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Multi-Scale Modeling the Mechanical Properties of Biaxial Weft Knitted Fabrics for Composite Applications

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Abstract In this paper a multi-scale numerical model for simulating the mechanical behavior of biaxial weft knitted fabrics produced based on 1×1 rib structure is presented. Fabrics were produced on a modern flat knitting machine using polyester as stitch yarns and nylon as straight yarns. A macro constitutive equation was presented to model the fabric mechanical behavior as a continuum material. User defined material subroutines were provided to implement the constitutive behavior in Abaqus software. The constitutive equation needs remarkable tensile tests on the fabric as the inputs. To solve this drawbacks meso scale modeling of the fabric was used to predict stress–strain curves of the fabric in three different directions (course, wale and 45°). In these simulations only the yarn properties are needed. To evaluate the accuracy of the proposed macro and meso models, fabric tensile behavior in 22.5 and 67.5° directions were simulated by the calibrated macro model and compared with experimental results. Spherical deformation was also simulated by the multi scale model and compared with experimental results. The results showed that the multi-scale modeling can successfully predict the tensile and spherical deformation of the biaxial weft knitted fabric with least required experiments. This model will be useful for composite applications.

Keywords Biaxial weft knitted fabric · Multi-scale finite element modeling · Tensile behavior in various directions · Fabric spherical deformation

1 Introduction

Nowadays, technical textiles, which have excellent mechanical behavior at the time of application, have attracted attention of engineers and designers. The use of these textiles in

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various areas of application such as automotive, transportation, construction, aerospace and clothing has been increased [1, 2]. Knitted structures due to their excellent formability can take the simple and complex shapes at the time of use as technical applications, especially in the field of composite manufacturing [3–5]. But from the other point of view, studies show that composites made from knitted textiles represent lower mechanical properties compared with other conventional reinforced textile composites [6–9]. Araújo et al. [10] recognized the non-linear behavior of a knitted structure under tensile loading as the main reason for its low stiffness and strength properties. Researchers have offered various techniques in order to improve the mechanical behavior of weft knitted structures to be suitable for composite manufacturing [11–13]. Considering the combination of weaving and knitting technologies, a new designed hybrid structure with improved mechanical behavior due to the constitutive straight yarns was proposed [14–17]. Along with this suggestion, it was concluded that by inserting the reinforcing yarns through the knitted structure in warp (wale-wise) or weft (course-wise) directions, the anisotropy characteristics of the resulted composite would become suitable for particular application [18]. Many researchers studied the application of the biaxial weft-knitted for reinforcing the thermoplastic and thermoset composites and the properties of the resulted structures [19–22]. Also, coated biaxial knitted fabrics are widely used for permanent works in various applications such as sport stadiums, transportation and commercial constructions. In fact, these structures constitute an alternative to classical stiff roofs.

Formability is defined as the deformation of a planar textile structure to fit a three-dimensional surface. Shear deformation is considered as the main deformation mode for biaxial warp and weft knitted fabrics in the forming process. Accordingly, shear angle between the warp and weft yarns is the only parameter used to describe the deformation ability of a biaxial knitted fabric [23]. Zhang [24] investigated the formability of the multi-layered biaxial weft knitted (MBWK) fabrics on double hemisphere. They reported that the angle between the inserting yarns had a linear relationship with the perpendicular distance from the measured points to the longitudinal axis of the hemisphere on +45° direction, and had a nonlinear relationship on −45° direction.

Taking into account the increasing applications of biaxial weft-knitted fabrics in the manufacturing of shell composites with complicated shapes, it is becoming more important to achieve a better understanding of their spherical deformation. In this study, the spherical deformation of the bi-axial weft knitted fabrics is investigated as the forming resistance of the fabrics against a hemispherical ball. This test is applied for all textile fabrics as bagging test. During bagging test, the fabric is subjected to tensile and shear forces. Thus, it can be used for evaluating the formability of the biaxial weft knitted fabrics.

