MULTI-SCALE MODELING OF TRIAXIAL WOVEN FABRICS. APPLICATION TO SATELLITE ANTENNA

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SUMMARY

This paper deals with an original multi-scale modeling approach for triaxial woven fabrics. Triaxial woven fabric (TWF) composites are made up of three sets of yarns woven at 60 degree angles. We present the modeling of the thermo-elastic behavior and strength of a satellite antenna reflector made of TWF using an original 3-scale modeling approach:

- The scale of the TWF yarn, modelled using mean-field homogenization theory
- The scale of the fabric, modelled using a finite element model of a unit cell
- The scale of the complete antenna.

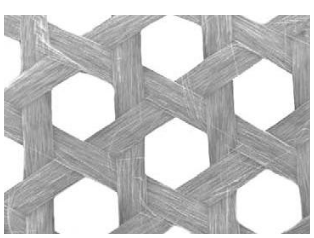

Figure 1: Close up view of TWF fabric. Typical cell size is around 2mm

INTRODUCTION

It is attractive to use single layers of TWF composites as the shell of antenna reflectors for communication satellites. Firstly, TWF composites offer a combination of extremely light weight and good stiffness and strength properties. Secondly, the anisotropy is less pronounced than for traditional biaxial woven fabrics. Thirdly, the open structure eliminates acoustic pressure loading because of the pressure being equilibrated on both faces.

The modeling of TWF composites has been the subject of a significant number of scientific papers. Most of the existing literature on TWF modeling is in linear and isothermal elasticity, with very few papers on other subjects such as thermo-elasticity and strength. . None of the available papers deals with the actual shape of the fabric as a consequence of the mould curing process. In this study we propose to model the thermo-elastic behavior and strength of Ultra-Antenna using an original 3-scale modeling approach

FIRST SCALE: MICRO-MECHANICAL THERMO-ELASTIC MODEL OF TWF YARN

The scale of the TWF yarn is the first and the smallest scale we have looked at in this study. The TWF yarn is a composite made of long, uniaxial high modulus carbon fibers bonded by a resin matrix. The two main matrix materials used with TWF are epoxy and cyanate ester.

The aim of this first step is to compute the thermo-mechanical behavior of this composite, based on different factors, like the thermo-mechanical phase behavior, the volume fraction and the shape of the reinforcing phase. One option is the commonly used models, like Voigt and Reuss or Halpin-Tsai models. These models describe the composite behavior without making use of information on the shape of the phase. They try to estimate bounds for the composite properties by a strain energy approach.

A second option is to use more advanced methods, based on the Eshelby solution (like Mori-Tanaka or Double Inclusion). These methods have the advantage of being more general (for example, it is possible to compute all the elastic constants with one single model) and more precise because they take explicitly into account the shape of the different phases. In this work, we mainly used DIGIMAT (ref. 1), a software package providing homogenization tools based on the Mori-Tanaka algorithm. The results obtained with DIGIMAT for a T300+Epoxy F593 composite are presented in the following table. The cyanate ester 954-2A has a Young's modulus of 3000 MPa and a Poisson's ratio of 0.38, and the T300 carbon fibers has the following properties.

Table 1: Mechanical properties of T-300 carbon fiber

	E1 (GPa)	E2 (GPa)	n12	n23	G12 (GPa)
T300	233	23.1	0.2	0.4	8.963

The DIGIMAT results have been compared to the results of other models (analytical models) :

- Composite cylinders model (CCM, see (ref. 2))
- Mixture law (based on Voigt and Reuss bounds)
- Jones: based on "representative volume element" with isotropic fibers (ref. 3)
- Schneider : Semi-empirical approach for carbon/epoxy (ref. 3)
- Tsa : Semi-empirical approach including transverse and shear modulus (ref. 3)
- HSB: Model of circular fibers with "square packing" (ref. 3)
- Föster-Knappe: Semi-empirical approach for glass/epoxy (ref. 3)
- Puck: Semi-empirical approach for glass/epoxy (ref. 3)

For longitudinal Young's modulus, all these models predict the same value, but for transverse and shear modulus, the predictions are much more scattered. This can be seen in Figure 2. One experimental value was available for a volume fraction of 55%. We can observe that the DIGIMAT prediction is in good agreement with this experimental value. Besides the accuracy, the main advantage of DIGIMAT in this case is that all engineering constants can be predicted in a single run, with no fitting parameter.

