

Advances in braided composites modelling: process and material points of view

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1. Introduction

Composite materials based on braids [1] are more and more attractive for aerospace and automotive industries for different reasons. First, their manufacturing relies on the automated production of dry braids that are then consolidated in an out-of-autoclave process (typically RTM): this decreases the energy needed for manufacturing and allows for repeatability in the process thanks to automatization. Secondly, the interlacement of the yarns that create the braid makes the final composite material more performant regarding delamination compared to unidirectional plies. Finally, by controlling the braiding machine parameters it is possible to tailor the resulting composite material to the application, by assigning optimal local fibres orientations. In this paper, we focus on 2D-triaxial braids (Figure 1). A typical architecture for such a braid is $[0_{12K}/\theta_{6K}/-\theta_{6K}]$, with θ being the bias angle, and 12K means that there are 12000 filaments in a yarn.

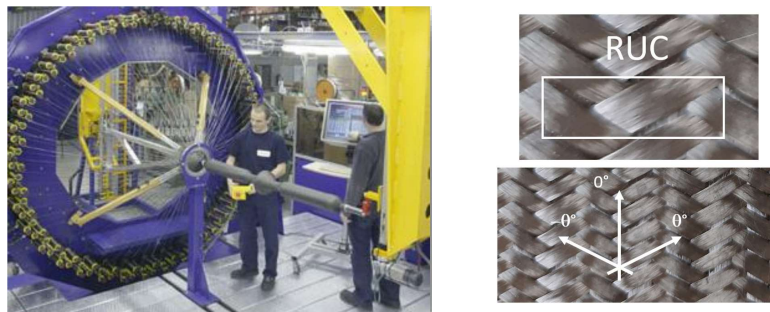


Figure 1. A braiding machine [2] and a 2D-triaxial braid

The goal of braiding process simulation is to be able, based on the machine parameters, to determine on a mandrel of a given geometry, the local fibers orientations of the braid, as well as the local cover factor and braid thickness. In the first part of this paper, we describe and compare different ways to simulate the braiding process. The different methods, of increasing complexity, generality and accuracy, rely on analytical and kinematic approaches [3,4], programmed here in Matlab, and on the finite element method (here, LS-Dyna is used). We briefly compare the merits and discuss the limitations of each approach.

In the second part of the paper, we focus on material modelling. The predicted local fiber orientations are the input of a dedicated material model that will determine the local mechanical properties of the composite that are then used in a finite element model of the part for structural analysis. In this paper, a multi-scale approach is used, which relies on the modelling and analysis of RVEs (Representative Volume Element, also called RUC – Representative Unit Cell) of the braid. The modelling approach for the RUC and the validation of the prediction of elastic properties are presented.

The developments presented here are conducted in the frame of the ViBra (Virtual Braiding) project (SPW Convention n° 8422), founded by the Walloon region of Belgium, and supported by the Walloon aerospace cluster Skywin. The 3-years project

started in September 2019 and involves several partners (GDTech, the University of Liège, SABCA, Open Engineering, ISOMATEX and Centexbel). The main points to be addressed in ViBra are illustrated in Figure 2.

