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DETERMINATION OF THE MECHANICAL PROPERTIES OF BRAIDED COMPOSITE BEAMS WITH EXPERIMENTAL AND NUMERICAL METHODS

Yordan Kyosev[1]*, Gaëtan Hello[2]*, Jana Reinsch[1], Zoheir Aboura[3], Julien Schneider[4]

[1]*Hochschule Niederrhein – University of Applied Sciences, Research Institute of Textile and Clothing, Mönchengladbach, Germanyffiliation*

[2]*Université d'Evry Val d'Essonne, UFR Sciences et Technologies, Laboratoire de Mécanique et d'Energétique d'Evry, Courcouronnes, France*

[3]*Université de Technologie de Compiègne, Laboratoire Roberval, Compiègne, France*

[4]*Snecma Villaroche, Safran Group, Moissy-Cramayel, France*

*corresponding authors: *yordan.kyosev@hs-niederrhein.de* *gaetan.hello@ufrst.univ-evry.fr*

ABSTRACT

Composite beams reinforced with braided fabrics exhibit good mechanical properties and are used for different applications as basic structural element. This work presents an investigation about the numerical determination of the mechanical behavior of braided architectures using geometrical modelling and subsequent voxel-FE homogenization of the structure for estimation of the tensile properties. The experimental and voxel-FE results are finally compared.

INTRODUCTION

In the last years, composite beams have started to replace their metallic counterparts for several structural components such as framework constructions. In particular, composite beams reinforced with braided fabrics should have better properties under twisting loads compared to pultruded parallel yarns from the same materials. The reason being that yarns axes follow a helix structure and thus half of the yarns (in plus or minus direction) are oriented nearly parallel to the twisting loading stress. From other side, beams with carbon fibers reinforcement have negligible thermal elongation and are used constructions where high geometrical accuracy under large range of temperature changes is required.

This paper presents a method for the computational estimation of the initial elasticity modulus of braided beams, which has the potential to be used as an automated procedure during the designing and optimization of braided composite beams. For the numerical investigation, the geometry of the braids is generated using parametric geometrical models obtained with the software TexMind Braider [1, 2]. The yarns geometric information is then translated into the input data format of the software REVoxel which provides Representation of material Elementary Volumes with voxels [3-5]. Voxel-FE models of the braided architectures can be generated with proper sets of boundary conditions. A homogenization procedure is then automatically performed with python scripts piloting Abaqus software [3]. Finally, estimations for the elastic moduli derived from experimental and numerical approaches are compared.

GEOMETRICAL MODELLING

There are several research works, describing methods for geometry generation of the tubular braided fabrics based on simplified geometrical or trigonometrical relations [6,7,8,9]. In this paper, the basic principle for modelling, described in [10] is used, which follows the definition of characteristic contact points for the topology of the structure and because of this has the advantage to be not limited to the main used structures like regular, diamond etc., but is able to represent tubular braids with any floating length and number of yarns in a group [2]. For the interpolation of the curve between the contact points splines of arbitrary power (3,4,5 or higher) can be used and the yarn volume around the curve is created by sweeping the yarn cross section as demonstrated in [7, 10, 11]. The use of minimal set of characteristic contact points leads to simple models, which are extendable for various others structures (flat, fancy, form braids) and needs minimal computational time, but have as well some disadvantages – the interpolated curves between these points can intersect, which is a problem for instance if homogenization procedure has to be started over this geometry. To avoid such intersections in the current implementation additional parameters for the distance between the yarns at the contact points is introduced, so that after visual or computational test this distance can be adjusted and no interaction in the another areas is presented. More accurate model would be obtained after checking the distance between the contacting yarns at some interval ΔL, but this requires more complex iterative procedure which is time consuming and not always leading to mechanically correct geometry, because still does not consider the mechanical properties of the yarns and the acting forces. The implementation of such FEM-like procedure is planned as refinement part of the models for the future.

The current geometric parametrical model is implemented in C++, within graphical user interface based on wxWidgets library and mathematical computations with Eigen library. The algorithms are integrated in the software TexMind Braider [1] which 3D visualization capabilities are used.

COMPOSITE BEAM PRODUCTION

Using 8 glass multifilament yarns with fineness 69tex of E-Glass with effective density (as yarn volume) 2.3g/cm^3 two different braids with floating length of two (carrier arrangement one full – one empty) on a braiding machine with four horn gears and four slots per horn gear are produced (Figure 1). The first braid type was produced with 9 pics per cm (Figure 2a) and the second with 4.5 pics per cm (Figure 2d). These braids were laminated with epoxy resin as beams with circular cross section using silicon negative form.

