for its suitable properties in automotive industry. The use of bio-based matrices will be considered in a future work.

2. Motivation

The public demand for sustainable development has been the main driving factor of the present study. Since a strong request for a sustainable mobility [38–40] is coming from the public sector. Innovation feeds the relationship between innovative companies and customers on new challenges with demanding requirements. For these reasons a two-seats micro-car with a bodywork in bio-composite material has been designed. The car has electric propulsion and high-end electronic equipment on board for a safe and sustainable urban mobility. The project includes also the construction of a car shelter, or garage, with photovoltaic tiles recharging the full electric car battery, with an off-grid system, in order to define a whole zero emissions mobility system. Present innovation can provide an important growth opportunity of GDP and GDP-pro-capita to many developing Countries that still base their own economy mainly on agriculture. As a matter of fact, the present project has been financed by POR CREO FESR project call (Regional Operative Programme Growth and Employment European Funding for Regional Development) which is a 50% co-financing between local Region and Europe, in addition, the project has received tax incentives from the MISE (Ministry of Economic Development). The micro-car will be made in two versions, one with carbon-linen shell and the other in bio-composite linen and denim-like cotton. Samples of such finishing are depicted in Fig. 1 for linen natural composites.

Obviously, such composites are highly user-adjustable and strongly versatile according to the market they are introduced in either Western or Eastern. This demonstrate on one hand the high flexibility of the working processes for the realization of composite shells, on the other hand the high performance achievable with these advanced bio-materials, in terms of both mechanical properties (strength, weight reduction) and aesthetic yield and customization for the end user. In both versions the micro-car will have a high technological content in terms of electronics for digital traction control and vehicle dynamics, sensors, man-machine interface with the possibility of remote monitoring of the state of charge of the accumulators and connection with the vehicle network.

The analysis of this novel composite body parts require a theoretical framework on bio-composite homogenization criteria as well as numerical modelling via finite element method. The present work aims to study and present a valuable homogenization method for several woven bio-composite configurations and present the results in terms of finite element modelling of such classical and innovative composites. Conclusions and remarks are drawn in the paper closure.

3. Homogenization of bio-woven fabric composites

The composite materials analyzed in this paper are made of a reinforcing woven fabric and an epoxy resin (matrix). The main aim of this Section is the analytical evaluation of the mechanical properties of these composites. A suitable homogenization procedure is presented to this aim.

As highlighted in [41], the first step of the current methodology involves the characterization of a unidirectional fiber-reinforced composite. At this stage, the overall mechanical features are evaluated by means of the well-known theory of mixture and are given in terms of longitudinal Young's modulus E_1, transverse Young's moduli E_2, E_3, shear moduli G_{12}, G_{13}, G_{23}, and Poisson's ratios $\nu_{12}, \nu_{13}, \nu_{23}$. It should be specified that the planar size of the composite is denoted by the principal directions specified by the labels 1 and 2, whereas 3 is the orthogonal direction. The volume fraction of the fibers is denoted by V_f. Consequently, the volume fraction of the matrix is computed as $V_m = 1 - V_f$. The rule of mixture provides the following definitions [42,43]

$$E_1 = E_1^f V_f + E_m V_m \tag{1}$$

$$E_2 = E_3 = \frac{E_m}{1 - V_f\left(1 - E_m/E_2^f\right)} \tag{2}$$

$$G_{12} = G_{13} = \frac{G_m}{1 - V_f\left(1 - G_m/G_{12}^f\right)} \tag{3}$$

$$G_{23} = \frac{G_m}{1 - V_f\left(1 - G_m/G_{23}^f\right)} \tag{4}$$

$$\nu_{12} = \nu_{13} = \nu_{12}^f V_f + \nu_m V_m \tag{5}$$

$$\nu_{23} = \frac{E_2}{2G_{23}} - 1 \tag{6}$$

where the index f denotes the properties of the fibers, whereas the matrix features are specified by m. In particular, E_1^f, E_2^f are the fiber Young's moduli, G_{12}^f, G_{23}^f the fiber shear moduli, ν_{12}^f the fiber Poisson's