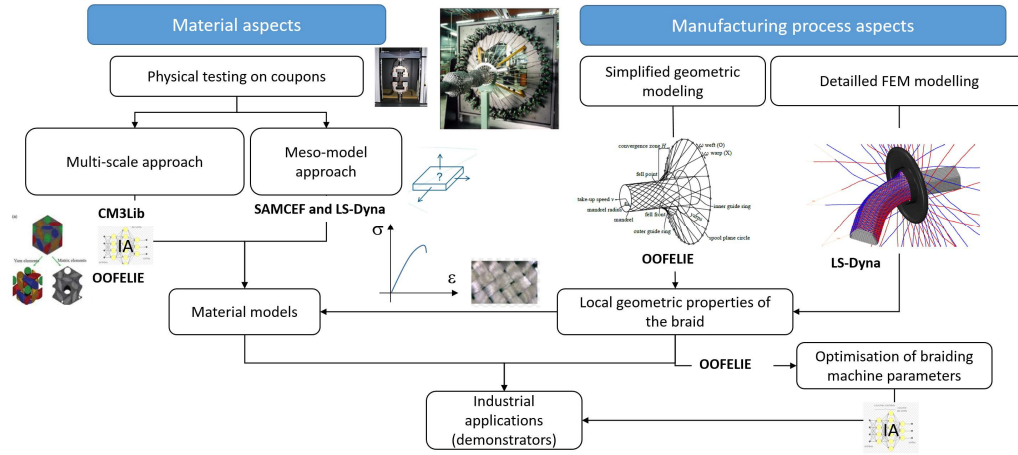


Figure 2. Research activities in the ViBra project

2. Process simulation for braided composites

2.1 Analytical and kinematic approaches

Based on geometric considerations, the deposition angle during the braiding process on a cylindrical mandrel can be obtained by the following formula [1], where R_m is the radius of the mandrel, w and v are the rotational speed of the carriers and the translational take-up speed of the mandrel, respectively.

$$\tan \alpha = \frac{wR_m}{v}$$

That formula is only valid for cylindrical mandrels and doesn't take into account the transient effects on the value of α occurring at the beginning of the process or when changes appear in the mandrel cross section geometry. With the approach proposed by Du [3], mandrels of variable circular cross sections can be considered, and the transient state is taken into account (Figure 3). That method, based on the solution of a set of differential equations, is very fast, and the solution is obtained in the range of few seconds.

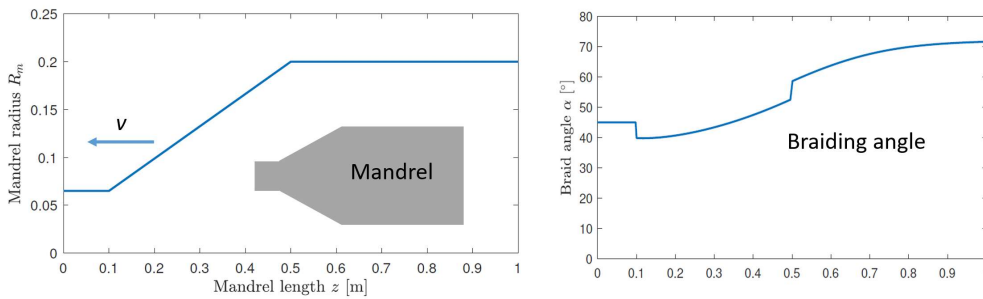


Figure 3. Solution obtained with the Du approach on a mandrel with variable circular cross sections

Van Ravenhorst [4] proposed a kinematic approach based on the computation of the projection of the yarns onto a meshed mandrel. In that method, the limitations on the shape of the mandrel do not exist anymore. The transient effects are also taken into

account (Figure 4). The approach requires a larger amount of computations compared to Du, and the solution is usually obtained in the range of one minute to one hour, depending on the mesh refinement of the mandrel.

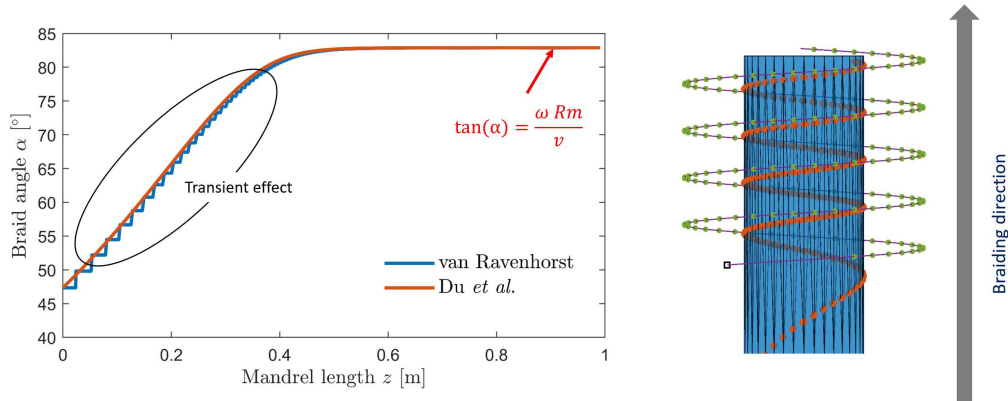


Figure 4. Comparison of analytical and kinematic approaches on a cylindrical mandrel

Figure 5 compares Du and Van Ravenhorst approaches for a mandrel with variable circular cross sections.

