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Nonlinearities in mechanical behavior of textile composites

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Abstract

In several configurations of fabrics, the fiber waviness can be significantly reduced under loading, introducing important modifications of mechanical behavior, mainly concerning the in plane textile stiffness; the phenomenon is of capital importance if the material has to be applied in single ply configuration. In the present paper a numerical approach is proposed for simulation of nonlinear behavior of some textile composite layouts.

The attention has been focused on plane weave textiles for aerospace and general applications: a triaxial carbon fiber/ester-cyanate resin and a biaxial glass fiber/PP textiles, which have been characterized on the basis of experimental or bibliography data, focusing the attention on main mechanical properties and their variation with the strain level in the material.

Experimental data show the importance of nonlinear effects mainly caused by the variation of the waving of fibers under loading.

A numerical analysis based on the use of standard finite element method has been developed, modeling the textile structure at a semi-microscopic level. Basic laminar theory has been used to calculate the elastic properties of a single yarn, whose geometry has been identified.

Numerical results demonstrated the ability of the model to describe the textile behavior and appears a powerful tool for development of new layouts to define the best textile configuration for the specific application.

Keywords: Textiles; Composites; Nonlinear modeling

1. Introduction

The interest in textile materials for current and future applications [1] is widely demonstrated by the large quantity of papers published in last years; in particular, as concerns structural modeling, several significant contributions have been given in the analytical and numerical field. These contributions are a continuously developing reference framework; the proposed methods have some limitations, appearing in specific applications or special textile configurations.

Although studies about textile composites date back to the end of the 1980s, some papers published after 1995 [2–5] show the most updated models and formulas. A summary of methods and scientific studies produced to date can be found in [6].

However, beside the modeling issues related to the structural behavior of textile materials, the contributions given for dealing with special aspects, which influence the behavior of textile materials used for industrial applications, are to be considered important. Published studies [7,11] have analyzed the issue about the actual geometrical configuration of textile fibers, considering alignment errors as compared with ideal textile geometry. Ref. [8] shows evidence of the level of textile imperfections, calculated through the number of cut fibers in a textile, currently applied in aerospace applications.

Refs. [8,9] show the opportunity of introducing appropriate calculation models in the application of

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multi-layer textiles, due to the presence of effects, which are much different than those occurring in composites consisting of unidirectional layers.

Although there is now a progressive systematization of knowledge about textile composites mainly related to NASA research activities [10–13], some issues are still open and can be solved using the most recent results [14–19] about modeling tools. Among these issues, geometrical and material nonlinearity effects have been highlighted; these effects can considerably affect the behavior of textile composite materials. Although the same issues had already been identified in previous studies [14–17], there are some recent contributions [18–25] that are important for the study of these phenomena.

The present study leaves from the experimental characterization of these effects for triaxial carbon fiber textile material, and uses a numerical modeling to predict material behavior. The capability of the model to describe the nonlinearity effects has also been used to predict the mechanical behavior of alternative textile configurations.

2. Materials and experimental data

The materials considered in this study are widely investigated in literature; the textile layout, and material characteristics are in Fig. 1.

As concerns the triaxial textile, experimental data are available. They were obtained from tensile tests according to ASTM D3039 [8,13], carried out on a single layer, in X and Y reference directions, as shown in Fig. 2.

The results obtained for a set of five test samples have been processed, and transformed from the Load-displacement to the modulus–strain% plane. The results obtained are shown in Fig. 3, for both X direction tests and Y direction tests by means the curve of mean values. On this plane, is more immediate the evaluation of nonlinearity effects characterizing the textile global behavior, also if the values for strain less than 0.1% are not significant.

All available experimental data clearly show that the considered materials are characterized by a clearly nonlinear behavior. As it is well known, this aspect introduces significant difficulties in the application of the material. The numerical modeling described hereafter is able to predict these nonlinearities, justify their origin and take them into account in structural design.

3. Numerical analysis

The analysis of textile structure at a semi-microscope level allows the hypothesis that the nonlinearities identified in the experimental investigation is to be mainly attributed to the following factors:

(a) geometrical nonlinearity;
(b) nonlinearity of bonding, which forms the matrix in the yarn overlapping areas;
(c) nonlinearity of yarn, due to the nonlinear behavior of the matrix.