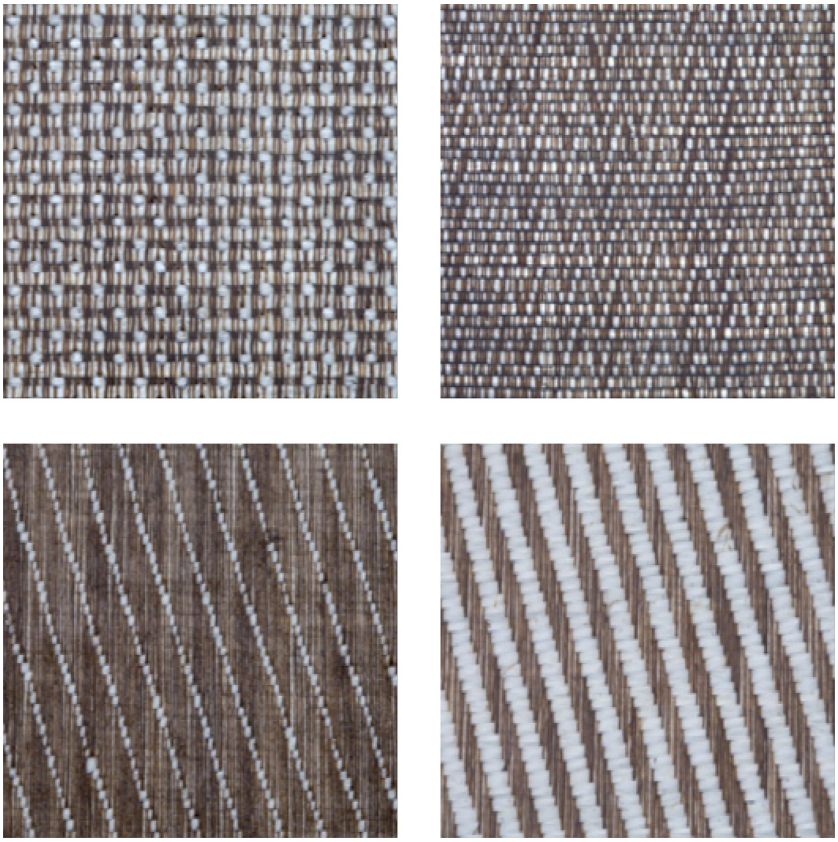

Fig. 1. Four samples of linen-based bio-composites.

ratio; on the other hand, E_m, G_m and ν_m are respectively the Young's modulus, shear modulus and Poisson's ratio of the isotropic matrix. Likewise, the density of the composite can be evaluated as follows

$$\rho = \rho_f V_f + \rho_m V_m \tag{7}$$

where ρ_f, ρ_m stand for the densities of the two constituents (fibers and matrix, respectively).

The value of the fiber volume fraction V_f depends on the texture of the reinforcing woven fabric [41]. In particular, the nominal areal weight ρ_{wf} (measured in $\mathrm{kg/m^2}$) and the thickness of the fabric h_{wf} are required. Its mass density ρ' can be consequently evaluated as shown below

$$\rho' = \frac{\rho_{wf}}{h_{wf}} \tag{8}$$

Then, the following expression is used to compute the fiber volume fraction

$$V_f = \frac{\rho'}{\rho_f} \tag{9}$$

as shown in the previous paper by the authors [41].

Once these features are known, the Young's moduli of the woven fabric composite can be introduced as E_x and E_y, where x, y represent the weft and warp directions of the material [44]. One gets:

$$E_x = kE_1 + (1-k)E_2 \tag{10}$$

$$E_y = kE_2 + (1-k)E_1 \tag{11}$$

where the parameter k is set equal to 0.5 for balanced woven fabric composites. Therefore, $E_x = E_y$ in this circumstance. As far as the overall Poisson's ratio ν_{xy} of the composite is concerned, the following expression can be used [44]

$$\nu_{xy} = \frac{\nu_{12}}{k + (1-k)E_1/E_2} \tag{12}$$

The shear modulus G_{xy}, instead, is assumed equal to G_{12}. Finally, the density of the woven fabric composite is still given by expression (7). It should be observed that the stiffness of the composite is less than the one that could be obtained by overlapping two unidirectional fiber-reinforced materials. In addition, the woven fabric composite turns out to be isotropic if $k = 0.5$ as in the current case.