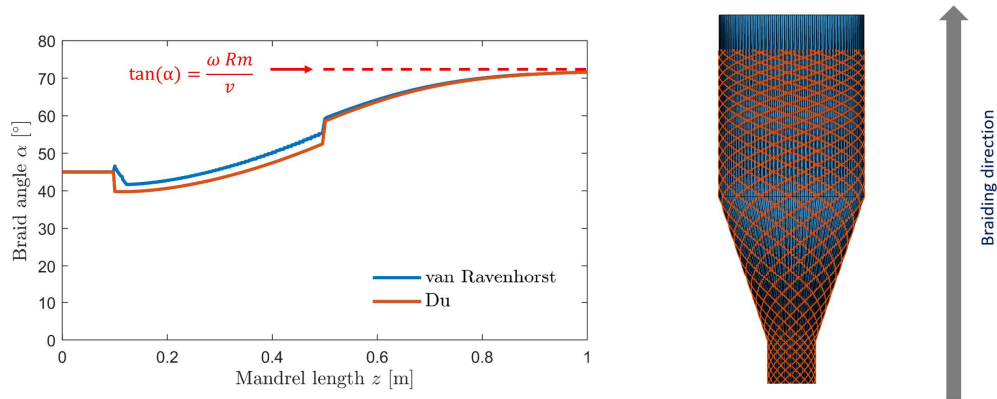


Figure 5. Comparison of analytical and kinematic approaches on a mandrel with variable circular cross sections

2.2 Finite Element approach

Here, LS-Dyna is used to model the braiding process. Yarns, collecting individual filaments, are modeled with specific beam elements. The serpentine motion of the carriers is defined as imposed displacements. The rigid mandrel is moved by the so-called take-up speed. A guide ring (illustrated in Figure 6) can also be taken into account in the simulation.

Using FEM is much more general than the analytical and kinematic approaches. First, it can be applied on mandrels of any shape. Secondly, material parameters like friction between yarns and the mandrel can be included in the analysis. However, such a FEM model is quite difficult to develop, and the computational time can be very large, and counts in terms of hours, or even days.

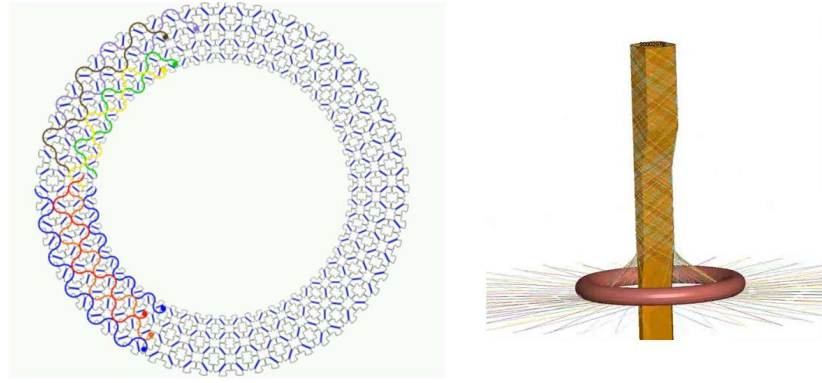


Figure 6. Serpentine motion of the carriers and braiding on a non-cylindrical mandrel

