Evaluation of Biaxial Stress-Strain Parameters for Architectural Fabrics using Finite Element Modeling

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Abstract: Architectural fabric structures are very important in both civil and military applications that require light weight, small packing volumes, and enhanced placement operations. Determination of stress-strain parameters of such materials is a very difficult process which may results in inaccurate or misleading values. Also, these fabrics may be loaded either uniaxially or biaxially, which means different sets of the mechanical properties. This paper aims to propose a simple Finite Element (FE) model using ANSYS that can simulate the actual mechanical behavior of coated architectural fabrics loaded uniaxially and biaxially. An experimental program was conducted to perform both axial and biaxial loading. For this purpose, a special designed apparatus was built to load the fabrics biaxially and the results were compared to those of the FE models. Three FE proposals for expressing the biaxial mechanical behavior of architectural fabrics are presented and examined. Both experimental and FE results are in a good agreement. This confirms the validity of the proposed FE model to determine stress-strain parameters that express the mechanical behavior of the architectural fabrics.

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1. Introduction

Coated woven fabrics, shown in Figure (1), are used in a wide range of structural applications to provide light weight, architecturally striking solutions.

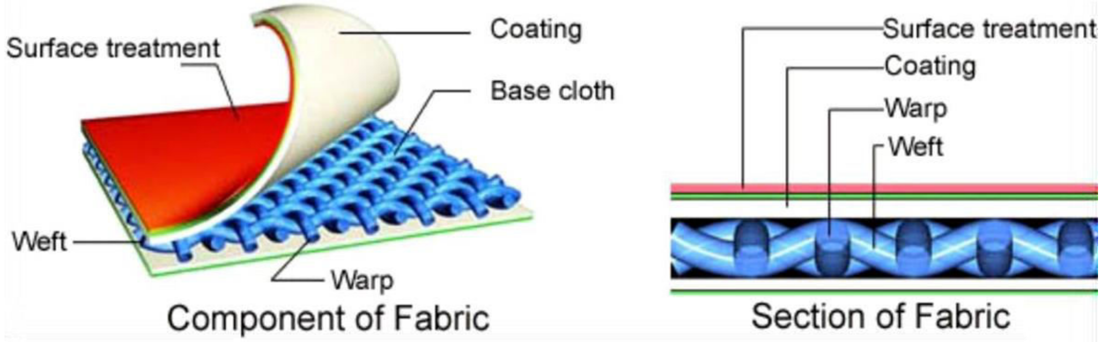


Figure (1): Coated Woven Fabric.

The design of fabric structures is complicated due the complex response of coated woven fabrics to biaxial loads in the plane of the fabric. The knowledge of the mechanical behavior of woven fabrics under uniaxial/biaxial tensile loads is necessary to predict the changes in their geometry during the processing of any industrial fabric. The woven fabrics are used extensively in architectural fabric structures because of their great advantages such as, ease of handling, ability to drape and resistance to damage. In addition, the prediction of the deformed geometry is equally important in the micro-mechanical analysis of all fabrics composites. One of the difficulties in analyzing the mechanical behavior of the fabrics lies in the fact that any extension occurring at an angle to the warp or weft direction usually involves a different mechanism of deformation. A better understanding of the behavior of architectural fabrics may significantly reduce levels of uncertainty in the design process and enable more ambitious architectural forms to be generated [1]. Different approaches based on the force density method, finite element method or discrete element methods have been developed during the last decades [2]. As the mechanical behavior of fabrics is highly nonlinear, anisotropic and hysteretic [3], many authors, such as [4 -9] have assumed linear elastic behavior due to great variation in fabric tensile properties with changes in direction. The subject of mechanical behavior of fabrics under uniaxial/biaxial loads has been studied by many research workers over many years such as Kawabata [10], Grosberg [11], Hearle [12], Freeston [13], Jong [14], Haung [15], Leaf [16], Dastoor [17], Potluri [18] And Boisser [19]. But there is no general model that can be considered for all the different fabric designs. In addition there is no general theory that can describe or simulate the mechanical behavior of a fabric when subjected to different types of loads under working conditions. Hence it is necessary in case of architectural fabrics structures for the designers and architects to know the stress-strain distribution of the fabrics in the architectural structures and determine the maximum stress and strain to prevent the failure of the structures. So it is essential to use another method to simulate the behavior of the fabrics under a certain load such as finite element method (FEM). Ren Shibo [20] modeled the Poly-Tetra-Fluoro-Ethylene (PTFE) coated fiberglass fabric using SHELL41 element of ANSYS. In this research, the authors use the Finite Element Package ANSYS [21] to model the tensile behavior of the architectural fabrics under both uniaxial and biaxial loading. Also, the paper aims to obtain a proposal for FE modeling process that can, accurately, predict the actual mechanical behavior of architectural fabrics subjected to in-plane loading, especially biaxial one.