Developing the analytical and numerical models of reinforced structures corresponding to their mechanical performance under different loading conditions, is considered as a key factor to achieve a desirable product [25]. Some researchers, such as Peng et al. [26], developed a non-orthogonal constitutive model to characterize the anisotropic material behavior of woven fabrics under large deformation. Xue et al. [27], also proposed a new constitutive model for characterizing the non-orthogonal material behavior for woven composites with different weave architectures under large deformation. Moezzi et al. [28], analyzed the mechanical response of a woven polymeric fabric with locally induced damage. The main drawback of these models is the required inputs that need remarkable experiments on the fabrics. Some researchers [29, 30], developed a multi-scale finite element method to numerical simulation of knitted fabric material. However, there is very limited works on the macro behavior of the biaxial weft knitted fabrics. In this paper a multi-scale numerical model is presented to simulate the mechanical behavior of biaxial weft knitted fabrics produced based on the rib structure. This model can be effective in predicting the mechanical behavior of these structures. Modeling of spherical deformation and tensile properties in different direction is performed by using a macro continuum model of the fabric. To calibrate the macro model results of meso scale modeling is used.

2 Material and Methods

The aim of the current paper is to simulate macro behavior of the biaxial weft knitted fabric using a macro constitutive equation. To calibrate the constitutive equation instead of the tensile test of the fabric in various directions, results of the meso scale modeling are used. Bagging test is chosen as a process that macro behavior of the fabric should be predicted in it, therefore after producing the fabric this test is performed on it. Elastic constants of the yarns are also required for meso scale modeling of the fabric and should be measured for both knitted and reinforcement yarns.

The biaxial weft knitted fabrics based on 1×1 rib structure were produced on a modern flat knitting machine (Stoll CMS 400, E5). Polyester and nylon yarns were used for stitch yarn and straight yarns, respectively. For inserting the warp yarns, a special yarn guide is required. Figure 1 shows the equipment required for warp and weft insertion through knitted structure.

The thickness of the fabrics was measured as 2.5 mm. The knit density of rib structure was 15.4 loop/cm^2. Also three warp and four weft yarns per centimeter were inserted in the knit structure. Linear elastic behavior was assumed for each yarn. The elastic modulus of the yarns is found by currying out tensile tests on several yarns for both nylon and polyester yarns. These tensile tests were performed by Zwick tensile tester.

Elastic constants and linear density assigned to weft, warp and stitch yarns are shown in Table 1.

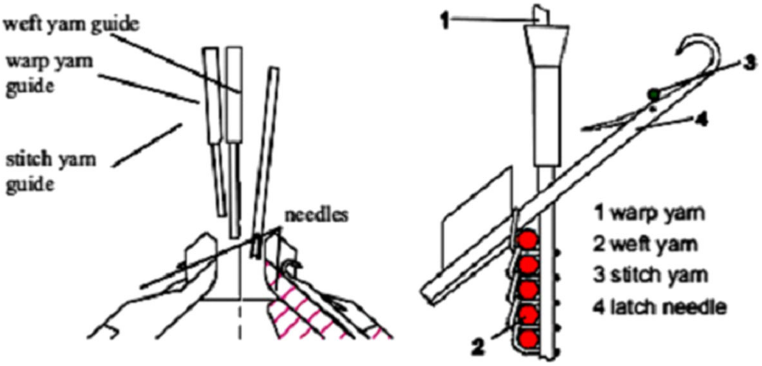


Fig. 1 Equipment required for warp and weft insertion through knitted structure [14]

Table 1 Elastic constants for weft, warp and stitch yarns

Component	E (*MPa*)	*(Poisson's ratio)*	Linear density (*denier*)
Weft and warp yarn (Nylon)	1113	0.3	2780
Stitch yarn (Polyester)	176	0.3	850

To investigate the model accuracy in various directions tensile tests in 22.5 and 67.5° with regards to the weft direction are also performed on the fabric.

