NON-LINEAR PROPERTIES OF PVC-COATED FABRICS USED IN TENSAIRITY STRUCTURES

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SUMMARY

The yarn-parallel and shear behaviour of PVC-coated polyester fabric is investigated. From biaxial tensile test results a simple material model is proposed and included as a Usermat in ANSYS. It is used for the finite element analysis of a 5 meter long Tensairity girder under bending load.

Keywords: Tensairity, coated fabric, biaxial testing, non-linear behaviour, finite element analysis

INTRODUCTION

Tensairity is a new concept for lightweight structures, where compression and tension are physically separated. In a typical Tensairity beam (Fig. 1), an airbeam is used for pre-tensioning the tension element and for stabilizing the compression element against buckling [1]. First buildings were recently realized with Tensairity, like a roof structure with 28 m span or a skier bridge with 52 m span (Fig. 2). The objectives are to investigate the behaviour of the PVC-coated polyester fabric, which is one of the materials used for the hull of the airbeam, and to model it for finite element analysis of Tensairity girders.

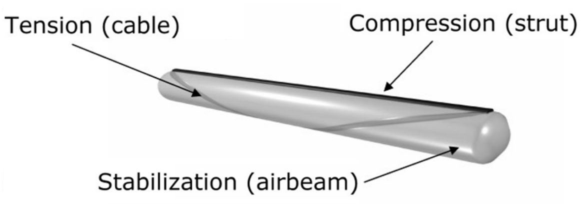

Fig. 1. The basic elements of a Tensairity beam.

Coated fabrics are non-isotropic and non-linear materials. Their behaviour is strongly influenced by the interaction between warp and fill yarns (crimp interchange). This is why micromechanical approaches have already been used in order to derive the material behaviour from a model of its microstructure [2-5]. These models are limited to a unit cell, which is representative of the material structure. Generally, a very good representation of the material response is achieved. However, such models often require a large amount of parameters and because of their complexity are not computationally efficient for the analysis of complete structures.

More recently, practical approaches have been proposed, where the material behaviour is directly described from experimentally determined stress-strain relationships [6-8]. In this case, a plane stress orthotropic model is generally chosen because it is numerically efficient. However it is not suitable to represent the entire non-linear material response, and is preferably used only for local approximations [6,7]. The most recent methods are based on response surfaces, which directly link the measured strains to the applied stresses through three dimensional representations. The correlation between the model and experiments is very good in this case, but it requires a very large amount of data. Its use for finite element analysis is presumably difficult and very time consuming.

The shear behaviour is also an important issue in the case of inflated structures. Several methods have been developed in order to estimate the shear modulus of woven fabrics, like for example the shear frame and the T-shaped specimen [9,10]. The main disadvantage of these methods is that they cannot be performed on a biaxial testing machine, or that they require a specific sample.

In this paper an overview of the research undertaken at the Center of Synergetic Structures on coated fabrics is presented. In a first part a simple model for the yarn-parallel behaviour of PVC-coated polyester fabrics is presented. Next a new method for the shear testing of cruciform specimens is proposed. This method uses the same sample and the same machine as for a biaxial extension test, and thus can be integrated within the whole material testing process. Finally, the measured material properties are used for the finite element analysis of a 5m long Tensairity girder under bending.

Fig. 2. Tensairity applications: Roof over a parking garage in Montreux with 28 m span (Luscher Architectes SA & Airlight Ltd, left) and a skier bridge with 52 m span in the French Alps (Charpente Concept SA, Barbeyer Architect & Airlight Ltd, right).

YARN PARALLEL BEHAVIOUR

Experiments

Cruciform specimens made of PVC-coated polyester fabric were tested on a biaxial testing machine. The test setup is presented in Fig. 3. The central square of the specimens was 500 mm wide. Each cruciform arm was made of five strips, which were independently loaded by an electromechanical drive mounted on linear bearings. Tests were load-controlled by the use of 10 kN load cells fixed between every pair of drive and grip. Strains were measured by the use of two needle-extensometers.