2. Experimental Work

Two types of tensile loadings were used; uniaxial and biaxial. The uniaxial tensile test was carried out according to ASTM D-751 [22] using CRE tensile testing machine to measure both the load and the corresponding elongation. However, to perform the biaxial loading, a special designed apparatus shown in Figures (2) and (3) was built to examine cruciform samples shown in Figure (4). All the results of uniaxial and biaxial loadings were the average of at least 3 specimens.

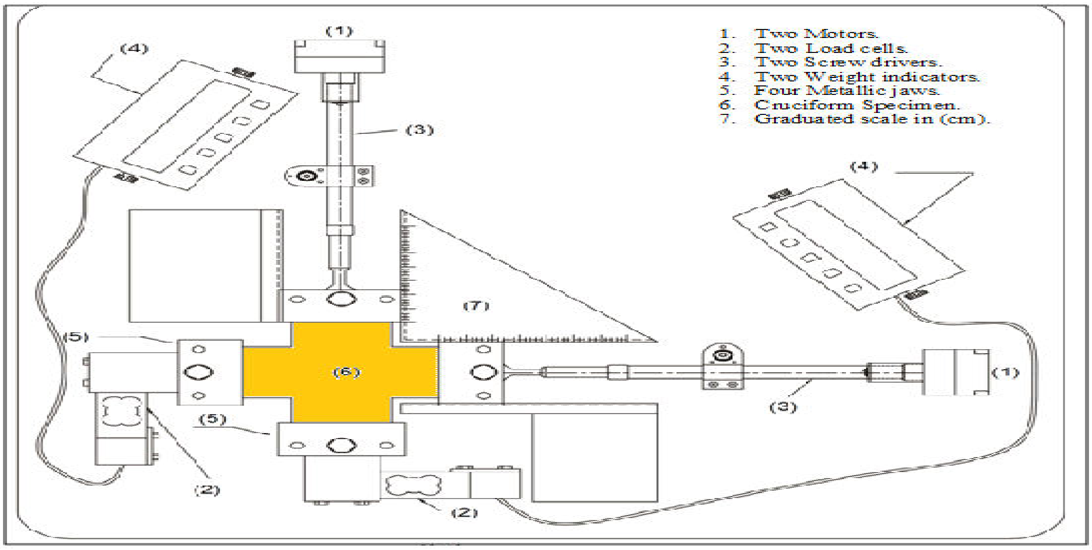


Figure (2): The Biaxial Tensile Tester.

Figure (3): Photo of the Biaxial Tester.

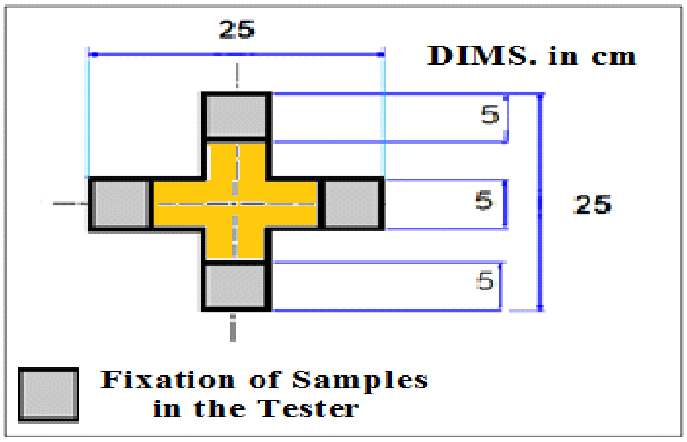


Figure (4): Dimensions of the Cruciform Sample.

Four fabric samples were chosen to compare their experimental results with those of the corresponding FE results. The specifications of these fabrics are given in table (1)

Table (1) Fabric Specifications

Sample No.	Fabric design	Warp count Ne1	Weft count Ne2	Ends /inch	Picks /inch	Fabric specific Weight (gm/m^2)
1	Weft Rib (4x4)	24/2	24/2	56	56	228
2	Cotton Duck Weft Rib (2x2)	10/3	12/4	46	26	640
3	Warp Rib (2x2)	24/2	24/2	56	56	228
4	Cotton Duck Double Warp Rib (3x3)	12/3	10/3	40	45	550

3. Finite Element Modeling

Since architectural fabrics are loaded in their planes, only tensile stiffness is needed without flexural stiffness which means membrane action. As a result, the samples may be modeled using 2D or 3D Finite Elements. Three types of elements are used to verify the most appropriate one to model the mechanical behavior of the architectural fabrics. These elements are PLANE42, SHELL43, and SHELL181. All these elements have plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

3.1 PLANE42 (2-D Structural Solid)

It is used for 2-D modeling of solid structures as a plane stress or plane strain element. The element is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions, as shown in Figure (5). Plane stress option is used since both normal and shear stresses directed perpendicular to the plane are assumed to be zero.