Several reinforcing natural fibers are considered in this paper. Their properties are listed in Table 1, together with the fabric commercial name (if available). In the same Table, the value of V_f computed as illustrated above is also shown. For completeness purposes, carbon and glass fibers are also included in the table. It should be also specified that different configurations have been also presented, which are denoted by IDs #4 and #6. For these cases, the value of V_f has been manually defined to investigate the effect of fiber volume fraction. Finally, the same value of $V_f = 0.38$ used for the Flax fiber-reinforced composite is employed also for Hemp and Jute fibers. Different Young's moduli for the Flax fibers are also taken into account. As far as the properties of the matrix is concerned, the following values are used: $E_m = 2.5$ GPa, $\nu = 0.34$, $\rho_m = 1100$ $\mathrm{kg/m^3}$.

For each kind of reinforcement presented in Table 1, the longitudinal and transverse Young's moduli E_1, E_2, the overall elastic modulus E_x, Poisson's ratio ν_{xy} and density ρ are computed. These values are evaluated by using the aforementioned approach and are listed in Table 2.

3.1. Comparison with experiments

The proposed homogenization technique is validated through the comparison of an experimental test. To this aim, the flax reinforcement denoted by ID #3 in Table 1 is considered. A unidirectional composite named FLAX UD 200 [46] is tested according to ASTM D3039 [47]. Specimens details (thickness and width) are listed in Table 3. After testing the elastic modulus of the composite is given as $E_1 = 19.6179 \pm 0.5157\mathrm{GPa}$, which agrees well with the aforementioned predic-

Table 1
Mechanical and geometric features of several bio-woven fabric reinforcements.

	Classification		Woven fabric prop.		Fiber properties				Volume fraction	
ID	Fibers	Fabric name	ρ_{wf} $[\mathrm{kg/m^2}]$	h_{wf} [mm]	ρ_f $[\mathrm{kg/m^3}]$	E_1^f [GPa]	E_2^f [GPa]	ν_{12}^f	ρ' $[\mathrm{kg/m^3}]$	V_f
#1	Carbon [41]	GG 200 T 3 K	0.2	0.37	1800	180	15	0.2	540.54	0.30
#2	Glass [42,43,45]	G200T-1270	0.2	0.17	2450	71	71	0.22	1176.47	0.48
#3	Flax [3,10]	-	0.2	0.38	1400	80	80	0.4	526.32	0.38
#4	Flax [3,10]	-	-	-	1400	80	80	0.4	-	0.50
#5	Flax [3,10]	-	0.2	0.38	1400	50	50	0.4	526.32	0.38
#6	Flax [3,10]	-	-	-	1400	50	50	0.4	-	0.50
#7	Hemp [3,27]	-	-	-	1480	40	40	0.1	-	0.38
#8	Jute [3,26]	-	-	-	1400	30	30	0.3	-	0.38

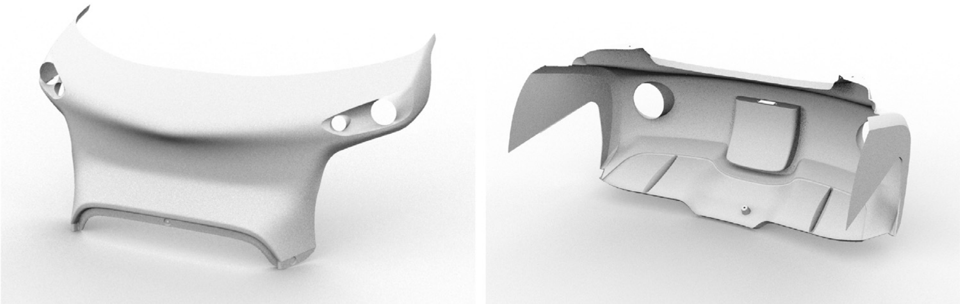

Fig. 2. Front and rear bumper for the micro-car model.

Table 2
Evaluation of the mechanical properties of several bio-woven fabric composites.

