Multi-scale modeling of triaxial braided composites for FE-based modal analysis of hybrid metal-composite gears

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Abstract

The paper presents a description of a methodology to accurately estimate the natural frequencies of a hybrid metal-composite gear, where the web is made of a polymer matrix reinforced with two-dimensional (2D) triaxial braided fabrics. The proposed approach is based on a multi-scale composite modeling starting from evaluation of homogenized material properties of the gear web at the meso-scale for a subsequent FE-based modal analysis. For this purpose, the mechanical behavior of a single Repetitive Unit Cell (RUC) at the meso-scale is analyzed with a FE procedure which takes into account the interweaving and cross-section geometry of the yarns, volume fraction and local fiber orientation. It is shown that the described modeling strategy allows to predict gear's natural frequencies that are close to the experimental results. Significant accuracy enhancement is achieved with respect to the model in which the web material is considered as perfectly isotropic.

Keywords: hybrid gears, mechanical transmissions, triaxial braided fabrics, multi-scale modeling, modal analysis.

1. Introduction

Mass reduction is one of the main innovation drivers in several industrial sectors, including the gear research and industry communities. The use of lightweight gears originated in the aerospace industry, where weight optimization has always been a key topic, and is recently extending to other sectors in the transportation industry, where huge benefits are expected from mass reduction to enable products to comply with the ever stricter regulations on fuel efficiency and emissions.

The most common approach to gear lightweighting is based on material removal from the gear body. In [1,2] a methodology has been proposed in order to analyze dynamic behavior of lightweight spur gears through the evaluation of the variable meshing stiffness, while in [3] the effects of holes in spiral bevel gear body have been considered. The major drawback of considering lightweight gears with geometrical modifications of the gear body is the possible introduction of additional dynamic excitations, which can increase vibrations in the mechanical system.

A more recent approach for weight reduction in mechanical systems and, specifically, in geared transmissions, is based on the exploitation of composite materials as standalone components or in a hybrid metal-composite design. Thanks to the higher strength-to-density ratio, combined with other advantages over traditional materials, such as resistance to chemicals, thermal and electrical insulating properties, composites have been gaining ground in different sectors. When using composites instead of, for example, steel and aluminum alloys, significant reductions in weight can be achieved, while preserving high load-carrying capability. Fiber-reinforced polymers represent a significant portion of the composites that are currently used in various industrial applications. This is also confirmed for applications in mechanical structures.

The use of composites for multi-material design of mechanical transmissions is mostly limited to housing and shafts [4,5]. Recently, efforts have been spent to expand the use of composite materials to the geared bodies and a new concept of hybrid gear, where a composite web is attached to the metal toothed part, has been proposed and investigated [6]. This combines the excellent contact stress and fatigue resistance of high-performance steel with the high strength-to-weight ratio of composite materials. In fact, from a functional, load-related standpoint, a gear can be split into three main regions, as shown in Figure 1: the rim (including the teeth), which is the outer region of the gear; the web, or central portion; and the hub, which is the internal part, connecting the gear to the shaft.

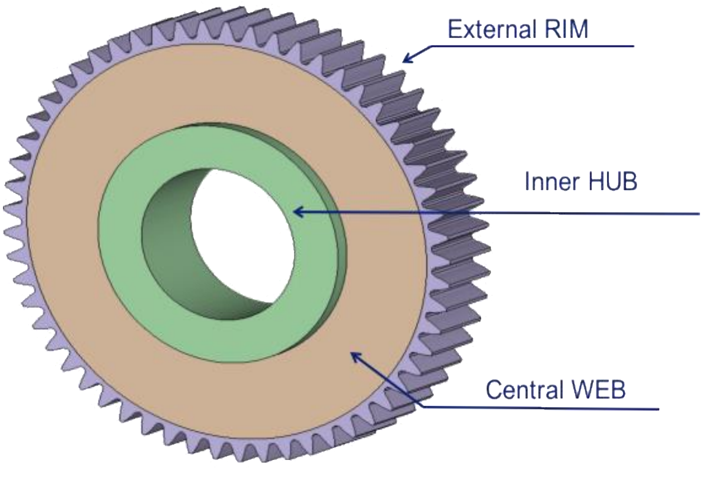


Figure 1: Gear zones definition.

To enable the fulfilment of a set of requirements linked to precise geometry, fatigue and wear resistance, the toothed part of the gear is the region where most of the design standards are applied, while the web is usually less prone to failure mechanisms. Being far from the local area of direct contact between teeth, the web is not subject to impacts, wear and other friction-related phenomena. Moreover, it contributes significantly to the overall mass of the gear and hence it offers a great potential for both mass reduction and noise and vibration (N&V) enhancement, which is fully exploited in the hybrid gear design.

Recent research efforts have focused on the applicability and the advantages of a hybrid design approach for weight and noise reduction in both small transmissions, consisting of a pair of identical gears [6], and in a full-scale bull gear used in rotorcraft applications [7]. More in detail, in [6] an innovative gear design has been proposed and investigated, based on the replacement of the metal web of the gears with triaxial braided composite material. The latter is characterized by high-strength properties and quasi-isotropic behavior in plane, which makes it suitable especially in aerospace drive system applications. The resulting hybrid gears have been prototyped and tested with the aim of assessing their modal properties and endurance performance.