Circular knitted samples with 110 mm diameter were prepared and placed into the clamp with 56 mm diameter [31]. The samples were then deformed using a steel ball with a diameter of 48 mm attached to the tensile tester. Bagging height of 12 mm, corresponding to approximately 25 % elongation at a cross-head speed of 20 mm/min was applied. All samples were conditioned at 65 % ± 2 % relative humidity and temperature of 21 ± 1 °C before each test.

3 Multi-Scale Finite Element Modeling of the Fabric

In this paper, the mechanical behaviors of biaxial weft knitted fabrics in terms of axial tensile strength and compression resistance are simulated by a macro constitutive equation which was calibrated by the meso scale modeling.

Prior to the modeling, macro constitutive equation based on the simulated structure is presented. Moreover, a suitable meso scale modeling to calibrate the presented macro equation would be described. The final calibrated macro model is then used to simulate fabric axial and bias tensile behavior as well as their bagging performance. In order to validate the simulated model, the theoretical results are being compared with the experimental data achieved from the mechanical tests.

3.1 Constitutive Equation of the Biaxial Weft Knitted Fabric

Based on the experimental data obtained from the tensile tests of the biaxial weft knitted fabrics, it could be understood that the reinforcing weft and warp yarns play important roles regarding the tensile load bearing during the axial tensile loadings in both wale and course directions. Regardless

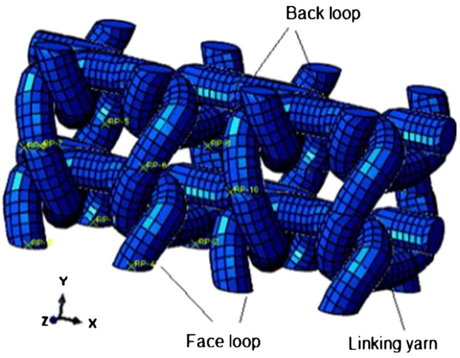


Fig. 2 Schematic of a 1×1 rib structure

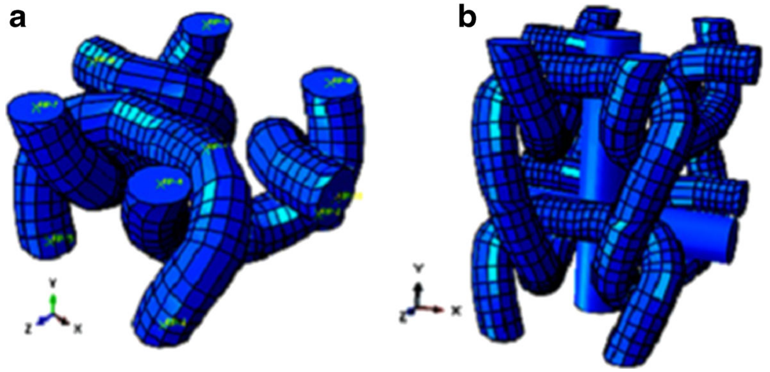


Fig. 3 **a**. Unit cell of 1×1 rib fabric; (**b**) unit cell model of biaxial weft knitted fabric based on a rib structure

of the load applying direction, it is also concluded that the knitted base structure has nearly no effect on tensile load bearing of the whole fabric. On the other hand, it is obvious that there is no interlacing point between the reinforcement yarns within the fabric structure, so that the yarns are not subjected to the applied shear force during tensile tests. Thus, it can be well concluded that the difference between shear behaviors of both 1×1 rib and biaxial fabrics with the same knitted structures, is mainly due to the association of reinforcing yarns. Consequently, the biaxial knitted structure shows more shear stiffness values while their jamming phenomenon occurs earlier. Considering these observations, the constitutive equation of the biaxial fabric can be defined as follows:

a) Assuming iso-strain condition in a unite cell, the stiffness matrix when the fabric is subjected to pure tensile force in wale or course directions is as follows:

$$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}^{BR} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}^{Re} + K \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}^{1\times1\ Rib} \quad (1)$$