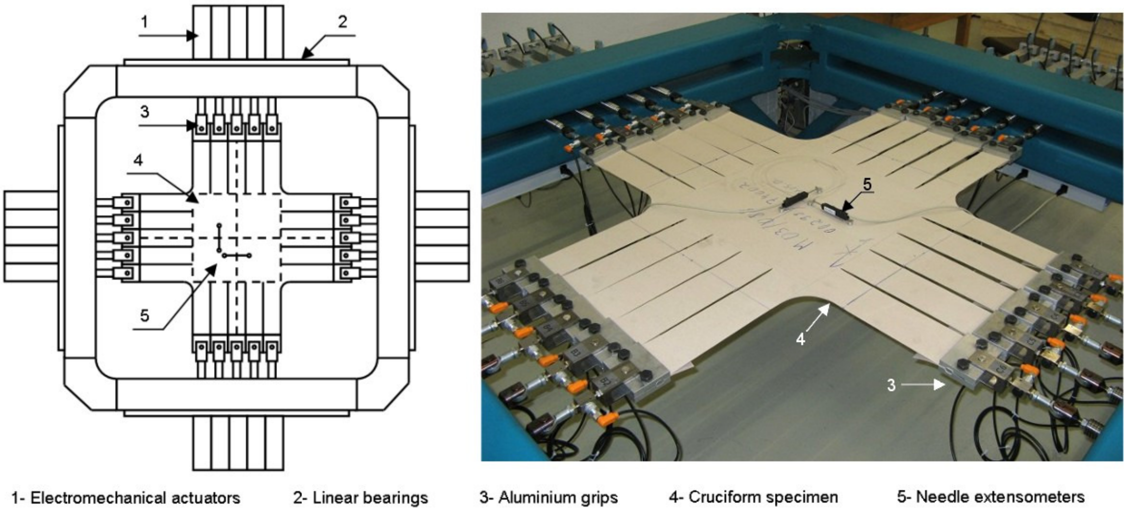

Fig. 3. Biaxial testing machine.

Table 1. Specifications of tested materials.

Sample	Manufacturer / Reference	Polyester	Warp/Fill tensile strength
V700	Mehler Texnologies Valmex FR700	Type I	3000/3000 N/5cm
V900	Mehler Texnologies Valmex FR900	Type II	4200/4000 N/5cm
V1000	Mehler Texnologies Valmex FR1000	Type III	6000/5500 N/5cm
V1400	Mehler Texnologies Valmex FR1400	Type IV	7500/6500 N/5cm
F702	Ferrari Précontraint 702	Type I	3000/2800 N/5cm
F1002	Ferrari Précontraint 1002	Type II	4200/4000 N/5cm
B1617	Verseidag Indutex B1617	Type II	4400/3900 N/5cm

Specimens were first loaded at pre-stress level and then from pre-stress up to maximum test stress. Strains were set to be equal to zero at pre-stress. The maximum test stress was set to one fifth of the tensile strength in order to avoid tearing of the fabric. The pre-stress was set to one fifth of the maximum test stress. Each loading/unloading was repeated five times in order to remove residual strains. Only the last load cycle was used to determine the material properties. Seven materials were selected from different manufacturers, representing a wide range of mechanical behaviour. Their main properties are listed in Table 1.

Stress reduction factor

Strains and stresses are not measured at the same location. The measurements do not represent the true material behaviour, since the stress is not uniformly distributed in the specimen. This is shown in Fig. 4, where finite element predictions of the stress distribution through the centre of the specimen are compared to the stress which is applied at the strip ends. Using a wide range of material properties and loads, an average stress reduction factor of 0.985 was determined in the centre of the specimen.