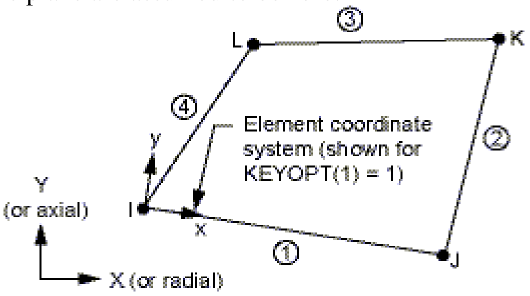


Figure (5): PLANE42 Geometry.

3.2 SHELL43 (4-Node Plastic Large Strain Shell)

It is well suited to model moderately-thick shell structures. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes, as shown in Figure (6). No membrane option is available in this element. The deformation shapes are linear in both in-plane directions. For the out-of-plane motion, it uses a mixed interpolation of tensorial components.

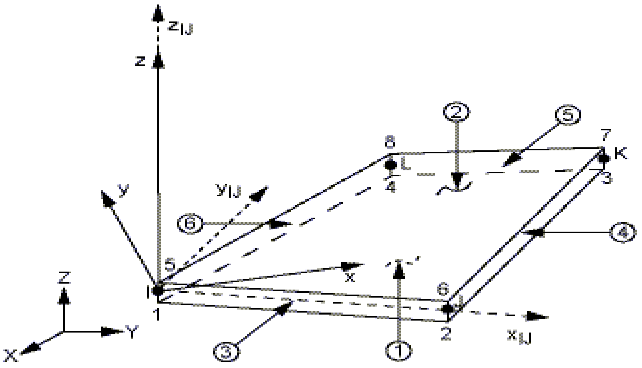


Figure (6): SHELL43 and SHELL181 Geometry.

3.3 SHELL181 (4-Node Finite Strain Shell)

It is suitable for analyzing thin to moderately-thick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes, as shown in Figure (6). Since the membrane option is used, only the translational degrees of freedom are considered.

3.4Materials

Fabric materials are anisotropic materials that have 6 x 6 and 4 x 4 elastic coefficient matrices for 3D and 2D analyses, respectively. Determination of these values for architectural fabrics is not available experimentally. As a result, another way for representing the materials of these fabrics is needed for FE modeling. As a preliminary thinking, these materials will be modeled as isotropic material. This is acceptable in uniaxial loading through the modulus of elasticity and stress-strain curve of the yarns in the direction of loading. This is not available for biaxial loading. In the same time, expressing the biaxial behavior of fabrics as orthotropic is not valid due to the presence of different stress-strain curves of the yarns in both directions, regardless the fact that fabrics are not orthotropic materials. As a conclusion, FE modeling of fabrics materials cannot be conducted easily although of the simplicity of their geometry. Three proposals for the modeling of fabrics loaded biaxially will be explained later based on the isotropic modeling of materials.

3.5Meshing, Boundary Conditions and Loading

Figure (7) shows the finite element models of the experimental samples either loaded uniaxially or biaxially. Loads are uniformly distributed line loadings applied incrementally till failure through many small equal load steps. Boundary conditions are put to forbid all the available movements in all the directions at the points of fixation. Also, points of loading are boundary-conditioned to move only in the direction of the loading according to the actual mechanism of the used testers. Meshing analysis was conducted to choose the suitable element size that balances between both time and accuracy of the solution.