The experimental results shown in [6] have highlighted a very good fatigue resistance of such hybrid gears, in which no detectable damage has been identified in a post-test inspection after $300x10^6$ cycles at 10000 rpm, and a 20% decrease in weight. On the other hand, the expected improvement of the N&V behavior has been demonstrated only at the highest speeds and loads, where hybrid gears exhibit lowest vibrations [8]. In addition, it has been shown that the fundamental frequency was lower than the one measured for standard steel gear of similar size and shape, while a higher structural damping has been noticed through impact testing.

With the aim of enabling simulation-driven design of hybrid gears with improved N&V behavior, a methodology is proposed for accurate FE modeling of such gears by taking into account the anisotropic nature of the composite web material and of the ply arrangement effects. The composite part of the gear was made of a polymer matrix reinforced with two-dimensional (2D) braided fabrics, for which a detailed description of architecture, manufacturing process, applications and predictive models has been given in [9]. In order to test and to model triaxial braided composites, different approaches have been investigated. An analytical method based on the rule of mixture for the evaluation of the stiffness properties of 2D triaxial braided composites has been presented in [10]. The architecture has been described as three separate layers, with the first two representing braided tows and the last being an axial tow. In [11] analytical models have been used to evaluate mechanical properties of quasi-isotropic triaxial braided composites made of glass fibers and epoxy resin.

A complete experimental characterization of the mentioned triaxial braided composite material has been described in [12], where a panel of six layers of plies has been tested to evaluate tensile and compressive moduli in axial (along axial yarns direction) and transverse directions, with the purpose of defining stress-strain curves. Moreover, a single RUC of such composite architecture has been split into four subcells and the Classical Laminated Plate Theory (CLPT) [13] has been applied for the evaluation of unidirectional laminate properties needed for a subsequent FE simulation for material characterization and validation. In a subsequent step [14], the subcell representation has been improved with a more accurate model that allows to determine ply thickness and volume fraction.

In order to enable predictive analyses with higher accuracy and without loosing information on local stress fields, the attention has been focused on micro and meso-scale modeling of triaxial braided composite panels, starting from the definition of a FE model of the RUC [15], which takes into account internal braiding architecture. In [16,17] a multi-scale FE model of a triaxial braided RUC has been developed for experimental and numerical correlations of axial and transverse tension response, while in [18] the three-dimensional (3D) FE model at meso-level has been used to predict the progressive damage behavior of single-layer braided composites. The application of FE techniques to different RUC models to support predictive analyses of the effective material properties as a function of the braiding angle have been described in [19].

In this work, a predictive model for the mechanical behavior of the composite gear body was developed through a FE multi-scale modeling approach that allows to evaluate the orthotropic material properties to be used in FE analysis. The proposed approach allows to reduce the efforts needed in hybrid gear development; an optimal design can be achieved by defining the geometry of the gear and the material itself, with no need for expensive and time-consuming experiments aimed at the characterisation of the composite material properties. The outline of the paper is the following: in Section 2 an overview of the proposed multi-step modeling approach is provided; Sections 3 is dedicated to the description of gear's FE model generation and Section 4 to the multi-scale approach used to compute homogenized, orthotropic properties of the composite web [20]. The accuracy of the resulting FE model is assessed in Section 5 by comparison between the gear's natural frequencies predicted through a numerical modal analysis and the experimental values reported in [6]. Conclusions are summarized in Section 6 followed by the discussion of the achieved results. These results show that the orthotropic description of the web material improves significantly the predictive accuracy of the FE model in comparison to an isotropic formulation.

2. Multi-scale simulation of hybrid gears: Methodology overview for FE model generation

A modelling procedure is developed covering all steps needed for evaluating the modal properties of a hybrid gear. Since this process is strongly based on the use of CAD, CAE and FE software [20], the proposed methodology can be applied in a generalized way to different kind of gears (e.g. spur, helical, bevel). In this paper all the considerations are done for a specific spur gear model, for which the results of experimental modal testing are provided in the literature [6,7].

The first step of the proposed methodology is the setting of gear geometry based on the definition of the rim, the web and the hub parts. The geometric description of the gear, obtained from the data reported in [6], was used to generate the CAD model, which was subsequently translated in a FE model of the gear by using a commercial software Simcenter 3D [21]. In the proposed analysis, the virtual model was enriched through a multi-scale approach. First, effective elastic orthotropic properties of the utilized triaxial braided composite were computed at the meso-scale using FE-based homogenization scheme. In the next step, the computed properties were used to define the material properties of the web part in the FE model at the macro scale. At the meso-scale the RUC was composed by interweaving yarns, braided according to the investigated composite. The geometry of the yarn, i.e. its cross-section, was reproduced in CAD environment, considering the local fiber orientation and the fiber volume fraction. Finally, a FE-based homogenization procedure was used to compute homogenized elastic properties of such composite at the meso-scale.

The flowchart of the overall methodology is presented in Figure 2. The various steps carried out to perform the entire modeling procedure are detailed in the following Sections 3 and 4.