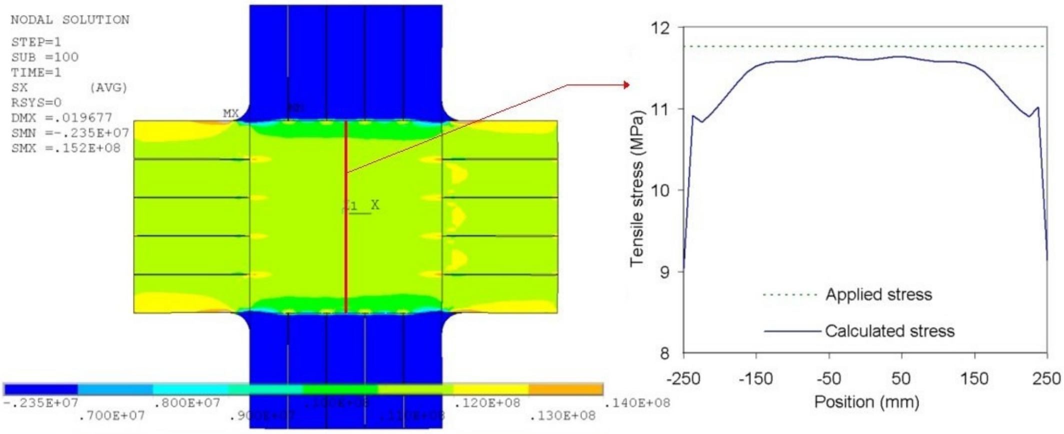

Fig. 4. Tensile stress distribution in the centre of the cruciform specimen.

Proposed model

Applied loads were selected so that the fabric response was explored as much as possible. Thirteen load ratios (ratio of the warp stress to the fill stress) were measured, namely 1:0, 11:1, 5:1, 3:1, 2:1, 7:5, 1:1, 5:7, 1:2, 1:3, 1:5, 1:11, 0:1.

For each load ratio, the measured stress-strain curves are quite linear. However, the overall material behaviour does not correspond to a plane stress linear orthotropic model. Such model is here only valid for one particular load ratio. A modified model is thus required, where elastic properties can vary with the applied load ratios.

Based on the experimental results, a non-linear model was proposed [11], as presented in Fig. 5. A linear relationship was found between the material elastic moduli and the normalized load ratios. The material model has five parameters: $E_w^{1:1}$ and $E_f^{1:1}$ are the reference values of warp and fill Young's moduli given for the 1:1 load ratio, ΔE_w and ΔE_f represent the variation of warp and fill Young's moduli on the whole range of load ratios ($0 \le \gamma_{w,f} \le 1$), and ν_{wf} is the Poisson's ratio. Material parameters were determined by a least square fit minimizing the deviation of experimental and modelled strains.

Stress-strain relationship

$$\begin{bmatrix} \Delta\varepsilon_w \\ \Delta\varepsilon_f \end{bmatrix} = \begin{bmatrix} \dfrac{1}{E_w(\gamma_w)} & \dfrac{-\nu_{wf}}{E_w(\gamma_w)} \\ \dfrac{-\nu_{wf}}{E_w(\gamma_w)} & \dfrac{1}{E_f(\gamma_f)} \end{bmatrix} \cdot \begin{bmatrix} \Delta\sigma_w \\ \Delta\sigma_f \end{bmatrix}$$

Elastic moduli

$$E_w(\gamma_w) = \Delta E_w \cdot \left(\gamma_w - \frac{1}{\sqrt{2}}\right) + E_w^{1:1}$$

$$E_f(\gamma_f) = \Delta E_f \cdot \left(\gamma_f - \frac{1}{\sqrt{2}}\right) + E_f^{1:1}$$

Normalized load ratios

$$\gamma_w = \frac{\sigma_w}{\sqrt{\sigma_w^2 + \sigma_f^2}}$$

$$\gamma_f = \frac{\sigma_f}{\sqrt{\sigma_w^2 + \sigma_f^2}}$$

(Subscripts w and f represent the fabric principal directions: w for warp and f for fill)

Fig. 5. Proposed non-linear model with stress-dependent moduli.

Model parameters were calculated for all tested materials. The model was included in ANSYS with a Usermat. A non-linear finite element analysis of the biaxial test was performed. For each material, a root mean square (RMS) of the difference between predicted and measured strains was calculated. It is expressed as a percentage of the strain test range and thus gives an impression of the model accuracy. Results are presented in Fig. 6a, where the proposed model is compared to a standard orthotropic material. The model mean error is about 2.5% of the strain test range, which is more than twice less than for a standard orthotropic material.