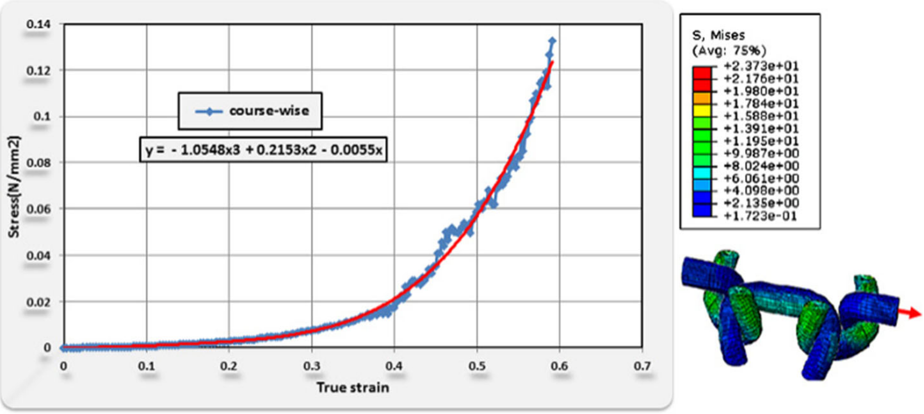


Fig. 4 The 1×1 rib fabric elongated in weft direction and the calculated stress–strain of the fabric with the fitted curve on it

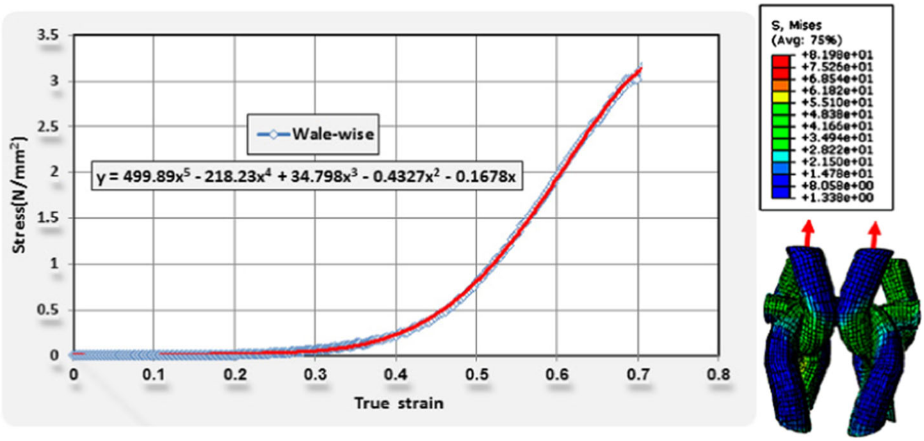


Fig. 5 The 1×1 rib fabric elongated in warp direction and the calculated stress–strain of the fabric with the fitted curve on it

where D^{Re} is stiffness of the reinforcements yarns, D^{Knit} is stiffness of the knit structure and D^{BR} is the total stiffness of the biaxial rib weft knitted fabric. It is worth mentioning that, components of stiffness matrix are functions of strain, in other words at a specific strain, tangent stiffness matrix related to this point should be used to calculate stress increment.

b) For other stress states, it can be concluded:

$$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}^{BR} = K.\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}^{1\times 1\ Rib} \qquad (2)$$

where $D^{1\times1\,\mathrm{Rib}}$ is stiffness matrix of the 1×1 rib fabric without reinforcement yarns and K is an effective index which shows the influence of inserting the reinforcing yarns within the knitted