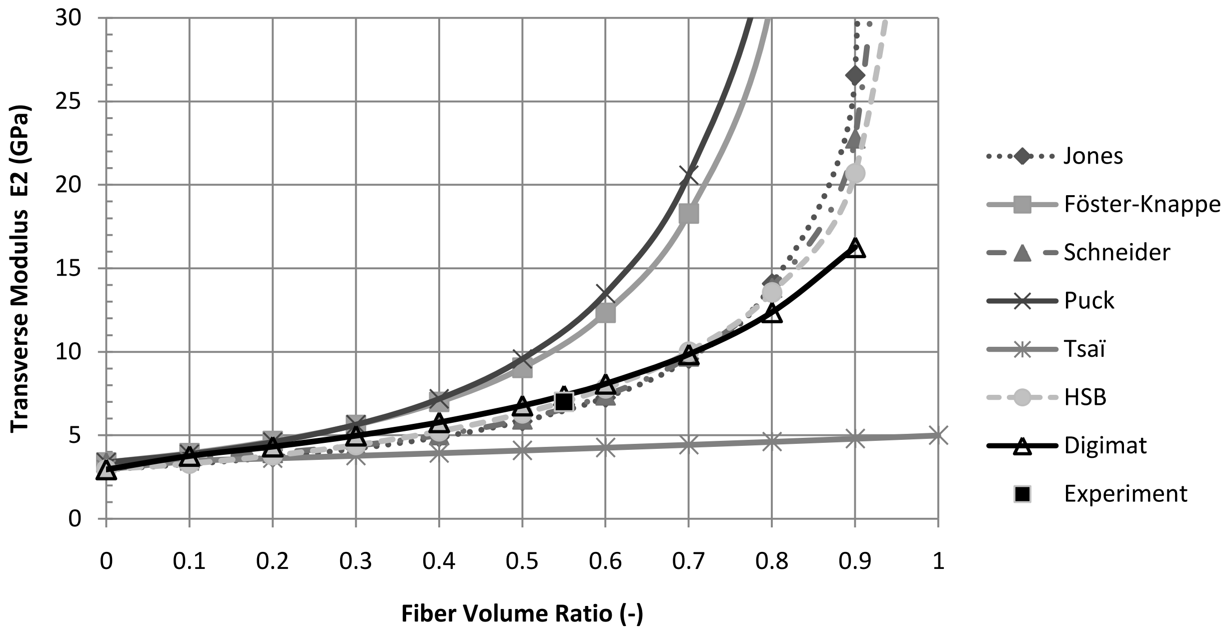

Figure 2: Comparison of predicted transverse Young's modulus as a function of the volume fraction of fibers

SECOND SCALE : UNIT CELL OF TWF FABRIC – FE ANALYSIS

In this step, each yarn's heterogeneous material is replaced at the macroscopic level with a fictitious homogeneous material whose effective properties are determined from the previous step. A unit cell is isolated and FE simulations are conducted in order to extract macroscopic properties of an equivalent, homogeneous Kirchhoff shell. The behavior of this equivalent shell can be fully described by means of a single 6*6 matrix, the ABD matrix.

The original three-dimensional problem is thus reduced to a two-dimensional problem in the mid-thickness surface. Mid-plane strains and curvatures are related to the forces and moments per unit length through the ABD matrix.

$$\begin{pmatrix} \underline{N} \\ \underline{M} \end{pmatrix} = \begin{pmatrix} [A] & [B] \\ [B] & [D] \end{pmatrix} \begin{pmatrix} \underline{\epsilon}^0 \\ \underline{\kappa} \end{pmatrix}$$

This matrix is symmetric, and the 3 x 3 submatrices A and D are symmetric as well. The submatrix B is also symmetric in the case of a laminate, but this is not necessary in the general case. The submatrix A provides the relation between in plane stresses and strains, the submatrix D between out of planes stresses and curvatures and the submatrix B provide the coupling between tension and bending.