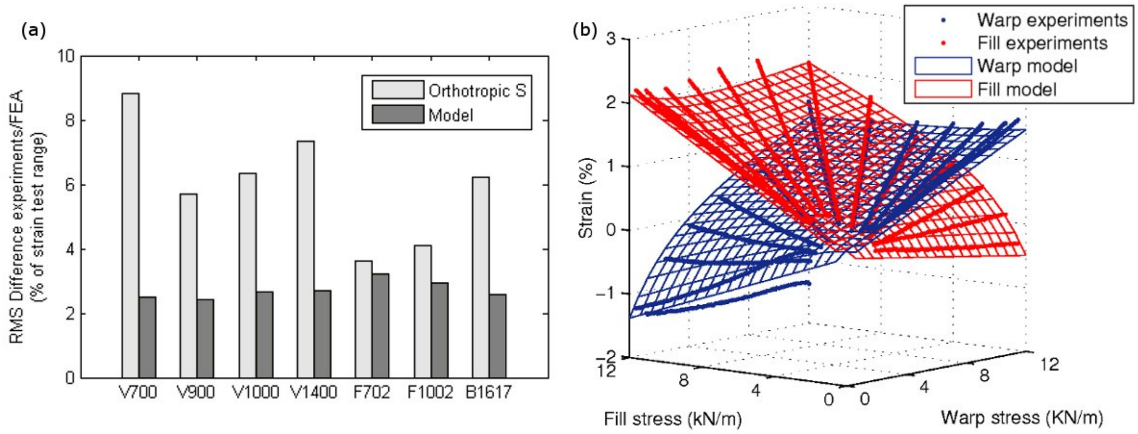

Fig. 6. (a) RMS of the difference between predictions and experiments - (b) Stress-stress-strain representation of experimental data and model for V700 specimen.

On Fig. 6b the model predictions (surfaces) are superimposed with experimental data (dots). It clearly appears that the experimental curves do not lie all on a plane and thus linear models have limited capabilities. For the proposed non-linear model, a curved surface enables a better representation of the experimental material characteristics.

SHEAR BEHAVIOUR

Experiments

The membrane shear modulus should be measured under biaxial loading in order to be consistent with the material use. It should be initially pre-stressed in both directions to represent the airbeam inflation, before a pure shear is applied. The classical method to get such loading is to use a cruciform specimen where the fibre orientation in the central square is rotated 45° with respect to the loading directions. The same amount of tensile pre-stress is applied in both directions, resulting in a biaxial extension with a 1:1 load ratio in the material. Then one direction is loaded, while the other one is unloaded. If the compressive and tensile stresses are equal one to each other, a pure shear stress is theoretically applied to the central square of the specimen (Fig. 7). The main disadvantage of this method is that it requires a specific test sample. It would be more convenient to use the same sample as for the determination of the elastic moduli, where fibres are aligned with the sample sides. A special feature of our biaxial machine, called “shear ramp”, controls the actuators so that the global loading leads to a shear deformation (lozenge shape) of the test sample (Fig. 7). This method was compared with the classical one for three different PVC-polyester samples.

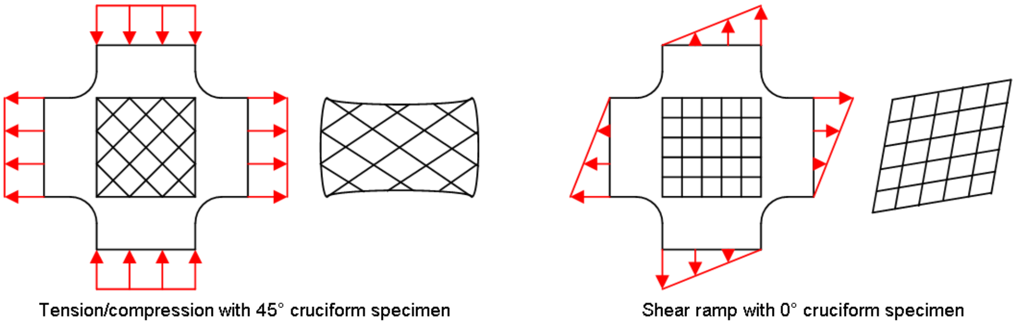

Fig. 7. Classical and new method for the biaxial shear testing of coated fabrics.