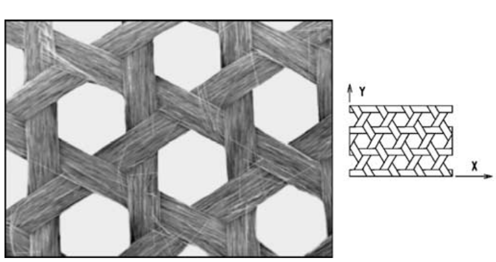
3.1. Strain analysis

The effect of geometrical nonlinearity, caused by the presence of yarn manufacture waving, play a crucial role in the interpretation of these behaviors. A reference value for the modulus of triaxial textile can be calculated considering only the section of yarns aligned with the load direction X; through the principle of material homogenization, the yarn elasticity modulus E_{yarn} can be calculated, and with reference to the nominal section A_{specimen} of a specimen, the E_X is calculated as follows:

$$E_x = E_{\mathrm{yarn}} \frac{N_{\mathrm{yarn}} A_{\mathrm{yarn}}}{A_{\mathrm{specimen}}} = 31.1 \text{ GPa},$$

$$\text{where} \begin{cases} A_{\mathrm{yarn}} = 0.08 \text{ mm}^2 \\ N_{\mathrm{yarn}} = 14 \\ A_{\mathrm{specimen}} = 8.49 \text{ mm}^2 \\ E_{\mathrm{yarn}} = 180.5 \text{ GPa} \end{cases} \tag{1}$$

The value obtained for E_X is the value found in the test sample, only considering the longitudinal yarn section (effective section). It is to be noted that the modulus value is slightly higher than the maximum value obtained through the tensile test in X direction (Fig. 3).



	Resin	Fiber
E [GPa]	3.4	326
σ_R[MPa]	69	3500
ν	0.4	0.3
Content (%)	45	55

Fig. 1. Textiles layout and properties of materials.

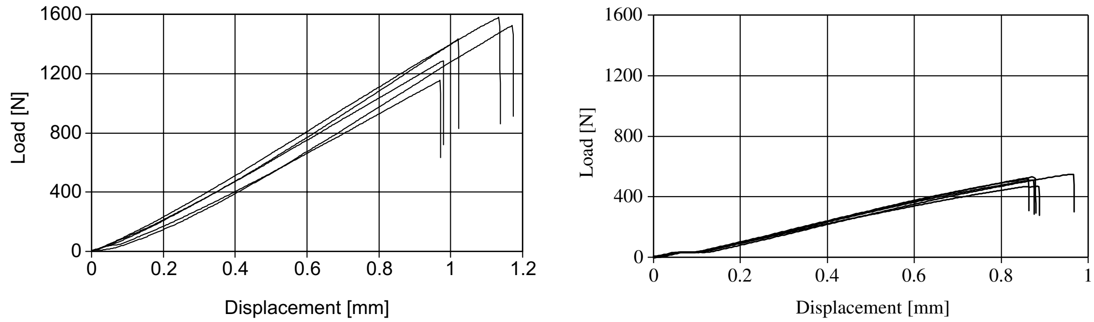


Fig. 2. Load vs. displacement in X and Y direction (five specimens).

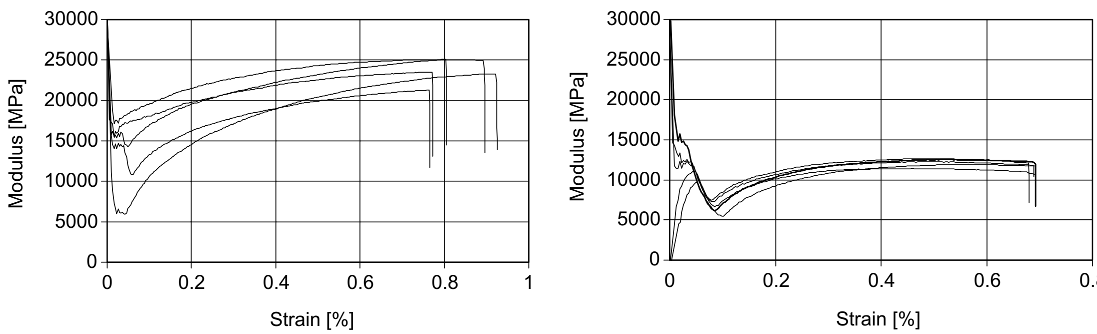


Fig. 3. Modulus vs. strain in X and Y direction (five specimens).

This allows the formulation of an initial hypothesis on material behavior: the waved axis configuration of non-loaded yarns tends to change under loading, depending on the axial stress of the inclined yarns which obstacle their straightening. According to the above-calculated value for E_X, we can say that the textile behavior, near the failure, is like the behavior of a unidirectional laminated material, the section of which is the same as the effective section.