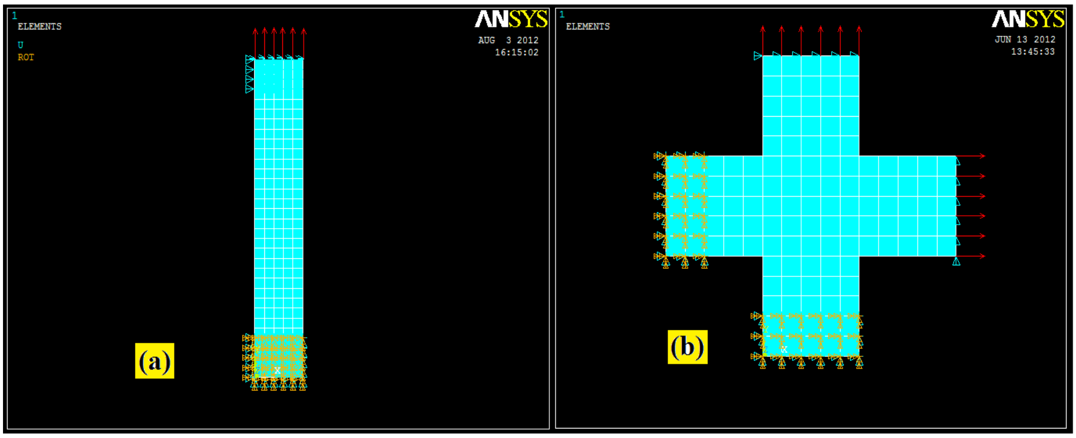
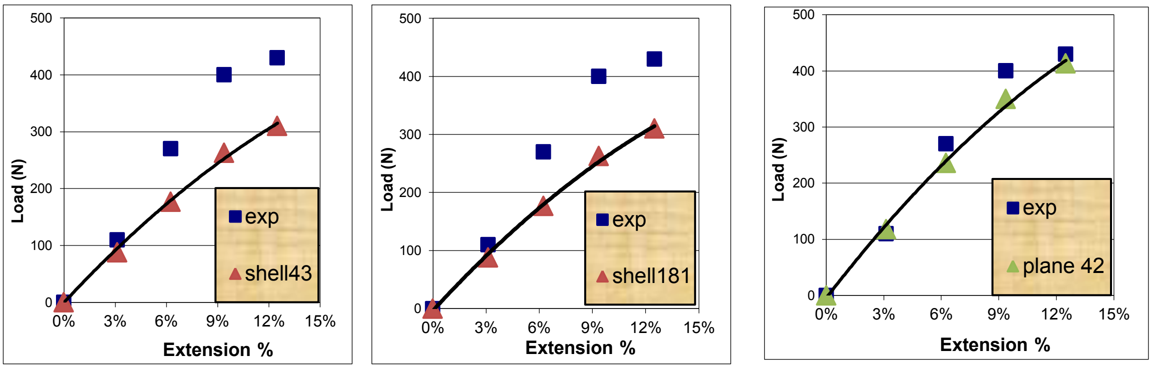


Figure (7): FE Models (a) Uniaxial Loading, and (b) Biaxial Loading.

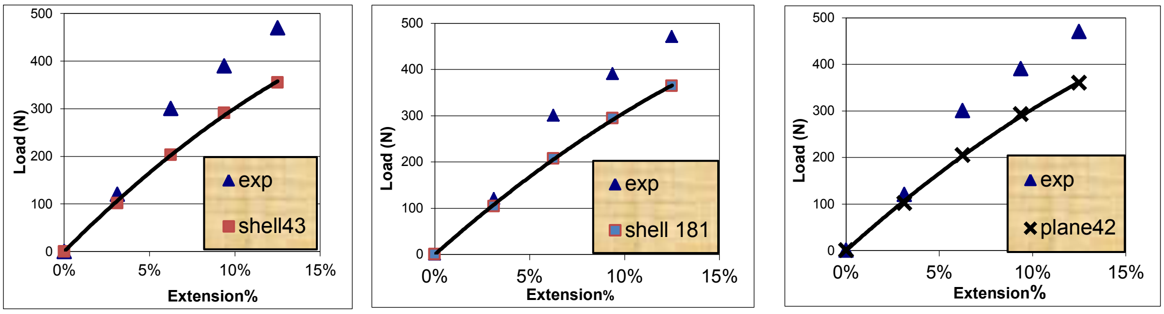
4. Results of Uniaxial Tests

Two fabrics are used in the uniaxial tests; weft rib (4x4) and cotton duck weft rib (2x2). Figures (8) and (9) show both experimental and FE results of the two fabrics, respectively, using different elements.



(a) SHELL43 (b) SHELL181 (c) PLANE42

Figure (8): Load-Elongation Curves for Weft Rib (4x4).



(a) SHELL43 (b) SHELL181 (c) PLANE42

Figure (9): Load-Elongation Curves for Cotton Duck Weft Rib (2x2).

Figure (10) shows the propagation of displacements and stresses for the uniaxial samples at ultimate load. Table (2) shows the values of the correlation and the root mean square deviation (R.M.S.D) between the experimental and FE results for the two sample fabrics. For weft rib (4x4), PLANE42 element is the most appropriate which is in agreement with [23] because this fabric has very small thickness and this type of elements is used for 2-D modeling of plane stress solid structures. On the other hand, duck fabric which has a relatively moderate thickness is preferred to be modeled using SHELL181 element which is used for modeling thin to moderately-thick shell structures and supports the membrane action.