Stress reduction factor

Because a uniform shear stress distribution is difficult to achieve, a stress reduction factor must be estimated for each sample. On Fig. 8 stress distributions calculated by finite element analysis are presented for both methods. Results show that for a 45° specimen the shear stress is quite homogeneous in the central square of the specimen, since the tensile and compressive stresses are supposed to be uniform along the sample sides. On the contrary the shear ramp, which tends to give a lozenge shape to the centre of the specimen, cannot bring a uniform shear stress within the specimen. To be able to consider the stress distribution as uniform, only a small part of the specimen will be studied. A 150mm wide square located in the centre of the specimen (corresponding to the grey part of the graphs on the right of Fig. 8) seems to be a reasonable choice.

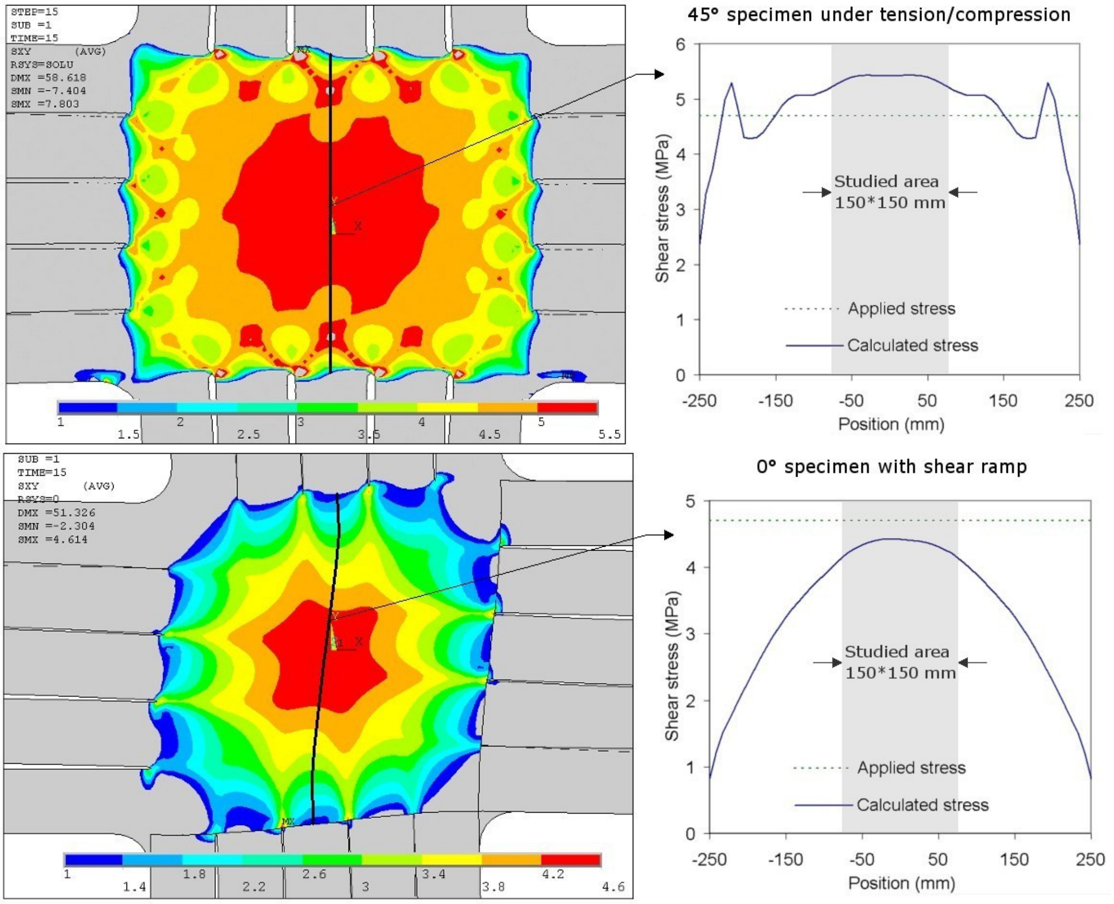

Fig. 8. Shear stress distribution in the centre of both specimens.