This structural behavior hypothesis shows the limits of linear modeling, which is able to give significant information on the behavior of textile stiffness only in some stress conditions. The textile behavior linear analysis is documented in [6]. This analysis had already highlighted the importance of geometrical nonlinearity. In fact, the stiffness of test samples appeared as dependent on model dimensions.

The first step with nonlinear analysis was taken with reference to a single yarn with the full-3D modeling indicated in [6]. The yarn numerical model and the modulus E_X vs. $\varepsilon_{\%}$ are shown in Fig. 4.

The stress–strain curve of single yarn shows geometrical nonlinearity effects due to the waving recovery under load. The modulus maximum value tends towards the yarn value, already calculated ($E_{\text{yarn}} = 180$ GPa) for strain values higher than 1%, which are not attained in the experimental tests.

The development of a global model through the full 3D geometrical modeling is not applicable, due to large elapsed time in numerical solution and problems related to the convergence of nonlinear analysis. Therefore, the model of an extended textile portion imposes the use of a simplified approach. In particular, this study has considered the use of a beam element (the model is shown in

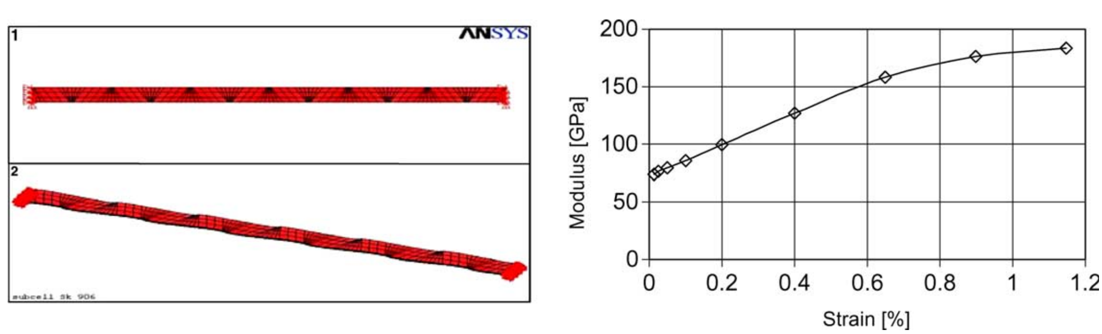


Fig. 4. Model and results of nonlinear analysis of the single yarn.

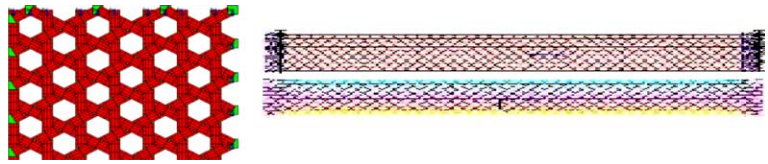


Fig. 5. FE model of the triaxial textile.

Fig. 5 where the wireframe is completed by the extended section display option) allowing analysis in large displacement condition.

In Fig. 6 the results of the numerical analysis are shown and compared with the experimental ones for test in X and Y directions.

The numerical model is able to describe the straightening effect of the yarns under loading; Fig. 7 shows the displacement of the yarn axis points under X direction test. The limit of this model is that the beam element does not consider the cross rotation of the section (also shown in Fig. 7), which characterizes the single yarn.

This figure shows that yarns do not completely straighten before failure (–○– strain 1%), justifying the difference between the model maximum modulus (about 26 GPa) and the modulus calculated with the relationship (1) (31 GPa), which would apply with the yarn in a straight axis.

The procedure above described has been repeated also on a second textile, made by the same material and yarn layout, but having a half thickness. The comparison of numerical and experimental results is proposed in Fig. 8 and confirms a good capability of the numerical model to calculate the moduli in X and Y directions.

The experimental results in Fig. 8 have been obtained with a more appropriate measuring system able to eliminate the errors on the results for strain less than 0.1%. Moreover, it can be noted that this textile, being characterized by more flat yarn axis, in comparison with the previous one, shows lower nonlinearity effects and higher moduli values.

The activity of fitting between experimental and numerical results have been documented to verify the ability of the proposed modeling to represent one aspect of the mechanical behavior of the textile. From this point, the capabilities of the tool are well appreciated in two main activities:

- Forecasting of properties of new (not available) textile or, on the contrary, define textiles having desired properties.
- Determination of the textile mechanical properties, difficult or very expensive to obtain experimentally.