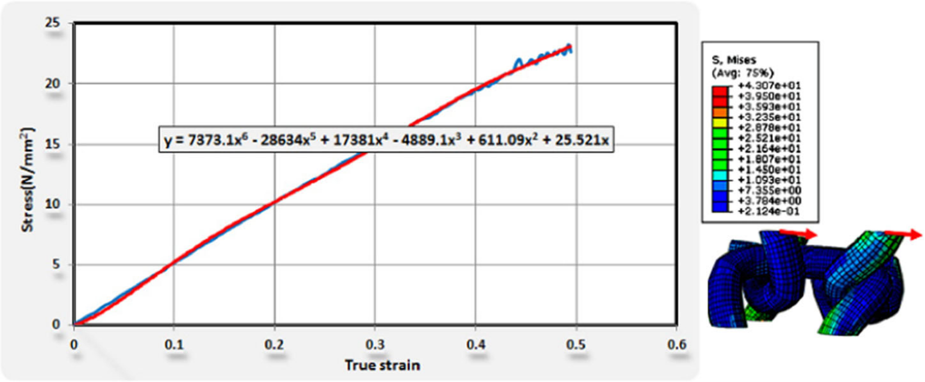


Fig. 6 The 1×1 rib fabric under shear test and the calculated stress–strain of the fabric with the fitted curve on it

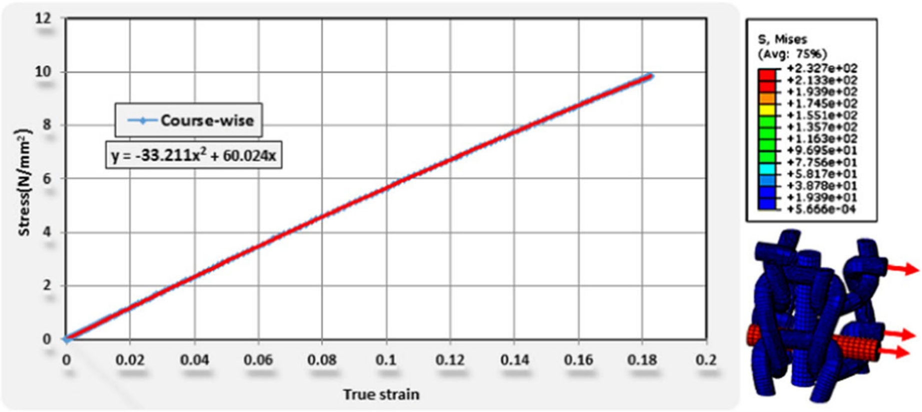


Fig. 7 The biaxial rib fabric elongated in weft direction and the calculated stress–strain of the fabric with the fitted curve on it

fabric structures on their shear stiffness. The above constitutive equation is implemented in Abaqus finite element software by writing a user material subroutine UMAT.

It should be noticed that after shear strain weft and warp directions do not remain perpendicular and a non-orthogonal coordinate system should be used to calculate stress and strain relationship [26].

The most important and time consuming part of using this constitutive equation is performing required tests and calibrating the stiffness components by the test results. This is described in the following section.

3.2 Meso Scale Modeling

In this paper meso scale modeling is used to calculate required inputs for the presented constitutive equation. Providing the stiffness matrices of biaxial and 1×1 rib fabrics are essential for the Eqs. 1 and 2; having these data, is required for meso scale modeling the