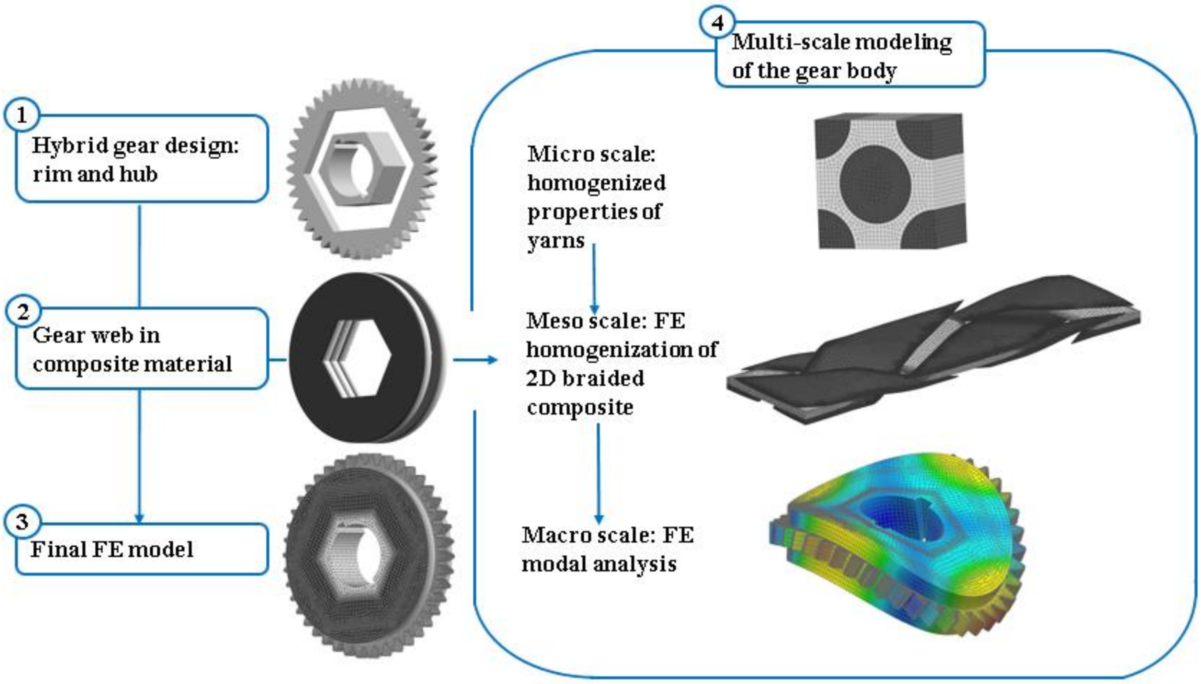


Figure 2: Flowchart of the proposed methodology for hybrid gear modeling

3. CAD and FE model generation of a hybrid gear

The design of the hybrid gear, based on the manufacturing process described in [6], started considering a detailed description of gear teeth surfaces. For this purpose, the FE model of the gear teeth was generated, in which all the gear specifications, such as number of teeth, addendum, dedendum, circular pitch, whole depth, pitch diameter and tooth profile modifications were considered. In such a way, an accurate model of the rim was created, which could be used for subsequent FE-based static and dynamic simulations of transmissions with hybrid gear pairs. In a next step, a parameterized CAD model of hub and web was generated, from which the FE models of those regions were derived and merged with the FE mesh of gear teeth to obtain a complete hybrid gear FE model description. The parametric approach facilitates the integration of the proposed workflow into an industrial design process allowing to easily change rim/web/hub CAD data. For model validation purposes, the FE model of the hybrid gear with the same isotropic material properties of the web as given in [6] (Young's modulus of 44 GPa, Poisson's ratio of 0.3 and mass density of 1522 Kg/m^3) was built and a modal analysis executed. Table 1 shows a comparison between the model developed and the one analyzed in [6] in terms of first 4 natural frequencies of the gear. The experimental results reported in [6] are illustrated as well.

FE-based predictions reported in [6]	**FE-based predictions with the proposed model**	**Difference**	**Experimental results in [6]**
[Hz]		**%**	[Hz]
7780	7851	+ 0.9	6270
7913	8014	+ 1.2	
13745	13656	- 0.6	9743
14592	14843	+1.7	10700

Table 1: Comparison between predicted and experimental frequencies of the hybrid gear

The results summarized in Table 1 show that FE predictions on the proposed model are very close to FE-based estimations reported in [6]. Small differences are likely due to geometry uncertainties since few geometric parameters were unavailable. In addition, by comparison against test data, it can be noted that both FE models overestimate all frequencies by a large amount, suggesting that an isotropic material formulation fails to catch the modal behavior of the gear in the frequency range that has been analyzed. For this reason, an improvement of the predictive accuracy was pursued through a multi-scale approach applied to the composite material of the gear web.

4. Multi-scale modeling of triaxial braided composite

As described in [6,8], the model of the gear web is created as a stack of several braided composite prepregs. Each layer of such material consists of an axial yarn (24k carbon fibers in 0° direction) and bias yarns (12k carbon fibers in ±60° direction). Bias yarns are alternately passing above and under axial yarns with equal amount of material by weight in each direction. Figure 3 shows a CAD representation of triaxial composite architecture with axial and bias directions.