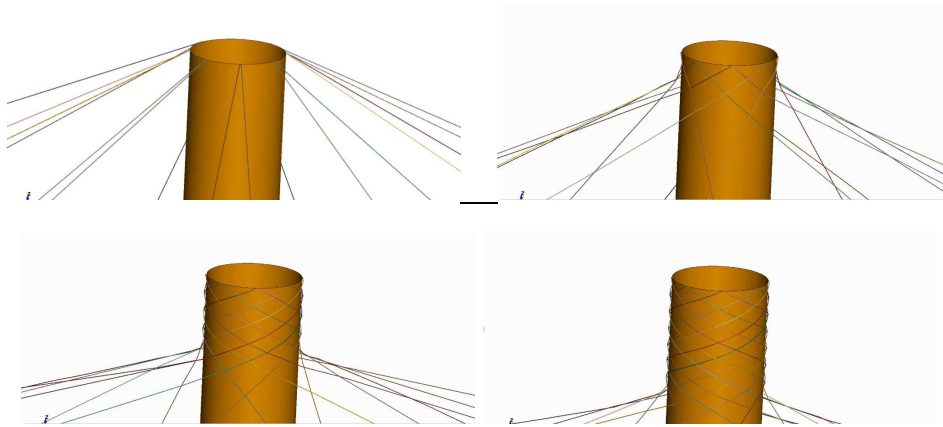


Figure 7. Braiding process simulation with FEM on a cylindrical mandrel

3. Material modelling for braided composites

The first step of the multi-scale approach developed in ViBra is illustrated in this Section. It consists in the modelling of a RUC of the material, and in the validation of the predicted elastic properties.

The modelling methodology carried out for creating a 2D-triaxial braided composite RUC is depicted in Figure 8. The creation of the RUC can be performed in 5 steps. First, the yarn cross-section shape must be determined. Cross-section of axial and bias tows can then be constructed using the corresponding inputs of width W and thickness t (note that in practice lenticular cross sections are preferred to elliptical ones). Second, the path of the yarns must be chosen. Axial and bias yarns follow totally different paths: axial yarns path is generally straight or contains small amplitude undulations whereas bias yarns path is clearly undulating as they need to pass over and under axial yarns. Moreover, the path of a bias yarn depends heavily on the braided pattern that is considered. Third, solid 3D yarns are generated by sweeping the yarn cross-sections along their respective path. The axial and bias yarns are then assembled to form the interlacing of yarns. As only the dry fibre braid is represented up to now, the fourth step consists in including the matrix in the geometry. To avoid useless computations, the matrix is shaped using the required RUC dimensions (i.e. generally a rectangular box) and then merged with the yarns. Last step is to cut out this merged part from the entire geometry to create the RUC. The approach was developed in the graphical user interface of the Gmsh code [5].