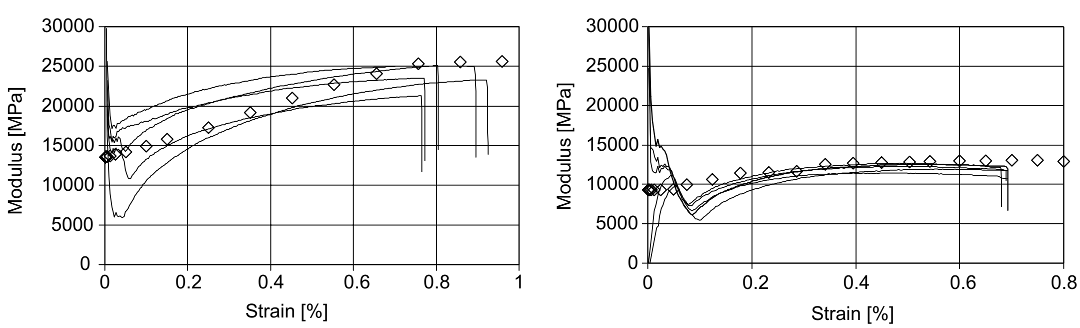


Fig. 6. Material stress–strain curve and results of nonlinear analysis (◊ numerical; — experimental).

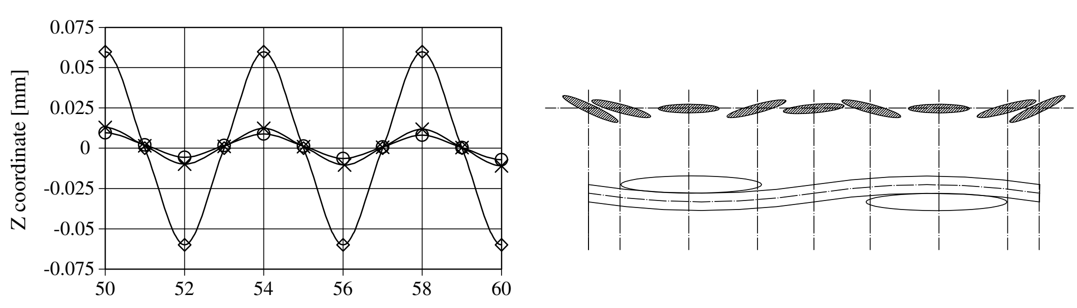


Fig. 7. Nodal position variation along yarn axis (–◊– undeformed;. –○– strain 1%; –×– strain 2%) and section rotation along yarn axis.

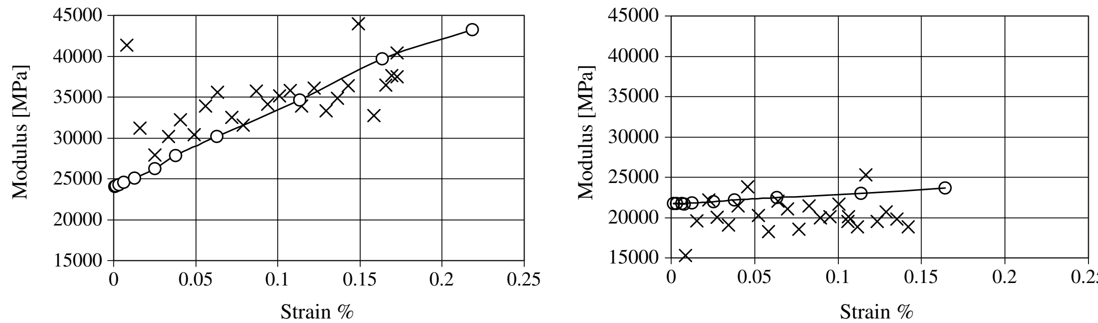


Fig. 8. Material stress–strain curve and results of nonlinear analysis (–×– numerical; –○– experimental).

Both these activities have been developed and here following documented; three different textile layouts have been considered, having the same layout, same materials but different weaving parameters. They are shown in Fig. 9 and will be referred as materials A, B and C.

In following figures the main mechanical parameters of the three textiles are shown. In Fig. 10 the tensile moduli E_X and E_Y are plotted vs. the strain; it can be verified the confirmation of a nonlinear behavior and differences among the three layouts.

In Fig. 11 the shear moduli G_{XY} and G_{YX} plotted vs. the shear strain; the graphs show the unstability of the structural model in a trellising loading.