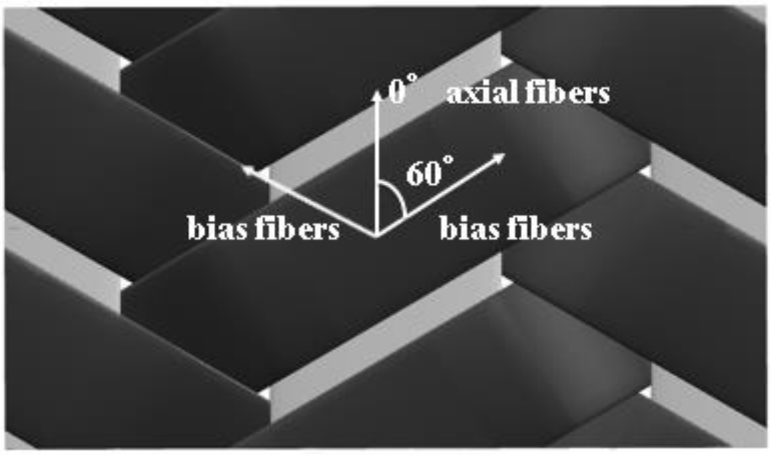


Figure 3: Triaxial architecture.

With such a triaxial architecture, it was shown that a single layer of braided fabrics is balanced, symmetric and quasi-isotropic. It is known from laminates theory that a symmetric laminate is composed by plies in which material, orientation and thickness are symmetric about neutral axis [13]. This condition allows to avoid undesired effects due to unbalanced loads in plane, which could cause warping phenomena during fabrication.

In general, composite modelling at the meso-scale can be achieved by considering two main scales, as shown in Figure 2:

- the micro-scale, in which fiber geometry, packing and interaction between fibers and matrix are considered;
- the meso-scale, where the architecture of the composite unit cell is defined. Here, yarn geometry, local fiber direction, fiber volume fraction inside yarns, interactions between the yarns and between the yarns and the surrounding matrix are taken into account.

Numerical homogenization of a triaxial composite unit cell is performed using the Simcenter™ VMC ToolKit (part of Siemens PLM Software): a set of software tools developed for virtual material characterization [20]. The tool is used to obtain homogenised properties of the impregnated yarns on the micro-scale and subsequently link them to meso–level in order to compute the homogenised properties of plies. The main idea is to reduce modelling efforts and number of physical tests on coupons required to characterize mechanical behavior of composites.

4.1 Micro-scale modeling

The multi-scale modeling approach started with the evaluation of local properties of impregnated yarns, taking into account local fiber volume fraction and orientation, based on Chamis formula [22]:

$$E_{11} = V_f E_{f11} + V_m E_m \tag{1}$$

$$E_{22} = \frac{E_m}{1-\sqrt{V_f}(1-\frac{E_m}{E_{f22}})} = E_{33} \tag{2}$$

$$G_{12} = \frac{G_m}{1-\sqrt{V_f}(1-\frac{G_m}{G_{f12}})} = G_{13} \tag{3}$$

$$G_{23} = \frac{G_m}{1-\sqrt{V_f}(1-\frac{G_m}{G_{f13}})} \tag{4}$$

$$\nu_{12} = V_f \nu_{f12} + V_m \nu_m = \nu_{13} \tag{5}$$

$$\nu_{23} = \frac{E_{22}}{2G_{23}} - 1 \tag{6}$$

where the subscripts f and m stand for fibers and matrix, respectively, while E_{ii}, ν_{ij} and G_{ij} (with $i, j = 1,..,3$ are the longitudinal, in-plane and out-of-plane transversal directions respectively) are the Young's moduli, Poisson's ratios and Shear moduli, while V_f and V_m are the volume fraction of the fibers and of the matrix respectively.

Material data used in this work for the analysis of yarns properties of the braided composite material was taken from [6] and [16], and summarized in Table 2. An important aspect of this micro-scale analysis is the definition of the fiber volume fraction in the yarns and in the entire unit cell, which have to be considered when using the Chamis formula. In [17], it is shown that the the maximum volume fraction of the fiber (V_f) achievable in a single layer panel is 0.48 due to the limitations of the manufacturing process. In the RUC models described in [17], such a value is achieved by setting the fiber volume fractions in axial yarns and bias yarns to 0.86 and 0.69 respectively, while the values estimated experimentally are 0.77 and 0.745. In the model presented here the overall volume fraction of the single layer is set to 0.48, which is achieved by defining a fiber volume fraction of 0.86 for both the axial and the bias yarns.

Property	**Fiber**	**Matrix**
Material type	Carbon T700S	Epoxy E862
Longitudinal Modulus [GPa]	230	2.7
Transverse Modulus [GPa]	15	2.7
Shear Modulus	24 Long./5.03 Transverse	1
Density [g/cm^3]	1.8	1.2
Single fiber diameter	7.0	--

Table 2: Fiber and matrix properties.

4.2 Meso-scale modeling

The meso-scale analysis was performed starting from the CAD model construction. This model was further imported in the VMC ToolKit, capable to mesh the geometry, to define the material properties for both matrix and fibers and to set the periodic boundary conditions [21]. The used strategy is described below.