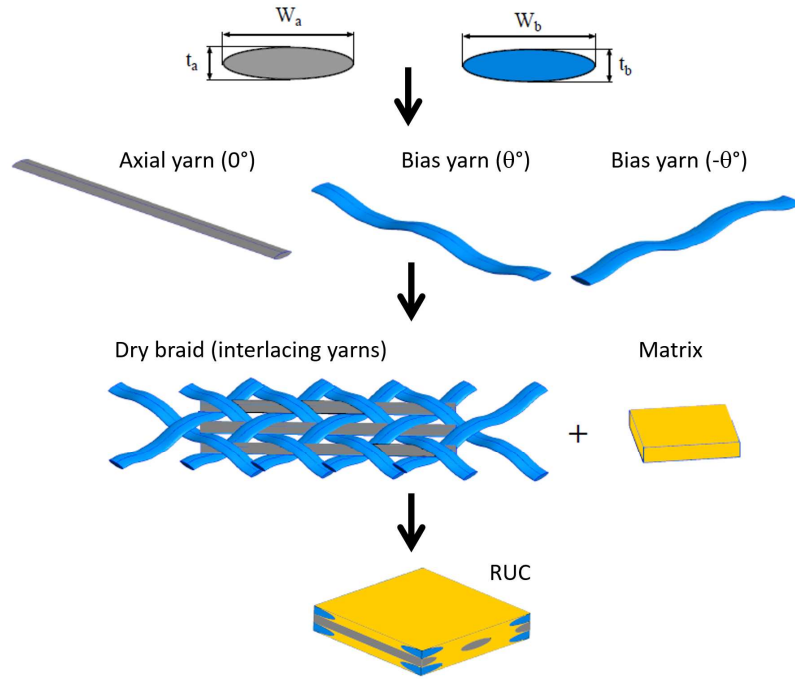


Figure 8. The different steps to create a RUC, based on the braid constituents

Specific strategies and adaptation of the approach to avoid surfaces interferences during the RUC creation are not presented in this paper, but were necessary to provide physically meaningful solutions that can be exploited in the frame of the finite element modelling (Figure 9).

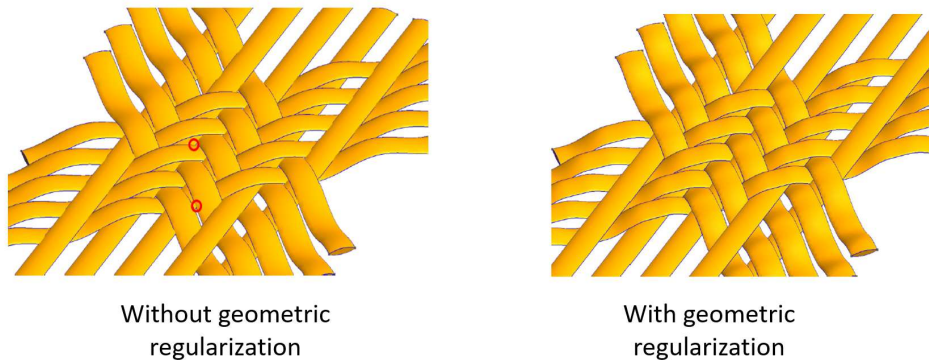


Figure 9. Illustration of a RUC generation with and without surface interpenetrations

The yarns contain fibers and resin; they can actually be represented by the properties of a unidirectional ply. It is then necessary to assign an orthotropic material in the yarns, and orthotropy axes must be defined along the yarn trajectories (Figure 10).

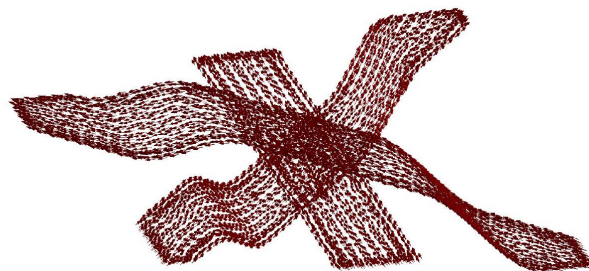


Figure 10. Local orthotropy axes in the yarns

The next step consists in meshing the RUC, here with tetrahedral elements, as illustrated in Figure 11.

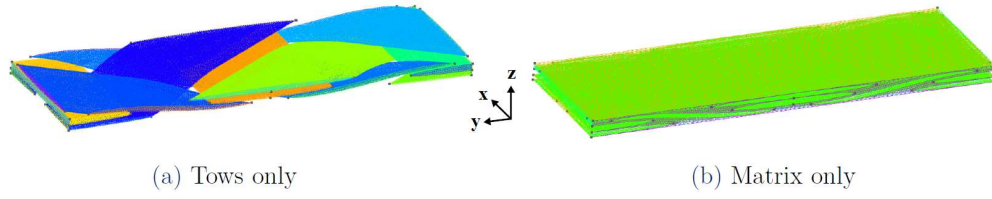


Figure 11. Meshing of the RUC with tetrahedral elements

Note that a specific methodology was also developed to mesh the matrix and the yarns with coincident brick elements (Figure 12; prisms with triangular or quadrangular basis). In the developed approach, cohesive elements can also be defined at the interface of the yarns and the resin region, in order to simulate delamination inside the RUC.