Building the finite element model

Several finite element models of a unit cell of TWF have been built. In this paper, we will concentrate on the SK-802 fabric (manufactured by Sakase Adtech). A lot of different unit cells are possible, but the aim is to choose a unit cell that is representative, as small as possible and not too complex, to avoid making the definition of the periodic boundary conditions overly complex.

Taking into account all these constraints, we have opted for a rectangular unit cell. The unit cell was built and meshed using Abaqus/CAE. We started by creating a single yarn by sweeping a cross section along a sweep path. Six copies of this yarn were then assembled together to form a unit cell. This approach is quite easy, but has some limitations. For example, there is no cross section twisting, the cross section remains constant throughout the yarn and the contact area between the different yarns is smaller than in reality. These limitations have been addressed in a preliminary FE analysis, consisting of a compression of the unit cell between two rigid plates. In this analysis, sticky contact is defined between yarns, so that at the end of the simulation, we end up with a unit cell with a morphology very close to the real TWF fabric.

This way of doing was inspired by the fabrication process most commonly used for TWF, Resin film infusion (RFI). This process uses a mould and vacuum bag. The dry fabric is laid up interleaved with layers of semi-solid resin film supplied on a release paper. The lay-up is vacuum-bagged to remove air through the dry fabric, then heated to allow the resin to melt and infuse into the fabric. The vacuum-bagged fabric is then cured, either in a classical oven or in an autoclave. This preliminary FE analysis thus somehow mimics the fabrication process to get a FE model as close as possible to reality. The actual mechanical simulations are then performed on the deformed geometry coming from the preliminary analysis.

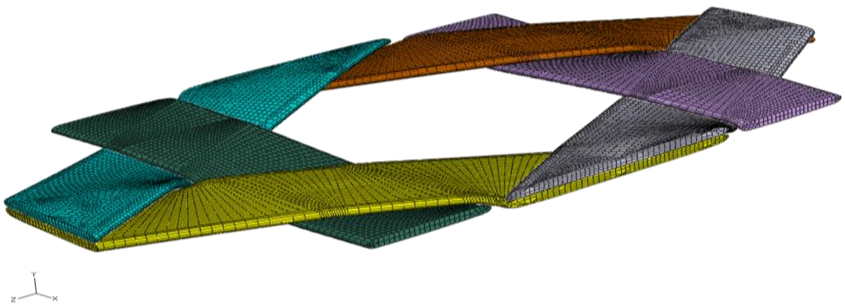

Figure 3: Finite element model of TWF unit cell

Computing the ABD matrix

To derive the ABD matrix, six deformations are imposed on the unit cell, in six separate FE analysis, using periodic boundary conditions (ref. 4,5). In each of these analysis, one of the six average strain/curvature is non zero, the five others are set to zero.

For each FE analysis, the output is a set of reaction forces/moments and corresponding displacement/rotations at the 8 reference nodes. With these outputs, it is possible to compute all the entries of the ABD matrix. In this work, we used the idea presented by Pellegrino et al (ref. 5) of using virtual work. The following results were obtained for the ABD matrix of a SK-802 fabric (made of 1-K T300 carbon fiber) impregnated with Hexcel 8552 epoxy resin.

Table 2: ABD matrix computed for SK802+H8552 (units are N and mm)

3201.24	1840.44	0	5.29204	3.842765	0.174171
1840.44	3134.11	0	3.842765	4.958135	-4.06554
0	0	679.02	0.17417	-4.06555	0.874809
5.29204	3.842765	0.174171	2.72112	0.503411	0
3.842765	4.958135	-4.06554	0.503412	3.49284	0
0.17417	-4.06555	0.874809	0	0	1.26749

We used the experimental data from Pellegrino et al. (ref. 5) for validation. They performed experimental measurements of the main engineering constants of a SK802+H8552. The comparison presented in table 4 shows that the proposed modeling approach gives results in good agreement with the experiment.