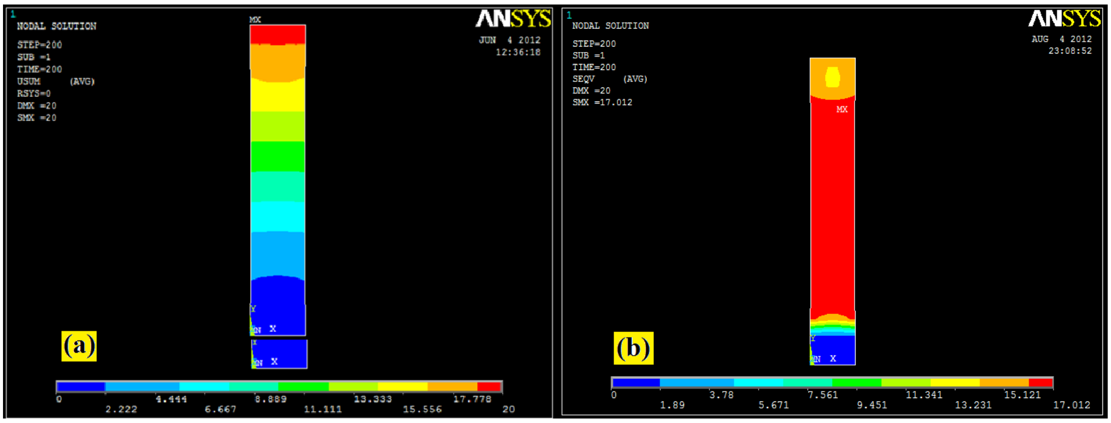


Figure (10): Propagation of (a) Displacement and (b) Stress for the Uniaxial Sample.

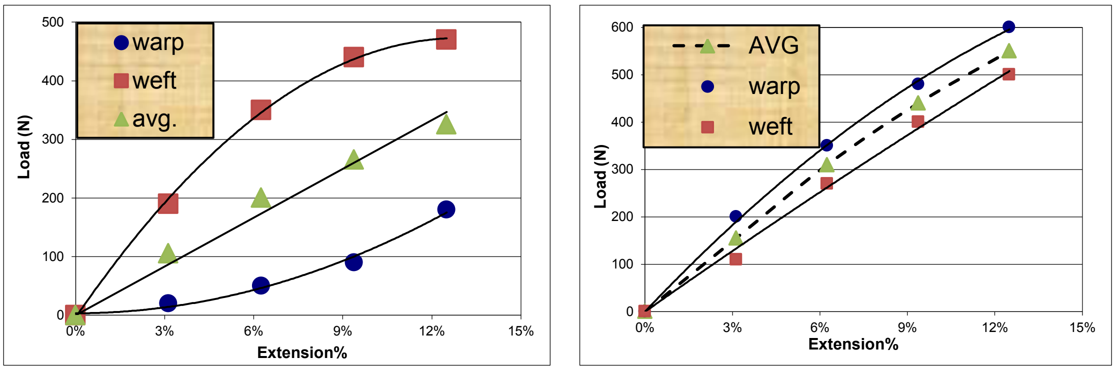
Table (2) Correlation and R.M.S.D between the Experimental and FE Results (Uniaxial)

Sample No.	Fabric Structure	Correlation and R.M.S.D		
		SHELL43	SHELL181	PLANE42
1	Weft Rib (4x4)	0.9925 102.8	0.9925 102.8	0.9923 31.6
2	Cotton Duck Weft Rib (2x2)	0.9930 90.6	0.9927 85.7	0.9929 88.1

According to Figures (8) and (9) and Table (2), a good agreement is shown between both experimental and FE results.