Results

Cruciform specimens were tested under biaxial tension (45°) or with the shear ramp (0°). Biaxial pre-stress was set to 5.5kN/m and applied shear stress to 4kN/m. The slopes of the stress-strain experimental curves were estimated with a linear fit. For each test and each material the stress reduction factor was calculated in a 150mm wide square. Shear moduli could finally be calculated using the slopes and the reduction factors. Results are presented in Table 2. They show that the new method gives quite similar results compared to the classical one. The observed difference in modulus is acceptable considering the significant reduction in testing time and the test simplicity.

Table 2. Shear modulus estimation: comparison between classical and new method.

	45° specimen / biaxial test			0° specimen / shear ramp		
Sample	Slope (MPa)	SRF	G_{wf} (MPa)	Slope (MPa)	SRF	G_{wf} (MPa)
V700	18.8	1.17	**22.0**	23.0	0.86	**19.8**
V900	13.9	1.17	**16.3**	19.4	0.84	**16.3**
F702	11.5	1.24	**14.3**	14.4	0.77	**11.1**

FINITE ELEMENT ANALYSIS OF A TENSAIRITY GIRDER

Measured material properties were used for the finite element analysis of a Tensairity girder under bending. The girder, presented in Fig. 9, was 5 m long and had a spindle shape. It was symmetrical so that the tension and compression elements were identical, made of aluminium, with a cross-section of $30*10\text{mm}^2$. The membrane was meshed with 2D shell elements, and the struts with 1D beam elements.

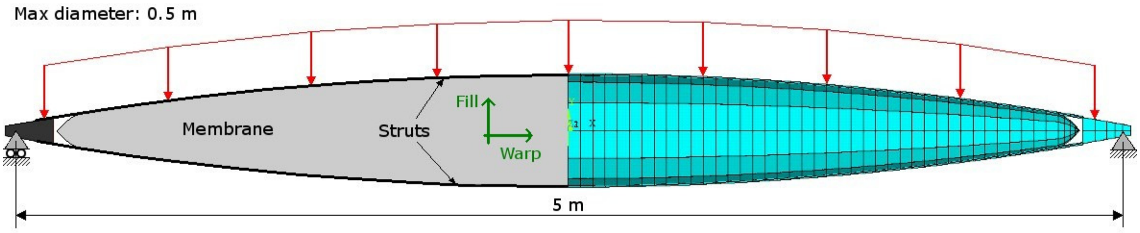

Fig. 9. Geometry and mesh of the Tensairity girder.

The airbeam was inflated with an internal pressure of 300mbar. A uniformly distributed load of 1kN/m was then applied on the top strut. Three different sets of material properties were used, in order to investigate the influence of both tensile and shear moduli: a standard linear orthotropic material with the shear modulus obtained with a 45° specimen, the same model with the shear modulus obtained with a 0° specimen, and finally the proposed non-linear material model. Predicted vertical displacements are presented in Fig. 10 for 4 different points, located on top (compression) and bottom (tension) struts, at one quarter and on half of the girder length.

During inflation the shear modulus has no influence on the structural behaviour. An observation of the stresses in the membrane shows that there is almost no shear in this case. There are mostly tensile stresses with a 1:2 load ratio. For a good modelling of inflation it is necessary to have a good estimation of the Young's moduli. The structure is in this case stiffer with the non-linear material model, which takes into account the actual load ratio in the material. On the contrary no significant change in structural behaviour can be observed during bending with the non-linear model. In this case there is mostly shear in the membrane. However, the little difference in shear modulus obtained from the two different test methods does not affect much the girder stiffness. Thus the shear ramp can be used for the estimation of the shear modulus.