Table 3: Comparison of computed and experimental values for engineering constants of SK802+H8552

	Computed values	Experimental value (average)
Extensional stiffness S_x(N/mm)	2111.87	2145
Poisson's ratio ν_{xy}	0.588349	0.586
Shear stiffness S_{xy} (N/mm)	673.4458	777.12
Bending stiffness D_x (N/mm)	2.640621	2.077

THIRD SCALE: APPLICATION TO A COMPLETE SATELLITE ANTENNA MODEL

The third scale is the scale of the complete antenna. The properties of the equivalent homogeneous shell computed in the second step are used (i.e. the ABD matrix). The studied reflector is made of a single layer of TWF, reinforced as sketched below for the SSBR concept (DSL-Cambridge Univ.). The parabolic reflector shell has a diameter of 6 m and a thickness of 0.39 mm, a conical stiffener, 36 radial ribs, 18 clockwise and 18 anticlockwise spiral reinforcements, and a central reinforcement. A schematic representation is provided in Figure 2.

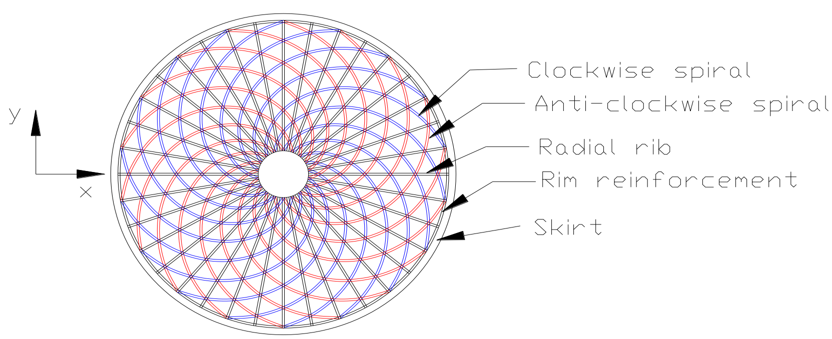

Figure 4: Left: Schematic representation of stiffeners (Figure credits: ESA). Right : Two Hughes Spring-Back Reflectors, one folded and one deployed, on MSAT-2 (courtesy of Canadian Space Agency).

A finite element model of this reflector has been built, using the computed ABD matrix of the equivalent shell as material properties. This means that simple triangular or rectangular shell elements can be used. The finite element model was submitted to 4 thermal loadings: two uniform low temperature (-150°C and 170°C), a temperature gradient through the thickness and a temperature gradient in the X direction. These load cases corresponds to actual in orbit situations when the reflector is exposed to the sun in different ways. The main output variables of interest in these simulations are the displacements. In orbit, a small distortion can result in a beam misalignment of several hundreds of kilometers down on the earth. It appeared that the most critical loading is the uniform high temperature case. Result obtained for this case is presented in Figure 4.

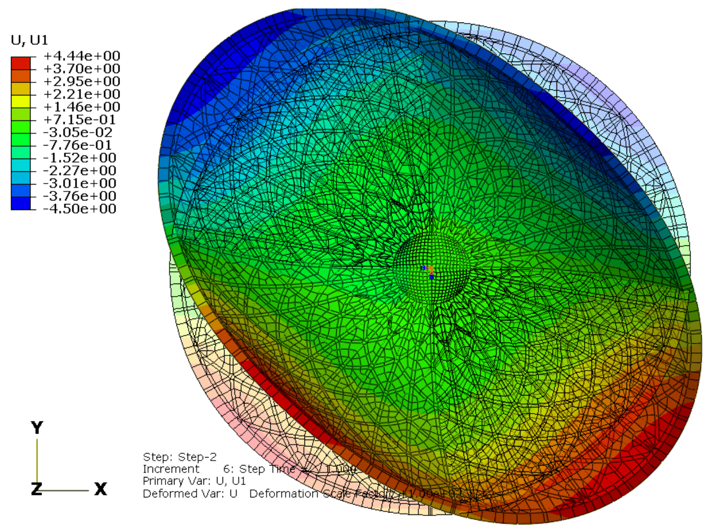

Figure 5: U1 displacement for the uniform high temperature case (scale factor 100). Maximum displacement values are +- 4.45 mm

REFERENCES

1. DIGIMAT v3.1.1, e-Xstream engineering ©
2. G. P. Tandon, Journal of Composite Materials, 29 (1995) 388
3. ESA. Structural Materials Handbook. Noordwijk : ESA. Vols. PSS-03-203, 1.
4. X. Tang and J.D. Whitcomb, Journal of Composite Materials, 37 (2003) 1167
5. S. Pellegrino and A. B. H. Kueh, in: 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23-26 April 2007, Honolulu, Hawaii.