ID	Fibers	E_1 [GPa]	E_2 [GPa]	E_x [GPa]	ν_{xy}	ρ $[\mathrm{kg/m^3}]$
#1	Carbon	55.803	3.334	29.569	0.034	1310.21
#2	Glass	35.393	4.658	20.026	0.066	1748.26
#3	Flax	31.635	3.932	17.784	0.080	1212.78
#4	Flax	41.250	4.848	23.049	0.078	1250.00
#5	Flax	20.357	3.889	12.123	0.116	1212.78
#6	Flax	26.250	4.762	15.506	0.114	1250.00
#7	Hemp	16.750	3.883	10.317	0.094	1244.40
#8	Jute	12.950	3.836	8.393	0.148	1214.00

Table 3
Geometric data of the specimens used for the ASTM D3039 test.

ID	thickness [mm]	width [mm]
S1	3.96	14.87
S2	3.95	15.06
S3	3.96	14.80
S4	3.95	15.24
S5	3.92	14.68
S6	3.95	15.04
Average	3.95	14.93
St.Dev.	0.02	0.22

Table 4
First 5 natural frequencies of the frontal bumper considering several woven fabrics.

	frequency [Hz]				
ID	1	2	3	4	5
#1	17.796	32.869	51.980	58.278	64.452
#2	12.731	23.429	37.119	41.467	46.028
#3	14.181	26.502	41.674	47.246	51.669
#4	15.876	29.732	46.708	53.054	57.910
#5	11.708	21.881	34.408	39.008	42.659
#6	13.023	24.389	38.315	43.520	47.503
#7	10.902	19.958	31.708	35.236	39.320
#8	9.809	18.186	28.706	32.302	35.593

tion provided by the homogenization technique (Table 2). Analogously, the density is given by $\rho = 1275 \mathrm{kg/m^3}$. Even this value is comparable with the one obtained analytically.

4. Finite element modelling

According to the material homogenization presented above the dynamic numerical modelling of two micro-car components are performed. The renderings of the front and rear bumpers of the micro-car are shown in Fig. 2. The modelling is performed with the software ABAQUS and S4R/S3R plate/shell finite elements for their robustness as suggested in the software documentation. Moreover, ABAQUS has been selected for its accurate results in terms of computational efficiency and high-end features for managing complex 3D models. Investigation based on variable mechanical properties are proposed in order to study the variation in the frequency response of these components.

The structural elements are made of a constant thickness of woven composite with 4 mm thickness. Material properties are taken from the ones listed in Table 2. In particular, the following woven fabrics will be utilized: #1 carbon, #2 glass, from #3 to #6 flax with different fiber volume fractions, #7 hemp and #8 jute. Carbon and glass are included in the study as a reference, since carbon and glass fibers are the most used ones in the automotive industry.

Both components are considered with bolt connection according to the designs selected by the company which consider the overall design of the micro-car.

4.1. Front bumper

The first 5 natural frequencies of the frontal bumper are listed in Table 4. As expected the carbon woven fabric leads to the highest frequencies due to its highest elastic modulus with respect to the other materials. A comparison in terms of relative frequency is depicted in Fig. 3 where the natural frequency of the structure made of carbon woven fab-

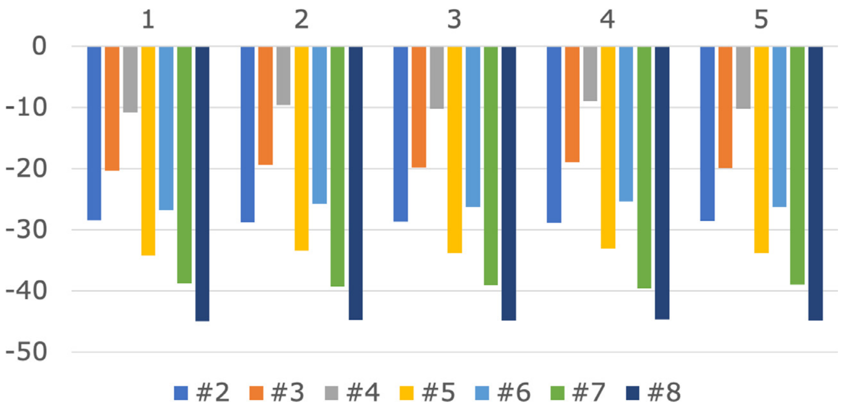

Fig. 3. Comparison of the first 5 natural frequencies of the frontal bumper with respect to the carbon woven fabric.