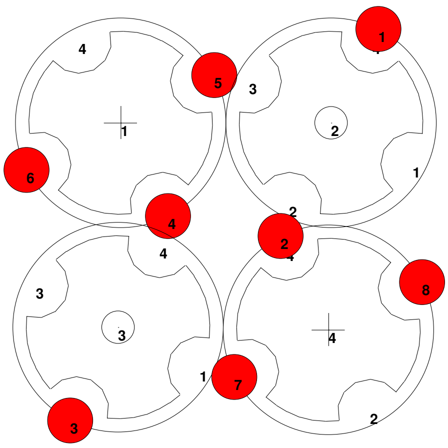


Figure 1 Configuration of the braiding machine for the braided beam production

Because the glass multifilament yarns are without twist, they change the cross section in the different area of the braid. The current geometrical model assume circular yarn cross sections of the yarns and because the geometry is controlled only on the topologically important contact points, there are slight intersections between the yarn volumes, if the outer diameter of the modelled braid is chosen to be the same as the real one(Figure 2b and 2e). The volume intersections actually cause increased stiffness during the homogenization procedure, and to avoid this, the yarn geometries are generated with small spaces between the yarn surfaces on the contact places, so that no volume intersection of the yarns is presented (Figure 2c and 2f). During this expansion of the structure of course the orientation of the yarn is slightly changed and lead to additional simulation errors, which has to be considered in the evaluation of the results.

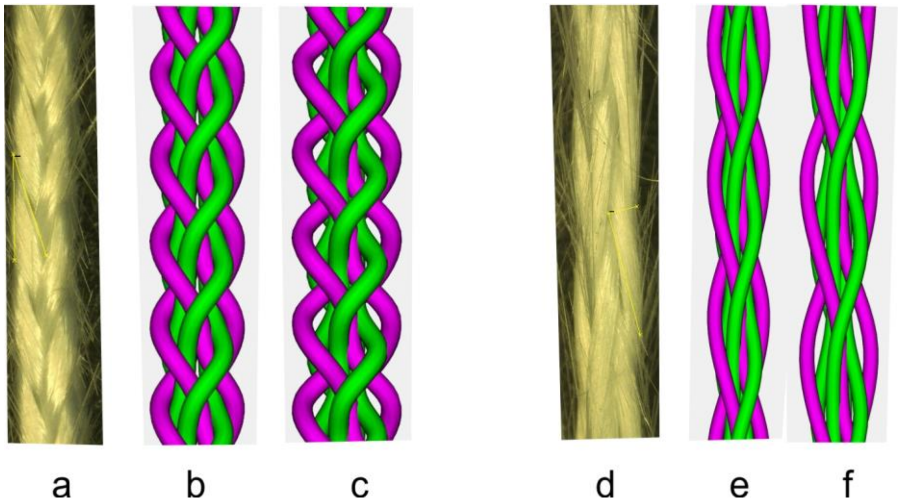


Figure 2 Investigated braids for beams a) ad d) produced structures with 9ppc and 4.5ppc, b) and d) - modelled geometry in correct scale, but with small yarn intersection regions, c) and f) slightly expanded geometry, free of intersections

VIRTUAL TESTING PROCEDURE

General Aspects

Composite beams reinforced with braided fabrics exhibit a complex material architecture. On the microscopic scale, glass fibers are gathered so as to build yarns. These yarns are then braided at the mesoscopic scale leading to a meso Representative Elementary Volume (REV). Finally, the macroscopic structure, here the beam, is obtained by using repeated meso REV. In order to perform accurate simulations, each scale of analysis then requires proper information about material properties, geometrical description of the architecture and boundary-conditions (BC).