5. Results of Biaxial Tests

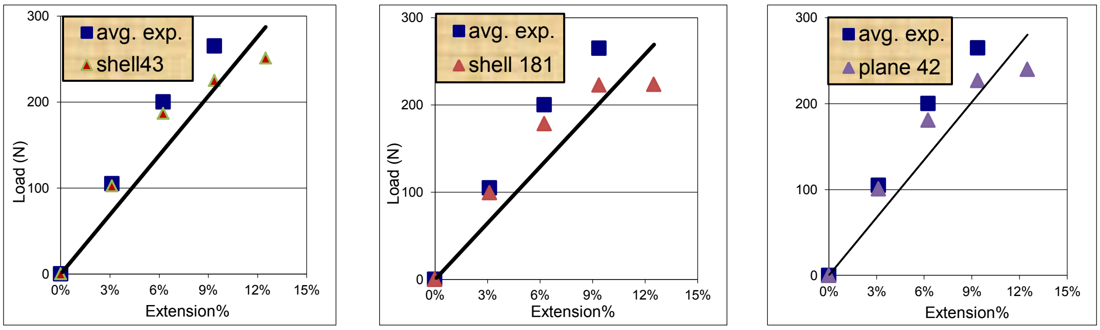
Two fabrics are used in the biaxial tests; warp rib (2x2) and cotton duck double warp rib (3x3). Figures (11) and (12) show the experimental results of the two fabrics in the two directions; warp and weft. The results of the two directions are not the same.



(a) Warp Rib (2x2) (b) Cotton Duck Double Warp Rib (3x3)

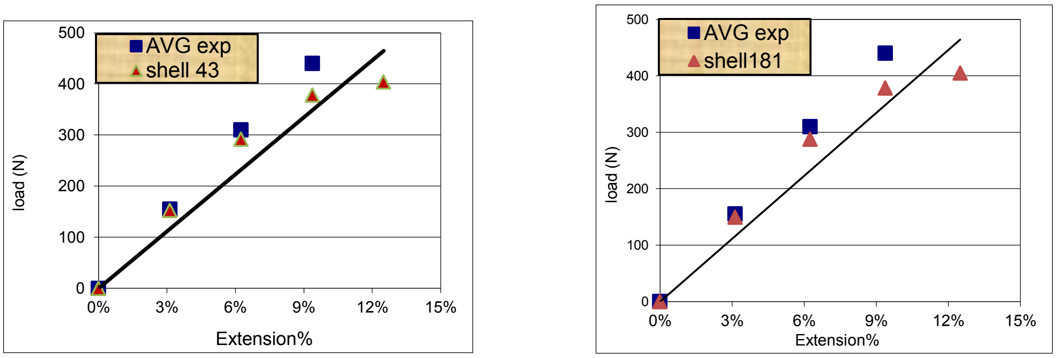
Figure (11): Experimental Load-Elongation Curves.

The reasons are the difference of modulus of elasticity and crimp percentage for each of the directions. For example and for the first fabric; warp rib (2x2), the modulus of elasticity of the weft direction is higher than the modulus of elasticity in the warp direction and the crimp percentage of the warp direction (C1=17%) is higher than that of the weft direction (C2=4%). So when the fabric is subjected to loads, the yarns begin to straighten, reducing the crimp and causing high elongation at low load in the direction of the greater crimp percentage and low elongation at the same load in the direction of the lower crimp percentage. For this reason, average values for the modulus of elasticity and stress-strain curve of the yarns in each of the two directions are calculated and used to model the fabric as isotropic material. Figures (12) and (13) show both averaged experimental and FE results of the two fabrics using different elements. Due to the moderate thick of the second fabric; cotton duck double warp rib (3x3), only shell elements are used to model the sample.



(a) SHELL43 (b) SHELL181 (c) PLANE42

Figure (12): Load-Elongation Curves for Warp Rib (2x2).



(a) SHELL43 (b) SHELL181

Figure (13): Load-Elongation Curves for Cotton Duck Double Warp Rib (3x3).

Table (3) Correlation and R.M.S.D between the Average Experimental and FE Results

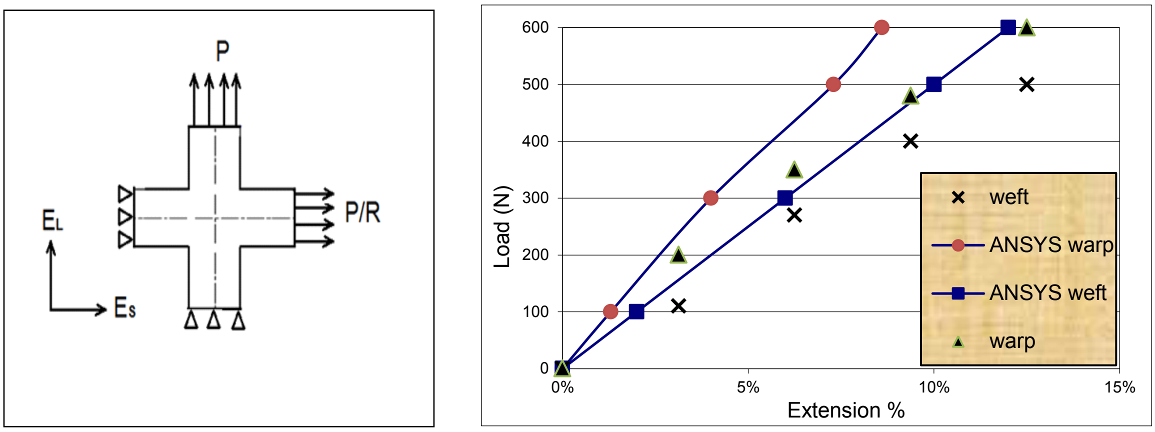
Sample No.	**Fabric Structure**	**Correlation and R.M.S.D**		
		SHELL43	**SHELL181**	**PLANE42**
3	**Warp Rib (2x2)**	**0.9903** **42.7**	**0.9775** **56.1**	**0.9863** **47.7**
4	**Cotton Duck** **Double Warp Rib (3x3)**	**0.984036** **80**	**0.98583** **79**	**-----** **-----**