4.2.1 CAD model generation for the unit cell

The geometric model of a triaxial braided composite unit cell provides a complete description of the internal geometric features, such as yarn cross section and interweaving and matrix dimensions. In detail, a parameterized CAD model was composed by multiple yarns built from a known elliptic cross section geometry. In order to obtain a solid volume starting from sketches in different 2D planes, cross sections were repeated along a specified direction described by a heart line, which was linked to a predefined crimp value. The proposed approach allows to take into account yarn width, thickness and spacing, in addition to the shape of the cross sections, as parametric features in the CAD model. A symmetric periodic unit cell is essential for the application of periodic boundary conditions. This requirement was met by trimming the overall geometry with specific symmetric planes and by extracting a solid 3D surrounding matrix, as shown in Figures 4 and 5.

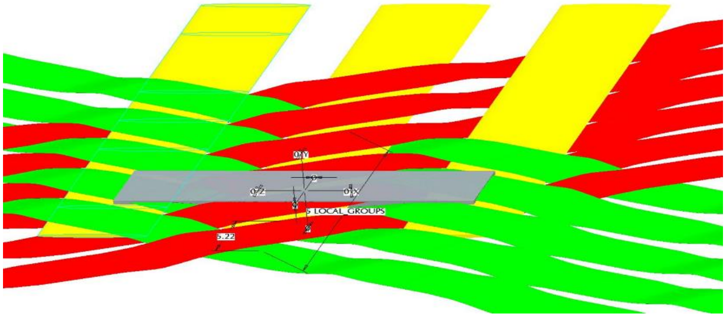


Figure 4: Braided fabric pattern.

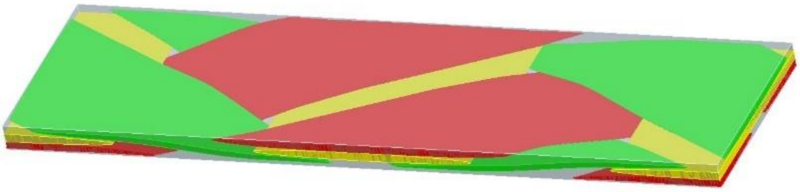


Figure 5: Unit cell obtained after trimming.

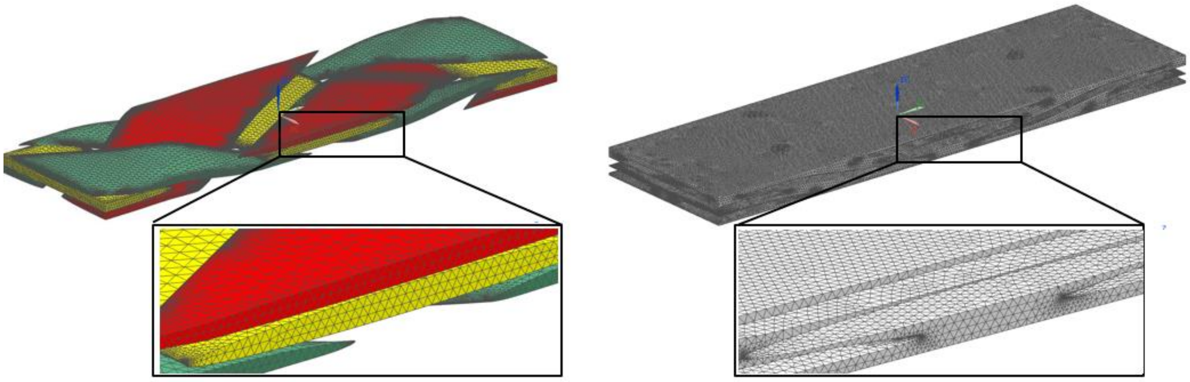
The CAD model was parameterized to enable geometric modifications with reduced modeling effort and time, as to enable the generation of a RUC model with an adequate distance between two or more solid volumes to avoid interpenetration. All geometric features used in the case study presented here are reported in Table 3 and are similar to those observed experimentally and considered in [16], as to enable a quality assessment of the resulting macro elastic material properties based on literature data.

Unit cell length	**Unit cell width**	**Unit cell height**	**Major dimension of axial elliptic cross-section**	**Major dimension of bias elliptic cross-section**	**Area of axial elliptic cross section**	**Area of bias elliptic cross section**
[mm]					[mm^2]	
18.08	5.22	0.73	5.5	3.7	1.2	0.62

Table 3: Unit cell geometry.

4.2.2 Mesh generation and local material definition

The main purpose in creating a mesh is to approximate properly the CAD geometry. In detail, yarns and matrix were meshed with linear tetrahedral solid elements, which can have very small dimensions and follow accurately the curvature of the yarns. Since the unit cell is characterized by a repetitive behavior in the plane, the mesh of the opposite faces was generated by imposing a constraint of identical discretization, both for yarns and matrix. Figures 6-a and 6-b show the generated meshes for the yarns and for the matrix respectively.



a) b)

Figure 6: Generated FE mesh of yarns only (a) and of the entire RUC (b).