Microscopic homogenization

Yarns are built with parallel glass fibers tied together with epoxy matrix. Both materials appear to have isotropic linear elastic properties and their elastic constants are known. Glass fibers are considered to have a Young modulus within the range [70-80] GPa with a Poisson ratio of 0.2 while the matrix has a Young modulus of 5 GPa and ν=0.3. Glass fibers are assumed to be bundled without twist. Yarns are also supposed to have a constant volumic fraction of fiber, neglecting there compaction effects. The REV may then be considered as the classical regular hexagonal pattern where fibers centerlines coincide with the vertices of a hexagon (fig. 3). The expected homogenized behavior of the yarn is less complex than orthotropic thanks to material symmetries. The number of free material variables is then at most 9. The identification of those parameters is performed through a numerical homogenization procedure. The material architecture being rather simple, standard FE conformal meshes may be generated automatically using a standard commercial mesher (in Abaqus CAE here). The element employed is the tetrahedron with 10 nodes which is considered reliable and accurate for general purpose implicit elastic simulations. Six simulations are run, each corresponding to a proper set of boundary conditions [3]. The results are then post-treated with classical averaging schemes and homogenized elastic properties are then estimated. All the procedure is performed automatically using Python scripts.

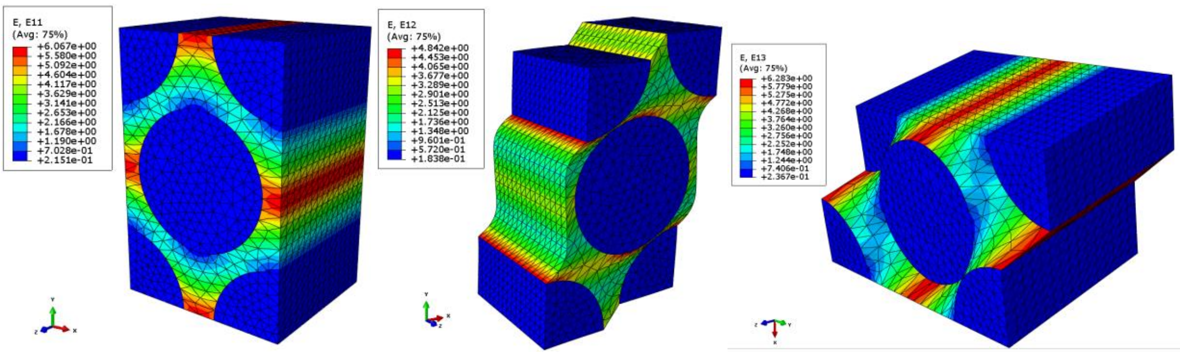


Figure 3 Deformed REV for the microscopic homogenization of yarns with boundary conditions sets: (left) 11, (center) 12 and (right) 13.

A significant parameter of the yarn material architecture is fibers fraction. With this hexagonal configuration of the REV, up to ~91% may be achieved. The influence of this parameter on homogenized parameters is assessed by performing numerical homogenization for 50, 60, 70 % of fibers within the REV (fibers radius being set accordingly). Results are gathered below:

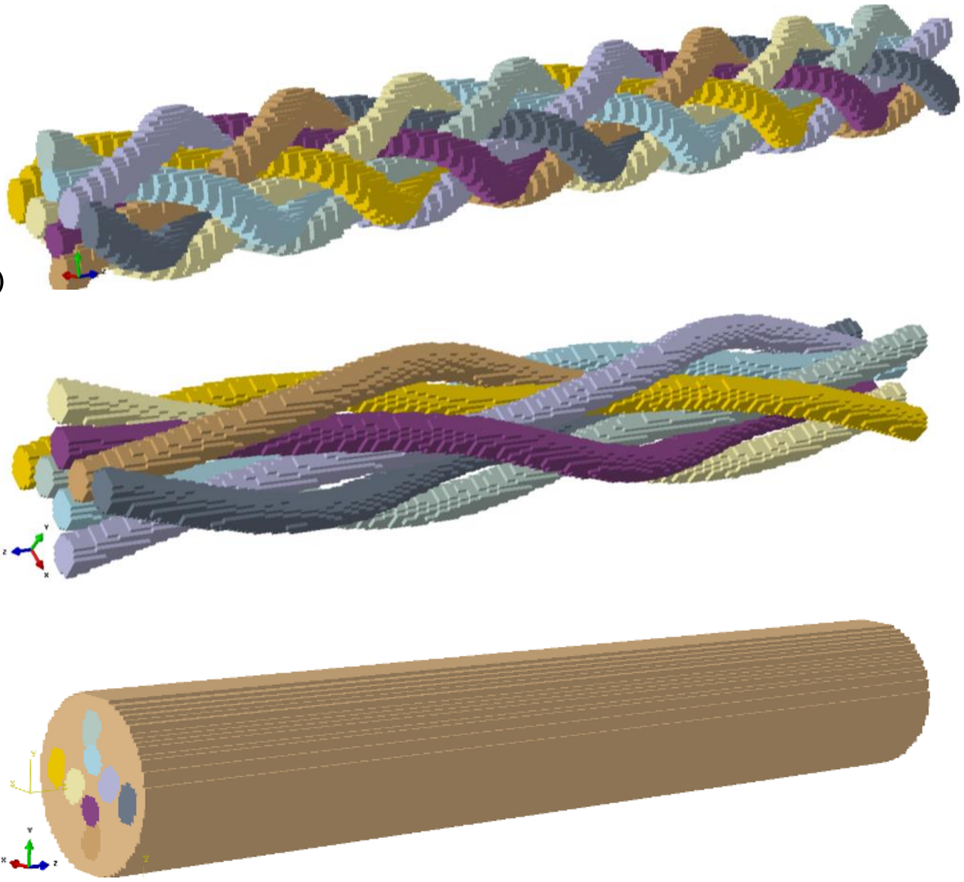
Table 1. Results of numerical homogenization