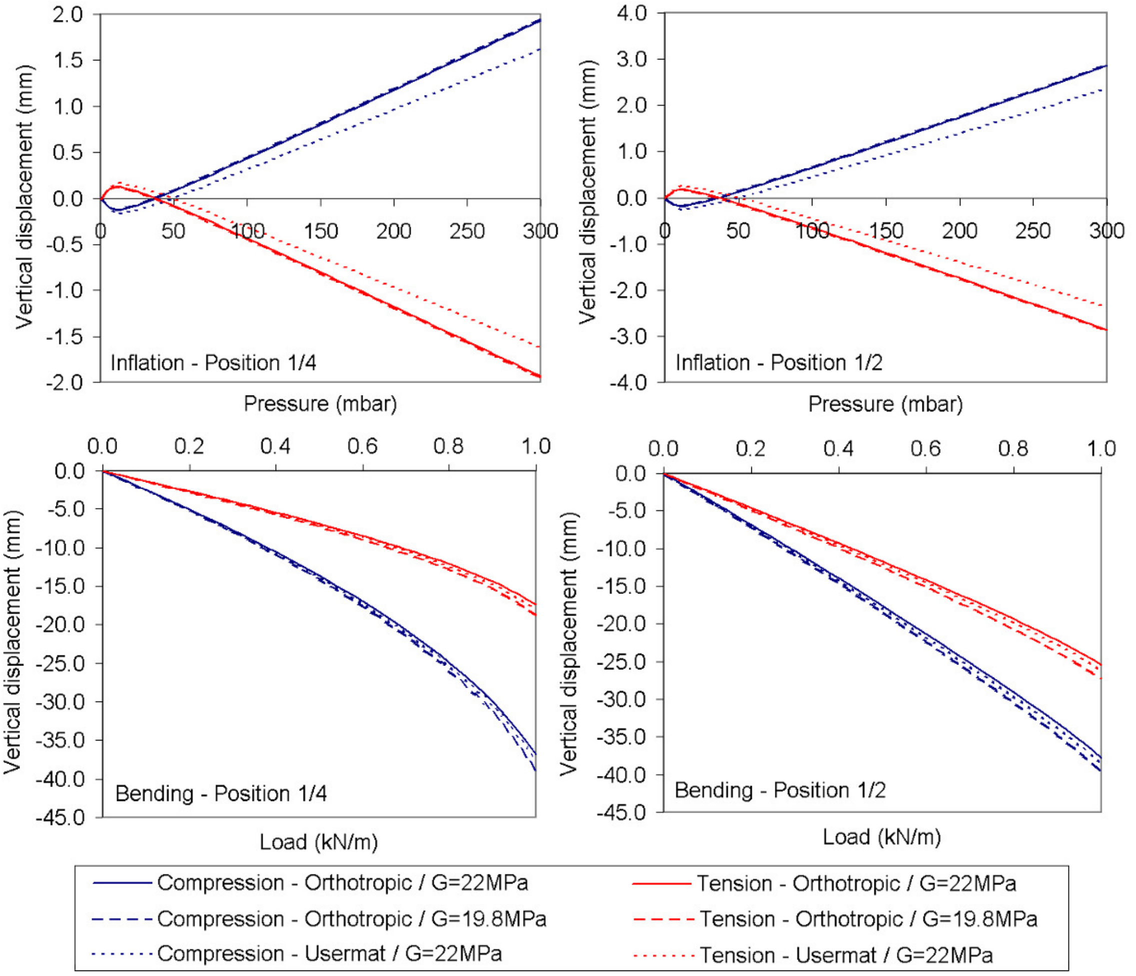

Fig. 10. FEA predicted displacements of compression and tension elements due to inflation of the airbeam and bending of the girder.

CONCLUSION

A simple non-linear model for the mechanical behaviour of PVC-coated fabrics has been presented. It allows a good representation of the overall material response, including the interaction between the warp and fill yarns in the fabric. A new shear test method has also been presented, and compared to a classical method. The new method proved to give satisfying results, while it significantly simplifies the material testing process. Finally the resulting material properties have been used for the finite element analysis of a Tensairity girder. Numerical predictions show that the choice of a material model does not significantly influence the structural response under bending. However, the non-linear model can be interesting for the simulation of the inflation because it can take into account the actual load ratio in the membrane.

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