Yarn’s material was considered with a transverse isotropic behavior and its properties were derived using the Chamis formula, as described in Section 4.1. On the contrary, matrix material properties were set according to the material specifications of Table 2, with an isotropic behavior. In order to complete the process of mesh generation of the analyzed composite, local material orientation of the fibers has to be taken into account. This was achieved in CAD environment by selecting a heart line in a yarn created in the solid model. In this way, material orientation effects with respect to various crimp angles of the yarns can be accurately captured in the subsequent FE analysis. Figure 7 shows how local material orientation is defined.

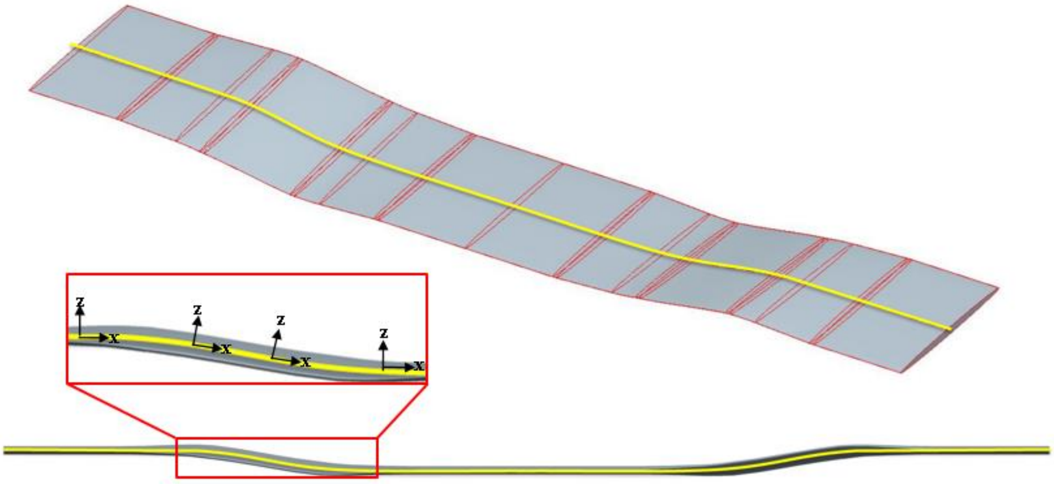


Figure 7: Heart line and local material orientation.

Finally, the interaction between yarns and the matrix, which are in contact during normal working conditions, was defined through a surface gluing function. No relative movement between the nodes in contact of the matrix and of the yarns were, therefore, allowed.

4.2.3 Periodic boundary conditions

The last step of the overall multi-scale pre-processing analysis is the definition of proper boundary conditions for the unit cell. Different types of boundary conditions have been proposed and discussed in the literature, as reported in [23]. In general, a proper choice is case-dependent and is to be based on the actual internal material structure at meso-scale level (e.g. straight/rectangular periodic, axisymmetric or aperiodic). Periodic boundary fluctuations proved able to provide reasonable estimates of the effective properties even for non-periodic heterogeneous materials [24, 25]. In the case study presented here, the material cell is rectangular-periodic, which makes the shape of the macro-scale application irrelevant. The virtual material characterization is then achievable by applying periodic boundary conditions to the model in order to simulate periodicity of a given unit cell geometry as described in [26]. Since the analysis is related to the single unit cell at the meso-level, the requirement of displacement continuity close to the opposite faces is fulfilled by imposing that any displacement on one side of the RUC is the same as in the opposite side plus or minus a constant value. Disregarding displacements and rotations of the unit cell, the displacement field can be written as:

$$u(\overline{x}) = \bar{\bar{\varepsilon}}\,\overline{x} + \tilde{u}(\overline{x}) \tag{7}$$

where $\bar{\bar{\varepsilon}}$ represents the macroscopic strain tensor and $\overline{x}$ the position vector of a material point in the RUC. The second term is a volume periodic term with zero average value, with $\tilde{u}$ being the local displacement field in the RUC.

Six different subcases of linear static analysis, three tensile load cases and three shear load cases, were created and solved for subsequent homogenization process.

4.3 Material homogenization

The final goal of the proposed multi-scale modeling approach is the evaluation of homogenized elastic properties of the analyzed unit cell. Such properties are calculated by post-processing the FE stress-strain results. Figure 8 shows the displacement field for the load case in transverse direction.

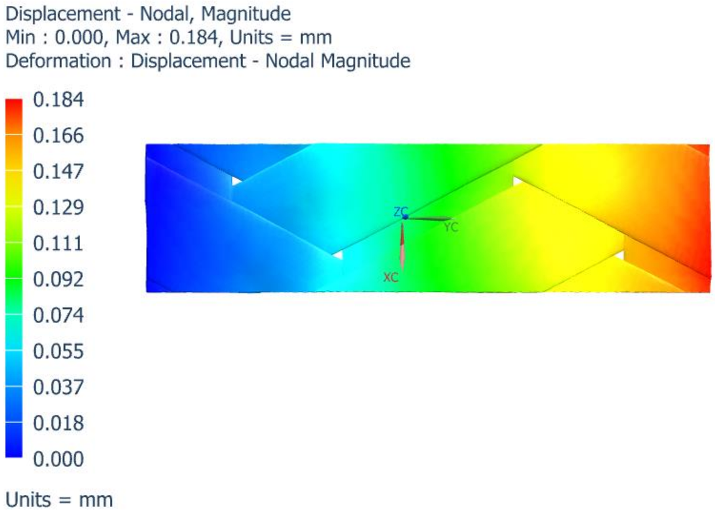


Figure 8: Displacement field of the yarns under the transverse tensile static load case analysed for material homogenization.