Glass type	E=70 GPa			E=80 GPa		
Glass %	0.5	0.6	0.7	0.5	0.6	0.7
E11 (GPa)	12.21	15.39	20.18	12,43	15,77	20,90
E22	12.21	15.39	20.18	12,43	15,77	20,90
E33	37.52	44.01	50.51	42,52	50,01	57,51
G12 (GPa)	4.525	5.795	7.753	4,595	5,927	8,018
G13	4.927	6.212	8.137	5,018	6,367	8,420
G23	4.927	6.212	8.137	5,018	6,367	8,420
nu12	0.349	0.328	0.301	0,352	0,331	0,304
nu13	0.0789	0.0815	0.0894	0,0709	0,0735	0,0813
nu23	0.0789	0.0815	0.0894	0,0709	0,0735	0,0813

As expected, pairs of moduli have the same values (E11/E22, G12/G13, nu13/nu23). For the materials investigated, the ratio between longitudinal and transverse traction moduli lies between 2.5 and 3.5 while for shear moduli values are close. These data can now be used to describe yarns behavior at the meso/macro-scale.

Macroscopic simulation

In the case of composite beams reinforced with braided fabrics, the distinction between meso and macro scales tends to disappear. In fact, the macro beam diameter is the same as the one of the meso REV. The beam may then be seen as the repetition of the REV along the longitudinal direction. This fact significantly simplifies the macro material parameters identification process. The REV having a cylindrical shape, it requires specific periodicity boundary conditions that differ from classical ones applied on hexahedral REV. Here, the virtual testing of beams may be performed by using simple BC that mimic those used experimentally. The difficult point on this scale is the description of the material architecture. A continuous description of yarns is first obtained from the TexMind Braider software. This information has now to be translated, as automatically as possible, into a FE ready simulation input file. The transformation is performed with the software REVoxel [4, 5]. This software is able to generate automatically FE input files for a large scope of complex material architectures (polycrystalline aggregates, 2D/3D woven, porous materials, laminated, braided etc.). It relies on the robust and efficient projection of material information on a regular voxel grid. This approach has the advantages of genericity, automation and straightforwardness. It is well suited for homogenization procedure even though FE models obtained tend to be rather large (typically a few millions of degrees of freedom). The two material architectures 9ppc and 4.5ppc are treated (Fig. 4).



(a) (b) (c)

Figure 4 Virtual beams voxel-FE models : (a) '9 variant' model 8 yarns architecture, (b) '4.5 variant' model 8 yarns architecture, (c) complete beam with glass/epoxy 9ppc yarns and epoxy matrix.

Once the beam voxel-FE model is properly defined regarding material properties and geometry, it only remains to apply proper BC. Here, one end of the beam is pinned while the other is submitted to a uniform longitudinal unitary displacement. After the completion of the simulation, nodal forces are retrieved on points where kinematic BC were imposed. The longitudinal elastic beam modulus is then retrieved using simple strength of materials formulae.

Table 2. Elasticity Modulus

Glass	E (GPa) - 9 ppc model	E (GPa) - 4.5 ppc model
70 GPa, 70% in yarn	11.89	15.04
80 GPa, 70% in yarn	12.63	16.50

As expected, the 4.5 ppc model exhibits higher moduli than 9 ppc model. These values lie between classical analytical bounds for the different materials investigated.