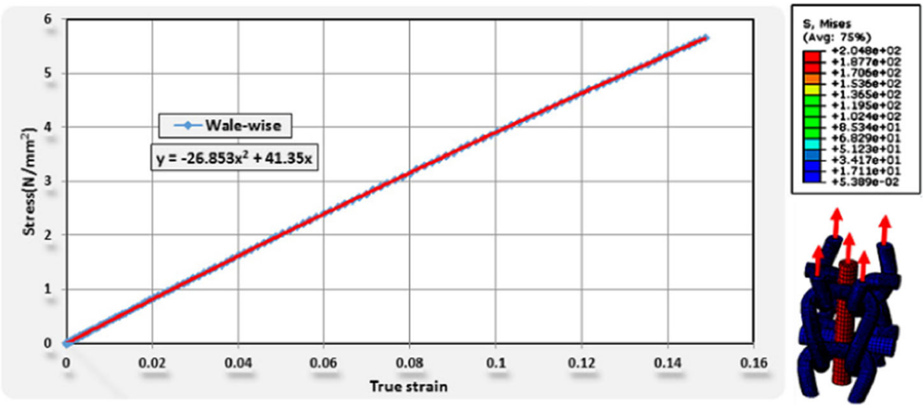


Fig. 8 The biaxial rib fabric elongated in warp direction and the calculated stress–strain of the fabric with the fitted curve on it

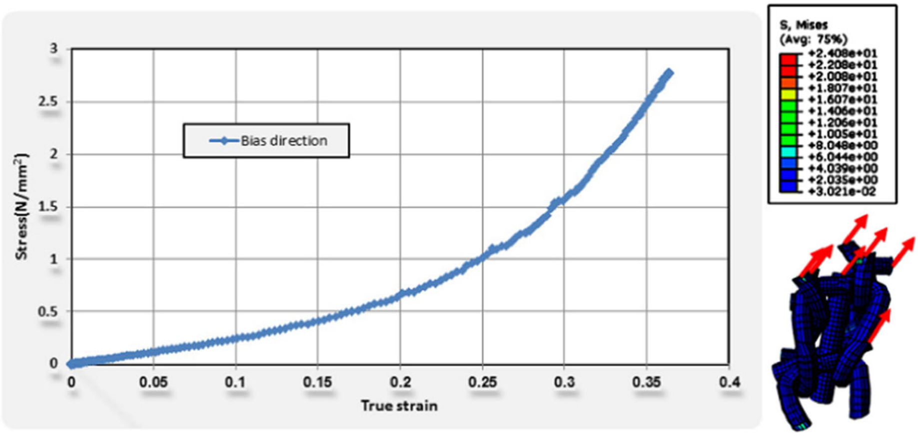


Fig. 9 The biaxial rib fabric elongated in bias direction and the calculated stress–strain of the fabric

applied tensile test through the various directions as well as the shear test on both fabric structures.

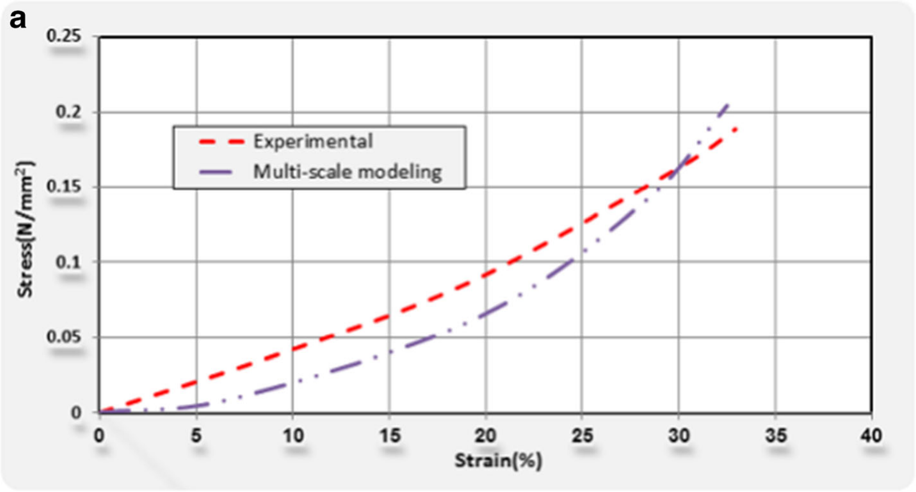
3.2.1 Geometrical Modeling of the Fabrics