The relationship between stresses and strains at the macro-level can be expressed as follows:

$$\sigma_{ij}^{H} = C_{ijkl}^{H}\, \varepsilon_{kl}^{H} \tag{9}$$

where C_{ijkl}^{H} represents the elasticity tensor at macro-scale. in order to obtain stiffness/compliance matrix and to derive elastic modulus values, the volume averaging technique was used, in which stresses are averaged over all the integration points of elements:

$$\langle\sigma\rangle = \frac{1}{V} \sum_{p=1}^{n} \sigma^{p} V^{p} \tag{10}$$

where σ^{p} and V^{p} are the stresses and the equivalent volume of the integration points respectively. In Table 4, the homogenized macro elastic properties are compared with the experimental, the analytical and the numerical values reported in [17]. The latter values are referred to a RUC model without axial fiber bundle undulation.

	RUC properties described in [17]: Experimental	**RUC model described in [17]: analytical approach**	**RUC model described in [17]: numerical approach**	**RUC properties with the multi-scale approach**
	[GPa]			
E_1	40.6	42.9	42.8	42.8
E_2	38.5	42.5	38.9	41.4

$\mathbf{E_3}$	------------	---------	--------	7.4
$\boldsymbol{\upsilon_{12}}$	------------	---------	-------	0.3
$\boldsymbol{\upsilon_{23}}$	-----------	---------	-------	0.39
$\boldsymbol{\upsilon_{13}}$	-----------	---------	-------	0.36
$\mathbf{G_{12}}$	----------	15.88	15.9	14.2
$\mathbf{G_{13}}$	----------	------	------	2.06
$\mathbf{G_{23}}$	---------	------	------	2.03

Table 4: Comparison of elastic material properties of RUC without considering axial bundle undulation [17].

Table 4 shows that the numerical results achieved with the proposed methodology are close to those presented in [17]. In addition, the axial fiber bundle undulation effect, which is currently neglected, can contribute to bring stiffness moduli much closer to the experimental values, as demonstrated in [17].

5. Macro scale FE modal analysis of a hybrid gear

A FE-based modal analysis was set up taking into account the gear model discussed in [6]. In detail, three thick plies, made of twelve layers of prepregs, were assembled in a hybrid gear model along the axial direction. The assembly was then attached to a steel gear rim through an adhesive bounding. Each layer was rotated by 60° around z-axis to increase through-the-thickness isotropic behavior. As a result, the same stack configuration proposed in [6] was, finally, obtained. Furthermore, solid laminate modeling, available in NX Nastran, was used to simulate ply arrangement effect on the gear web, by considering transverse shear effects and out of plane stresses. The solid model was implemented with the calculated homogenized orthotropic elastic properties of the triaxial braided composite material. The results of the FE modal analyses of the proposed gear model in free-free boundary conditions are presented in Figure 9. Table 5 summarizes the obtained hybrid gear eigenfrequencies for the two models (isotropic and anisotropic composite materials) comparing them with the experimental and numerical data published in [6].