VALIDATION

For the determination of the tensile properties the ends of the dry braids and the beams were embedded in epoxy blocks (Figure 5), in order the damages in the clamp area during the testing to be avoided.

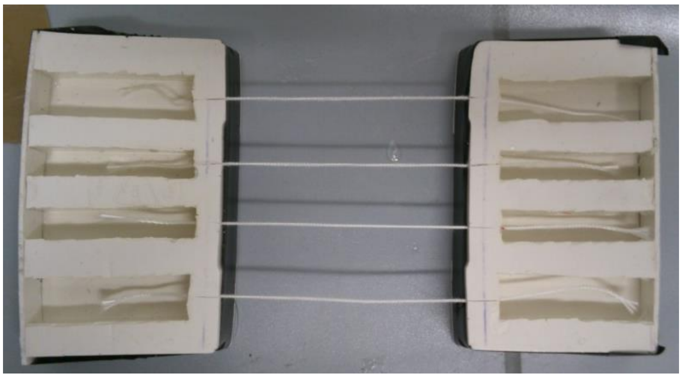


Figure 5. Embedding the samples in epoxy blocks at the both ends for avoiding the influence of the clamp damages over the testing results

Tensional elasticity modulus were estimated based on the force elongation curves of the braids, as given in the Table 3. As the results show, the meazured elasticity modulus is significantly lower the the calculated one, but it is clear that the braid with higher number of braids per cm (Braid 2), which has as well lower braiding angle – has higher elasticity modulus.

Table 3. Elasticity Modulus

	Braid 1 (9ppc)	Braid 2 (4.5 ppc)
Elasticity Modulus Measured	70,9 MPa	80,2 MPa

Because of the large difference between the simulation and the measurement, even after repeating the tests and checking the results the place for this problem was looked. It was observed hairiness of the dry braids, which means that some part of the filaments ware broken during the preparation for braiding and the braiding process, which reduce significantly the mechanical properties of the braid. An REM image of the dry braids confirmed this expectation, and demonstrated, that at the current equipment the damages of the fibres are very significant (Figure 6). Additionally to the several bending areas during the winding and braiding, during the production of such micro beam the crimp of the yarns is very significant and lead to the several broken ends.

Because of these significant fibre damages on the current set of samples it was not possible to perform correct validation of the modelling at the current time.

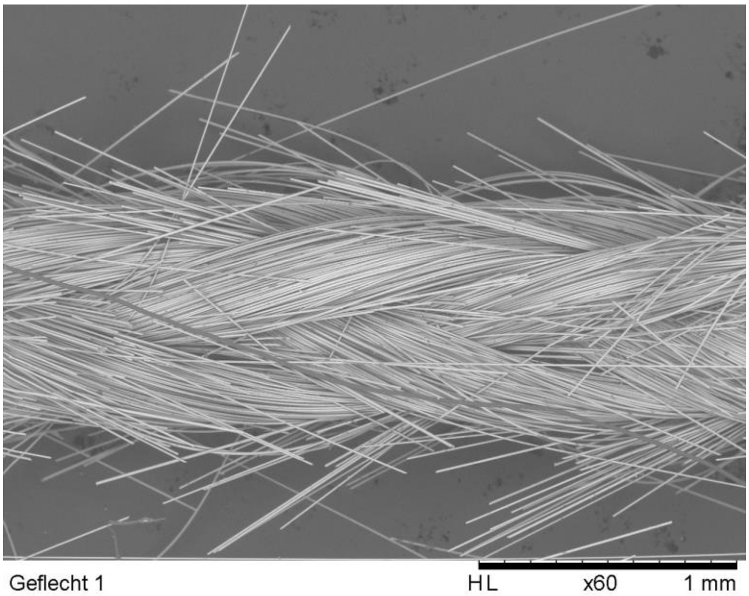


Figure 6. REM image of the dry braid, where the large amount of fiber damages are visible.

CONCLUSION

An automated procedure for the prediction of the elasticity modulus of braided composites is developed and tested. It is based on geometrical modelling of the geometry of the braids, subsequent homogenization of the composite material with Voxel grid and simulation of the tensile behavior within the commercial code Abaqus. Because of detected significant fiber damages during the production, it was not possible to validate the simulated results with experimental. Nevertheless the method has large potential for prediction of the properties of braided beams not only under tension, but as well for other loading cases.

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