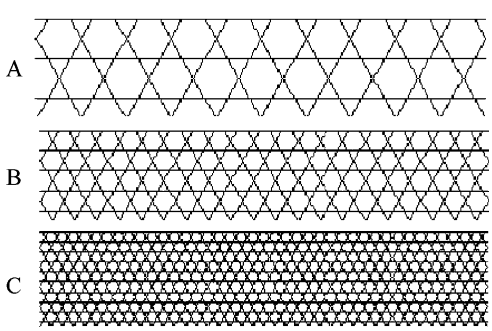


Fig. 9. Three different textile layouts.

In Fig. 12 are shown the Poisson's factors showing themselves the dependence by the strain level.

In Table 1 are reported the values of coefficient of thermal expansion in both directions for all layouts.

4. Stress analysis

The numerical models described above allow considerations about the stress levels and failure modes. Fig. 13 shows the distribution of stress in a representative portion of the numerical model and the yarn section with the related reference system. The model shows the scale of strains acting with an applied deformation, corresponding to the condition appeared at failure in experimental tests (0.8%). Although the stress contour distribution cannot be read, the MX label allows the point subject to the maximum stress: it is a boundary point of the specimen, near the tabs. The experimental tests documented in [8] confirm the failure starts in the area shown by the numerical model, which corresponds to the area constrained against transverse displacement, near the outlet section of tabs.

As concerns the stress level, if the loading in the section subject to the maximum stress is considered, tensile load and bending moments are known, worst stress value can be calculated:

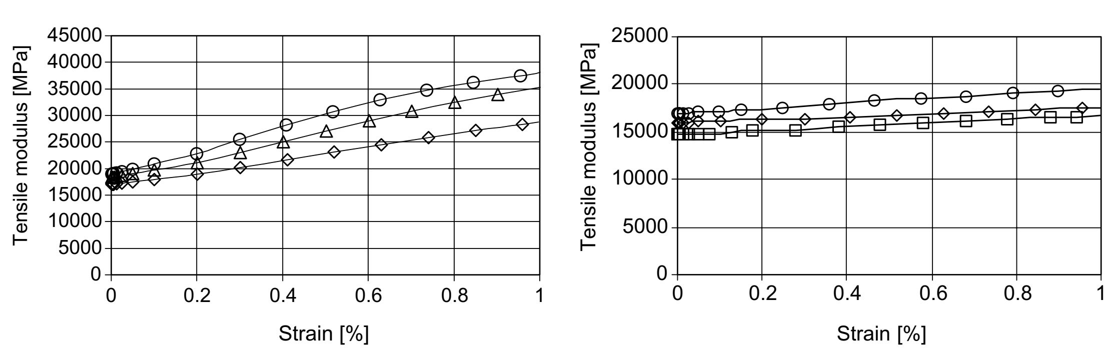


Fig. 10. Tensile moduli (X and Y) for the three materials (A –◇–; B –△–; C –○–).

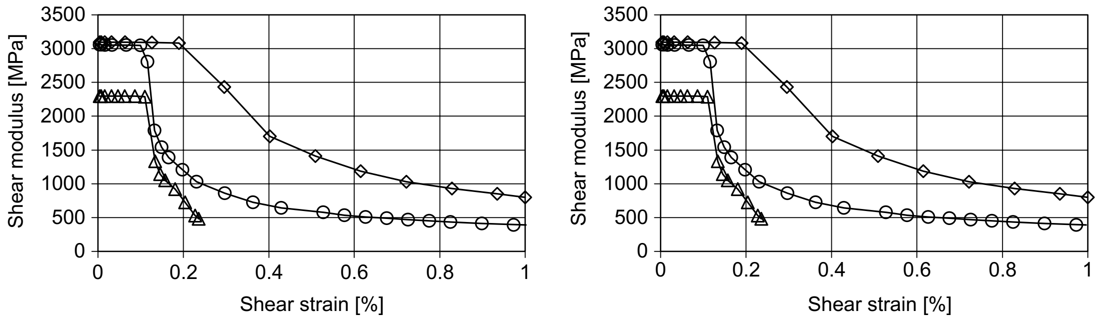


Fig. 11. Shear moduli (XY and YX) for the three materials (A –◇–; B –△–; C –○–).