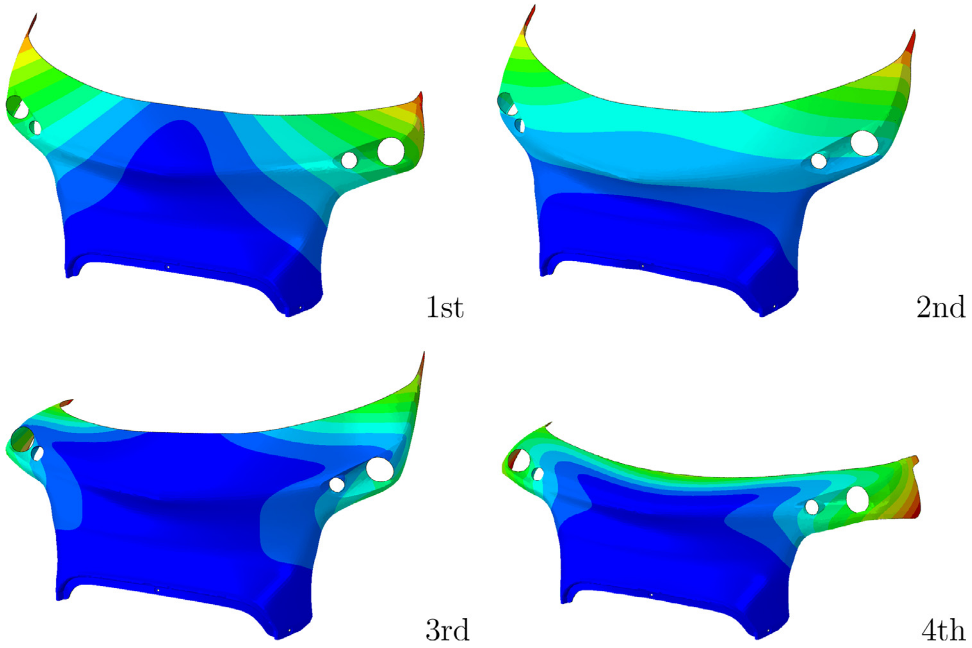

Fig. 4. First 4 natural frequencies of the front bumper.

ric is considered as a reference. The differences in terms of rigidity and overall mass are between -10% (flax woven fabric) to -45% (jute woven fabric). Among all the flax woven fabrics lead to the lower reductions due to their high stiffness and low density. On the contrary, it is clear that glass woven fabric leads to results closer to hemp natural fibers or flax with low fiber volume fractions. This is due to the high density of the glass which is more than 40% higher than the one of flax. A graphical representation of the first 4 natural frequencies of the frontal bumper is depicted in Fig. 4, where it is clear that the top portion is the one more subjected to structural vibrations due to the fact that bolted connections are present only in the bottom part of the component. This choice does not adversely affect on the mechanical performances of the frontal body part.

Table 5
First 5 natural frequencies of the rear bumper considering several woven fabrics.

	frequency [Hz]				
ID	1	2	3	4	5
#1	31.514	31.903	95.488	101.310	122.640
#2	22.533	22.810	68.001	72.196	87.449
#3	25.163	25.476	77.172	81.712	98.748
#4	28.182	28.533	86.605	91.666	110.750
#5	20.776	21.034	63.715	67.464	81.529
#6	23.118	23.405	71.041	75.193	90.848
#7	19.282	19.519	57.842	61.467	74.527
#8	17.381	17.596	52.878	56.066	67.830

4.2. Rear bumper

The first 5 natural frequencies of the rear bumper are listed in Table 5. Also in this case it was expected that the carbon woven fabric leads to the highest frequencies due to its highest elastic modulus with respect to the other materials. A comparison in terms of relative frequency is depicted in Fig. 5 where the natural frequency of the structure made of carbon woven fabric is considered as a reference. The differences in terms of rigidity and overall mass are between -10% (flax woven fabric) to -45% (jute woven fabric). As shown in the previous Section, the flax woven fabrics lead to the lower reductions due to their high stiffness and low density. On the contrary, glass woven fabric leads to results closer to hemp natural fibers or flax with low fiber volume fractions. This is due to the high density of the glass which is more than 40% higher than the one of flax. A graphical representation of the first 4 natural frequencies of the rear bumper is given in Fig. 6, where it is clear that the bottom portion is the one more subjected to structural vibrations due to the fact that bolted connections are mainly present in the top part of the component. The bottom part has a bolted connection