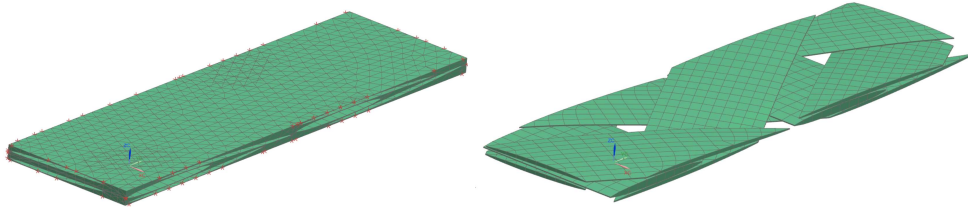


Figure 12. Meshing of the RUC with prism elements

First results are reported in Table 1, for the elastic properties of a quasi-isotropic braid $[0_{24K}/60_{12K}/-60_{12K}]$, for a numerical solution with and without local oriented orthotropy axes in the yarns (“true direction” and “projected direction”, respectively). They show a good agreement with the reference values in [6] (simulation and experimental results).

	Catera et al.		Case 1	
	Experimental	Numerical model	Projected direction	True direction
E_x [GPa]	40.6	42.8	43.2 (+0.9%)	43.2 (+0.9%)
E_y [GPa]	38.5	42.5	39.2 (-7.8%)	42.6 (+0.2%)
E_z [GPa]	/	7.4	7.09 (-4.2%)	7.10 (-4.2%)
ν_{xy} [-]	/	0.3	0.29 (-3.3%)	0.29 (-3.3%)
ν_{xz} [-]	/	0.36	0.34 (-5.6%)	0.34 (-5.6%)
ν_{yz} [-]	/	0.39	0.37 (-5.1%)	0.39 (+0.0%)
G_{xy} [GPa]	/	14.2	13.6 (-4.2%)	14.1 (-0.7%)
G_{xz} [GPa]	/	2.06	2.09 (+1.5%)	2.10 (+1.9%)
G_{yz} [GPa]	/	2.03	2.06 (+1.5%)	2.11 (+3.9%)

Table 1. Comparison between the solution described in this paper and reference [6]

4. Conclusions

First results obtained in the ViBra project were presented. Different approaches for the modeling of the braiding manufacturing process were discussed, and compared. The methodology for material modelling was explained and it was demonstrated that elastic mechanical properties can be predicted with the developed approach. More details are available in [7-8].

5. Acknowledgements

Acknowledgements: the authors would like to thank Wallonia and Skywin (ViBra project; Convention n°8422) for their support.

6. References

- [1] Carey J.P. "Handbook of advances in braded composite materials: Theory, production, testing and Applications", Elsevier, 2017.
- [2] Eurocarbon. www.eurocarbon.com/assets/uploads/Eurocarbon-Brochure.pdf
- [3] Du G.W., Popper P. "Analysis of a Circular Braiding Process for Complex Shapes", Journal of The textile Institute, 85, pp. 316-337, 1994.
- [4] Van Ravenhorst J.H. "Design tools for circular overbraiding of complex mandrels", PhD Thesis, University of Twente, The Netherlands, 2018.
- [5] Geuzaine C., Remacle J.F. "Gmsh: A 3-D finite element mesh generator with built-in pre-and post-processing facilities", International journal for numerical methods in engineering 79 (11), 1309-1331, 2009.
- [6] Catera P.G. *et al.* "Multi-scale modeling of triaxial braided composites for FE-based modal analysis of hybrid metal-composite gears". Composite Structures 182, 2017.
- [7] Bruyneel M., Altemirov A., Haeseleer M. "Comparison of different numerical methods for braiding process simulation". ACOMEN 2022 Conference, 31 August-2 September 2022, Liège, Belgium.
- [8] Rothkegel J., Bruyneel M., Noels L. "Development of a geometrical modelling procedure of braided composites for improved robustness". 11th European Solid Mechanics Conference, 4-8 July 2022, Glasgow, Ireland.