The results show good agreement between the average experimental results and that of the FE modeling. However

6. Proposals for the FE Modeling of Mechanical Properties for Biaxial Loading

In order to feed the data for ANSYS as isotropic material, it is required to have one value of Young's modulus and one stress-strain curve to represent the properties of this fabric in the warp and weft directions. Therefore, three trials are done to solve this problem by using the following approaches:

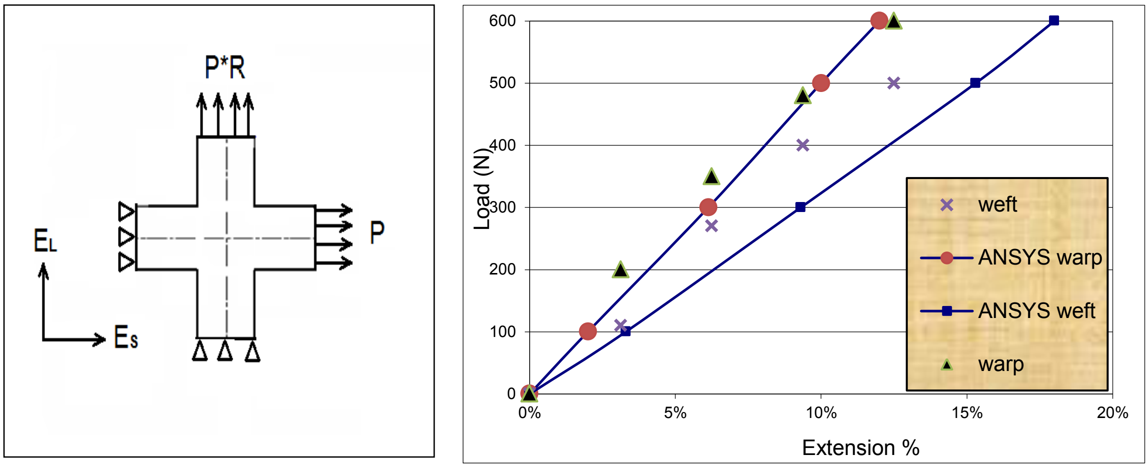
1. By calculating the average of the mechanical properties of the warp and weft directions and tacking these averaged values as an input, as done in the previous section.
2. By using the mechanical properties of the direction that has the largest value of modulus of elasticity as an input. Then, the directions of the largest modulus (E_L) and the smallest one (E_S) will be loaded by (P) and (P/R), respectively, where ($R = E_L/E_S$), as shown in Figure (14-a). The experimental and proposed FE results are shown in Figure (14-b).



(a) (b)

Figure (14): (a) 2nd Proposal, (b) Load-Elongation Curves.

3. By using the mechanical properties of the direction that has the smallest value of modulus of elasticity as an input. Then, the directions of the largest modulus (E_L) and the smallest one (E_S) will be loaded by (P×R) and (P), respectively, as shown in Figure (15-a). The experimental and proposed FE results are shown in Figure (15-b).



(a) (b)

Figure (15): (a) 3rd Proposal, (b) Load-Elongation Curves.

Figures (14) and (15) show a good agreement between both experimental and proposed FE modeling results. However, the third methodology, Figure (15), is more suitable for modeling the textile fabrics subjected to biaxial loads using FEM, since it gives more accurate results.

Figure (16) shows the distribution (contours) of stresses at failure using any of the proposed models, while Figure (17) shows the experimental failure mode of the biaxial architectural fabric. As shown, there is an exact match between the position of maximum strains/stresses in the proposed FE models and the position of the maximum strains/stresses in the experimental model where the failure occurred. This confirms the ability of the proposed FE models to follow the exact behavior of architectural fabrics subjected to biaxial loading.

