# The FEM-prediction on Tensile Performance of Woven Membrane Materials under Uni and Bi-axial Loads

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***Abstract:*** In this study, the mechanical model of the woven PVC-coated membrane materials had been built. By the FEM analysis, it was found that when tensioned under uni-axial loads, the tensile modulus in the warp and fill direction of woven membrane materials was predicted satisfactorily, especially after the revision of properties of the fiber materials. The effect of the tensile moduli of the fiber and the PVC coating materials on the modulus of the woven membrane fabrics had been discussed. It was concluded that with the proper improvement of the modulus of the fiber materials in the fill direction, the discrepancy between the modulus of woven membrane materials in the warp and fill direction can be reduced to a certain extent. Considering prediction of modulus of the woven membrane materials under bi-axial loads, large difference was found between the predicted results and the experimental results, especially in warp direction. This was due to the fact that the mechanical analysis model reflected only the differences in geometric configuration between the warp and fill directions. However, the reinforcement of membrane materials in warp direction during weaving and coating processes had been ignored.

***Keywords:*** FEM, membrane materials, coated fabrics, tensile modulus, uni-axial, bi-axial.

## 1. Introduction

Lightweight structures, such as tension structures and air-supported structures, have been applied widely in the past four decades. Membrane materials as roof materials used for this kind of structures play an important role in the application of lightweight structures. As a kind of flexible materials, membrane materials have virtually little bending stiffness. To sustain a shape, the membrane materials must be in tension. Mechanical performances of the membrane materials in tension are therefore significant for structural design, installation and maintenance of the lightweight structures.

PVC-coated woven polyester fabrics are one of the two principal types of membrane materials used for lightweight structures. The tensile behaviour of woven membrane material features nonlinear and inelastic properties, therefore, it is difficult to obtain the material elastic constants through tensile experiments.

The nonlinear behaviour of woven membrane materials had been investigated by several researchers since 1970's. Minami [1] tried to linearize the initial curve within lower tensile loads to identify the tensile stiffness of coated fabrics. Chen [2] employed a second order polynomial to fit the tensile curves of several kinds of coated fabrics. Hino [3] regarded coated fabrics as a continuous material and evaluated the material elastic constants by means of dividing the stress-strain curves into many parts and assuming the response within each part to be linear. Minami [4] put forward another method to establish elastic constants using a multi-step linear approximation. In his research, the 3-D coordinates systems were established under biaxial tensile loadings. The 3-D expression of test results under bi-axial loads has been applied in the study of Bridgens [5]. The response surface provides a useful visualization of the fabric stress-strain response. Although these methods had tried to express precisely the complex and nonlinear tensile properties under uni- or bi-axial loads, rarely this information is useful for the membrane structure engineering. Until now only the elastic constants of the membrane materials under uni-axial loads are consulted with a much higher safety factor, typically between 5 and 10, which is two to four times of that used for the supporting cables, rods and webbing [6].

Mechanical modeling has been made a common practice to perform the prediction of bi-axial tensile response of membrane materials. Menges and Meffert [7], Stubbs [8] proposed and modified a space truss model. Since then, the truss model had been revised

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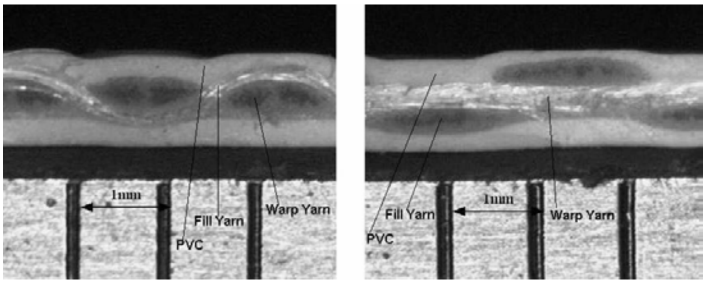
and modified by other researchers, such as Schock [9], Kato [10], and Pargana [11]. The model studies the bi-axial tensile properties of coated woven fabrics mainly by analyzing the deformation mechanisms of the two principal directions of orthogonal yarn system as well as the shear response with the influence of coating materials. The prediction based on the formulation of the model had a very good agreement with experiments. Only drawback is that the prediction models are too complicated to be applied practically.

This study focused on the FEM-prediction of the tensile elastic constant of woven membrane materials under uni-axial and bi-axial tensile loads, trying to provide a simple method for the design of the woven membrane materials for appropriate occasions. Firstly, the tensile modulus in the warp and fill direction of woven membrane materials under uni-axial loads has been predicted by the FEM mechanical analysis model. Then, the effects of the tensile moduli of the fiber and the PVC coating materials on the modulus of the woven membrane fabrics have been analyzed by mono-factor method. Finally, the modulus of the woven membrane materials under bi-axial loads has been studied by FEM.

## 2. FEM modeling of woven membrane material

For the analysis of the geometric configuration of the woven coated membrane material, pictures have been taken along the fill and the warp directions of the sample, as shown in Figure 1. It was found that the geometric asymmetry between the fill and the warp direction is significant. All the voids in woven fabric have been filled by the PVC coating material. Then the finite cell of the FEM modeling, shown in Figure 2, is based on the real geometric configuration of the coated membrane material.

According to the finite cell shown in Figure 2, the mechanical analysis model of woven membrane material has been established. The gridded one is shown in Figure 3. The X and Y direction is along the warp and the fill direction, respectively. The unit cells are 3-D tetrahedrons. This gridding criterion is applicable for the mechanical analysis of linear and elastic material. In our early work [12], a conclusion has been obtained, that is to say, for the woven membrane materials, after three loading cycles, the linearity of tensile property was greatly improved, and the membrane material was treated as a linear and elastic material when loaded within the 20% of the ultimate tensile stress. Then this conclusion is acceptable for the gridding of the mechanical analysis model with 3-D tetrahedrons.




(a) the fill direction (b) the warp direction

Figure 1 The cross-section of woven PVC-coated membrane material.

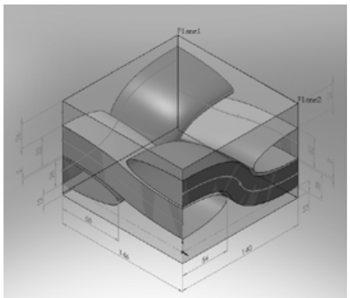


Figure 2 The finite cell of woven membrane material, (unit: $10^{-2}$mm).

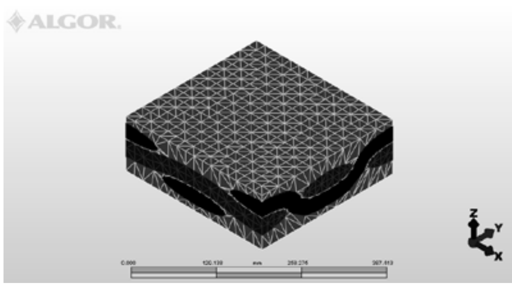



Figure 3 The gridding of the mechanical analysis model.

## 3. The FEM-prediction of tensile performance

According to the mechanical analysis model of the woven membrane material built-up above, the tensile properties under uni-axial and bi-axial loads were FEM-predicted respectively. The parameters for the components of the woven membrane material were identified as listed in Table 1.