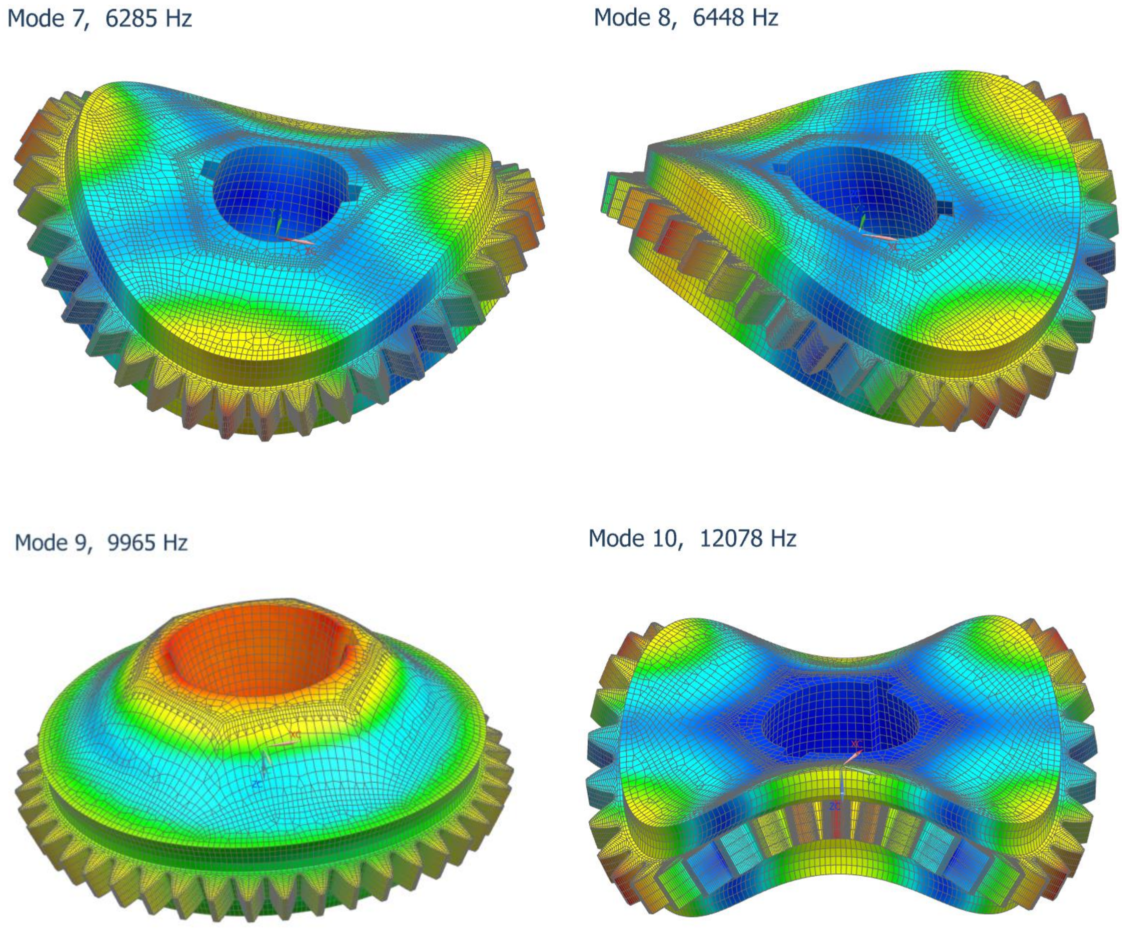


Figure 9: First four shape modes evaluated with anisotropic web properties.

Experimental results in [6]	**FE results in [6]**	**FE results: proposed model with isotropic material**	**FE results: proposed model with orthotropic material**
[Hz]			
6270	7780 (+24%)	7851 (+24.9%)	6285 (+0.2%)
	7913 (+26%)	8014 (+27.2%)	6448 (+2.8%)
9743	13745 (+41%)	13656 (+40.4%)	9965 (+2.3%)
10700	14592 (+36%)	14843 (+37.3%)	12078 (+12.8%)

Table 5: Comparison of predicted and experimental natural frequencies for model validation.

As already commented in Section 2, the numerical model proposed in [6] and the one proposed in this paper, implemented with isotropic material properties, generated frequency predictions that are very close to each other but significantly different from the experimental ones. This confirms the quality of the generated CAD and FE models of the gear. The FE model with the orthotropic formulation of the composite web material, achieved through the proposed multi-scale modelling approach for the triaxial braided composites, enabled more accurate predictions, which are much closer to the experimental results. This is more evident for the first two natural frequencies, where the difference between predicted and measured values is 0.2% and 2.8%, while differences of up to 41% are reported for the model with isotropic formulation of web material.

The model accuracy decreases when the third frequency was considered, with a difference slightly higher than 10% between experimental and orthotropic FE results, which is likely due to inaccuracies in the model linked to the web-rim interface and inter-laminar connection. Both factors, in fact, were neglected in the present model and are expected to play an important role on the overall modal response of the hybrid gear.

6. Conclusions

In this paper a multi-scale modeling approach was employed to predict natural frequencies of a hybrid gear. The gear was presented with web body made of stacks of braided prepregs. The composite web geometry was analysed by considering micro, meso and macro scales. In the micro scale, elastic properties of yarns were homogenized using analytical formulation taking into account the local fiber volume fraction. In the meso scale, the RUC of the braided composite was defined in a parameterized CAD model composed by multiple yarns built from a known elliptic cross section geometry. Then, the CAD geometry was accurately meshed and periodic boundary conditions were applied to simulate periodicity of the given unit cell. Finally, macro elastic properties were evaluated through a homogenization process, based on the volumetric stress averaging.

Two FE models were executed: the web being modelled as an isotropic and an orthotropic solid body. In the latter case, effective homogenized orthotropic properties of the triaxial braided composite were considered. Even if the braided material has quasi-isotropic properties in plane and the ply stack configuration is set up to achieve the best isotropic behavior along the axial direction of gear, by comparing the numerical results with the experimental data available in the literature, it was shown that the natural frequencies of the gear cannot be accurately predicted if anisotropy along axial direction is neglected. On the contrary, it was shown that the modal results achieved with a model with orthotropic material formulation are close to the experimental evidence for the first and second natural frequencies, while a more significant difference still exists for the third normal mode.

Even if further investigations are needed to explore the origin of this difference, the achieved results show the potential of the proposed approach to accurately model hybrid gears.

The presented approach can be used in subsequent FE-based simulations aimed at assessing the static and dynamic stiffness performance of such advanced transmissions in comparison to conventional, full metal gears. Moreover, the parametric definition of the hybrid gear geometry implemented in the overall multi-scale modelling procedure can be exploited to reduce modelling effort and time for further design optimization of the composite web part (stacking sequence, geometrical shape, etc.).

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