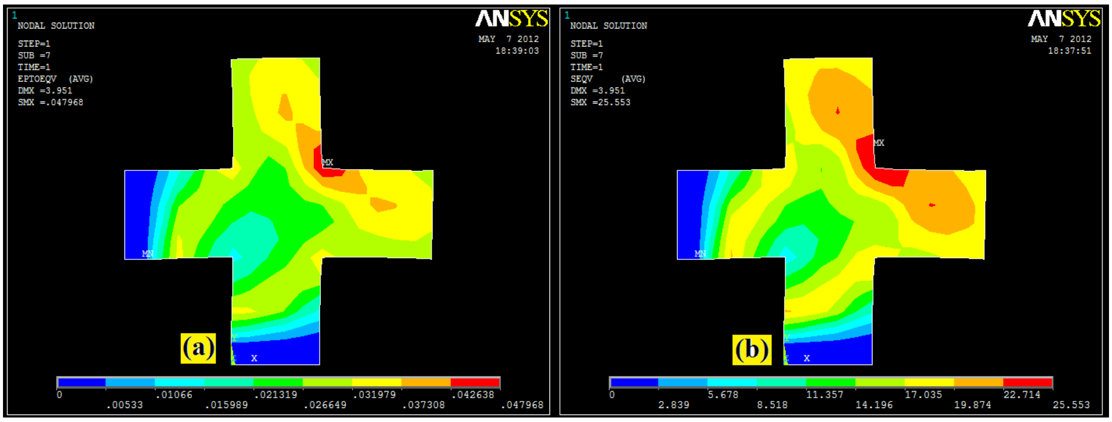


Figure (16): Propagation of (a) Strains and (b) Stresses of the Biaxial Sample.

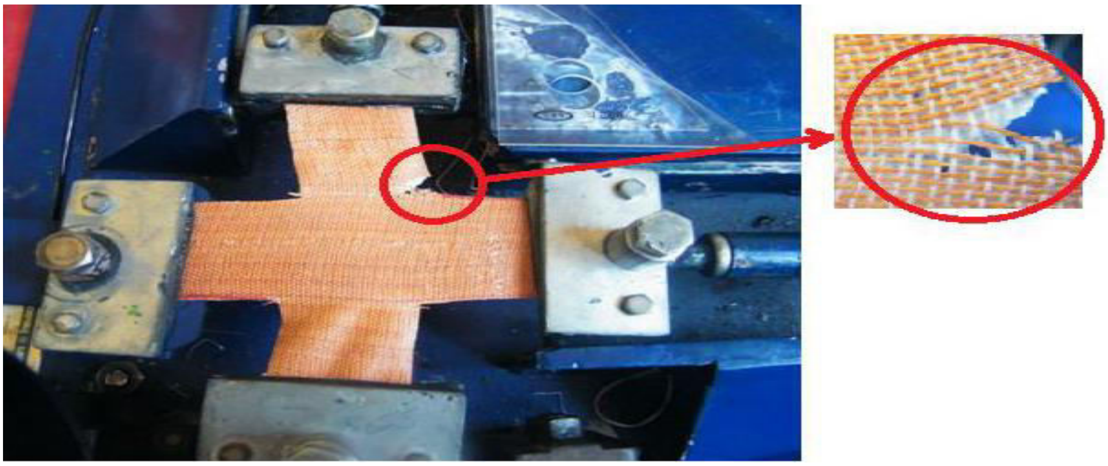


Figure (17): Failure Mode of the Biaxial Sample.

7. Conclusions

a) Architectural textile fabrics are anisotropic materials that need the determination of 16 and 36 parameters to be modeled in 2D and 3D analysis, respectively. These parameters cannot be obtained experimentally till now.

b) Three FE proposals for modeling these fabrics as isotropic materials when subjected to biaxial loading are examined and found to have a good agreement with the experimental results.

c) The verification of the experimental work using ANSYS software proved that it could effectively predict the response of the fabrics in different conditions and the use of ANSYS software gives the possibility to study the stress and strain distribution of the fabric under the applied loads.

d) If the variation of the tensile properties between weft and warp directions is small, it is recommended to use the first methodology by using average values for the mechanical properties of the two directions.

e) If the variation between weft and warp directions is effective, it is recommended to use both the second and third proposals to get the more accurate behavior for each of the two directions. However, using each of them alone gives good results.

f) Plane stress elements, i.e. PLANE42, are the most appropriate choice to simulate very thin fabrics.

g) Shell elements, i.e. SHELL181, are suitable to simulate the fabrics with thin to moderate thickness. Also, they are recommended to be used in case of nonlinear behavior.

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