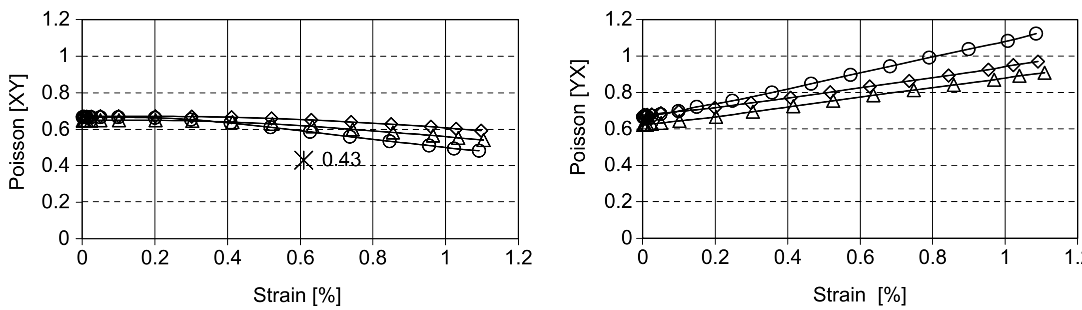


Fig. 12. Poisson's factors (XY and YX) for the three materials (A –◇–; B –△–; C –○–; ∗Experimental).

F_x (N)	130.097	
M_y (N mm)	4.48363	$\sigma_{\text{worst}} = \dfrac{F_x}{A} + \dfrac{M_y}{W_y} + \dfrac{M_z}{W_z} = 3582.37$ MPa
M_z (N mm)	16.7642	

Table 1
Coefficients of thermal expansion in X and Y directions for the three materials

	CTE-X	CTE-Y
A	−1.33E−06	−1.50E−06
B	−1.30E−06	−1.38E−06
C	−1.45E−06	−1.54E−06

There are two points of maximum stress, they are located on the section external profile and indicated with A and B in Fig. 13. Due to the combination of stresses, fiber ultimate tensile stress is reached (3500 MPa) both in A and in B, therefore specimen failure is confirmed.

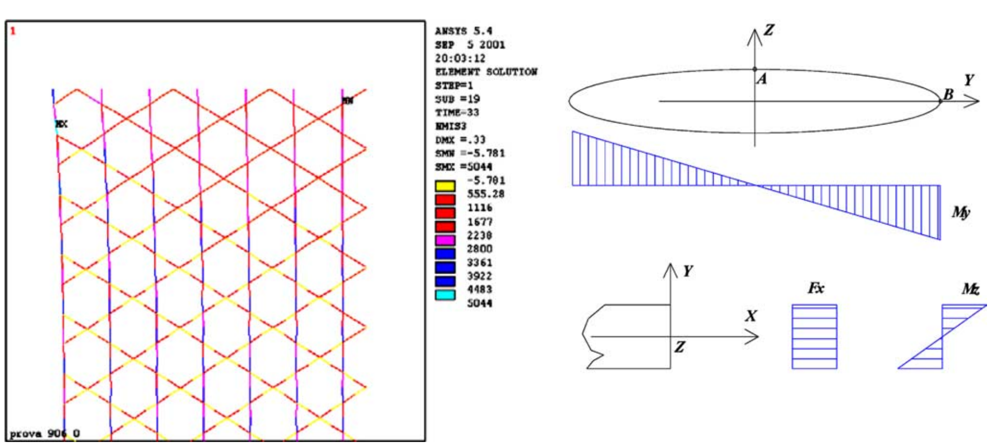


Fig. 13. Stress distribution in the wireframe model and in the yarn section.

5. Conclusions

The results of a study about the nonlinear behavior of a triaxial textile composite material have been illustrated. The numerical model adopted allows the representation of waviness progressive variation of yarns under load, and showed the subsequent textile global stiffness variations.

For the numerical modeling, the moduli to be attributed to single yarn and textile effective section through the homogenization technique have been calculated; the yarn tensile modulus was used as a comparison parameter for the results of a single yarn numerical model. This allowed the description of yarn's straightening and the importance of this phenomenon near the failure; the model was made with brick elements in full-3D modeling.

According to these results, global models of the textile have been developed, using beam elements. These models, analyzed with the geometrical nonlinearity appeared adequate to describe the significant variations of moduli detected by means of experimental tensile testing of the material.

The numerical modeling has been then used in two important activities:

- Forecasting of properties of new textile or, on the other hand, to define textiles having desired properties.
- Determination of the textile mechanical properties, difficult or very expensive to obtain experimentally.

In both cases the tool showed his effectiveness in supporting industrial design of components made of composite materials.

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