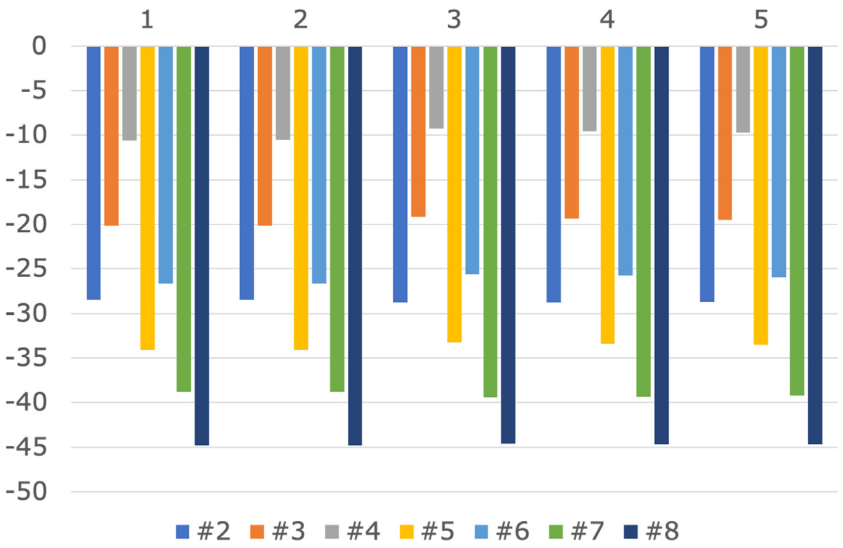

Fig. 5. Comparison of the first 5 natural frequencies of the rear bumper with respect to the carbon woven fabric

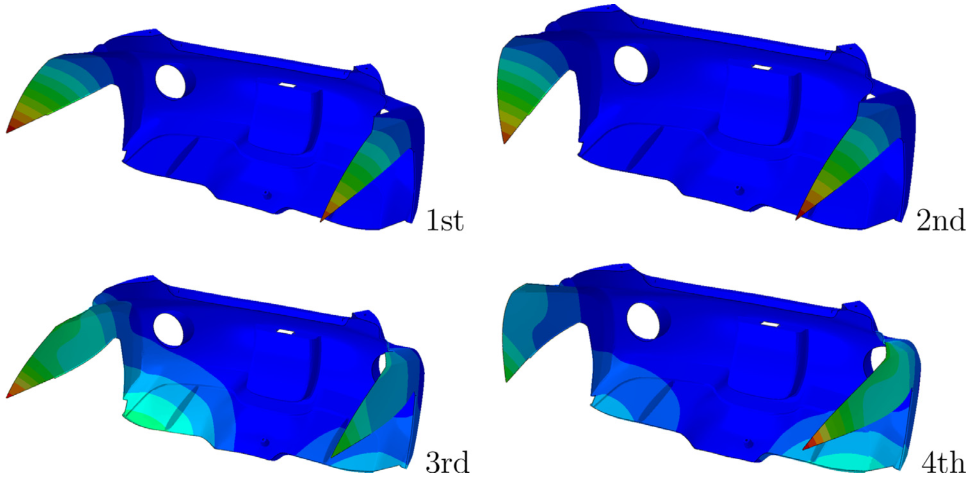

Fig. 6. First 4 natural frequencies of the rear bumper.

which is asymmetric for constructive purposes which leads to slightly asymmetric vibration modes.

5. Conclusions

In this paper a material characterization for woven bio composites is presented and verified via laboratory testing. The aim of the study was to study the applicability of bio composites for industrial applications as an alternative to classical carbon and glass reinforced structural components. The industrial application aimed at the present study is the design of an electric micro-car for the green innovation of automotive industry. A finite element model is set up for testing the mechanical behavior of the micro-car components by varying the fiber reinforced materials. The comparison showed that bio composites based on flax fibers represent a very good candidate for promising innovative use in automotive industry in terms of raw material cost and socio-economical impact.

Declaration of Competing Interest

The authors declare that the present research receive the finantial support of POR CREO 2014-2020 and no other general and institutional competing interest has to be declared. Moreover, no potential conflict of interest is provided.

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