The first step in the meso scale modeling of biaxial and 1×1 rib fabrics is using an appropriate geometrical model for the weft-knitted rib structure. As illustrated in Fig. 2, the structural shape of rib knitted fabric unit cell is divided into two segments. One segment consists of face and reverse loops, which follow the mathematical equations improved by Vassiliadis et al. [25]. Another segment is the linking portion between face and reverse loops. The equations required for determining the geometrical situation of reverse loop, face loop and linking yarn were presented by Abghary et al. [32]. The biaxial fabric also is comprised of knit-loops and reinforcement yarns integrated within the knitted structure in both warp and weft directions; therefore, it can be constructed by adding the reinforcement yarns to the rib structure. All the yarns are assumed to behave as a cylindrical elastic rod and follow the linear elastic property.

Using the modified loop for connecting the reverse and face loops, unit cell of a rib structure is obtained (Fig. 3a). The warp and weft yarns can be inserted into this structure as shown in Fig. 3b to construct the unit cell of the biaxial fabric.

3.2.2 Finite Element Modeling of the Fabrics

A suitable simulating code is created in Python software based on the mentioned geometrical model. Giving the values of fabric thickness, wales and courses distance and yarn diameter as input parameters, a three dimensional construction of the simulated fabrics model unit cells is designed in Abaqus software by the prepared programming code. Linear elastic behavior is assumed for each yarn. Penalty method is used to define all contacts between yarns in the unit-cell models. After designing the geometrical model, meshing phase is followed. To solve the task, the explicit numerical method of Abaqus software is used. Since the unit-cell represents the full



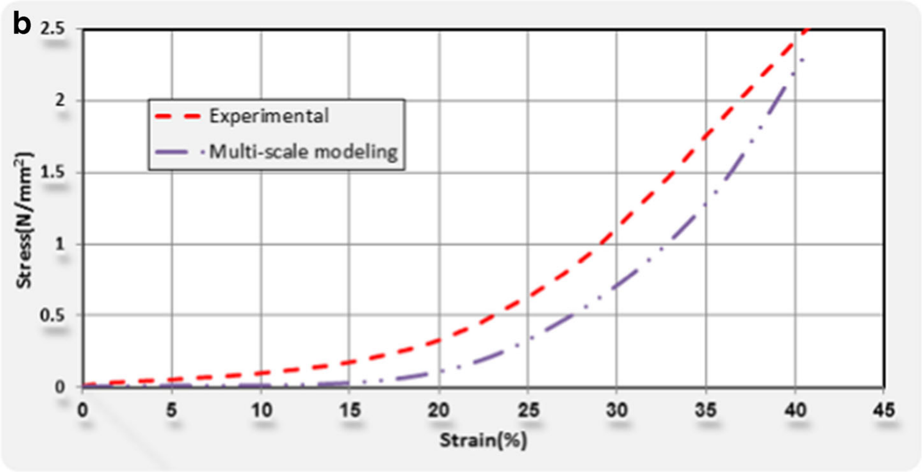


Fig. 10 Stress–strain curve obtained from expremintal and multi-scale modeling method in state of (**a**) 22.5° loading and (**b**) 67.5° loading

thickness of the fabric, the upper and lower surfaces are unconstrained. Periodic boundary conditions are applied to the other surfaces of the models.

3.2.3 The Results of the Meso Scale Simulation of the 1×1 Rib Fabric

In order to calculate each of the components of the stiffness matrix of 1×1 rib fabric ($D^{1\times1\,Rib}$) the proposed method by Peng et al. [26], is used. For this purpose, the stress–strain curves of the 1×1 rib fabrics are obtained by meso scale modeling of the tensile test in course and wale directions. The shear test is also modeled to find shear stiffness of the fabric. The stress–strain curves are fitted by appropriate equations and components of the stiffness matrix are the derivatives of resulted equations.

Fig. 11 **a** The meshed shell model; (**b**) the boundary conditions for the model [33]

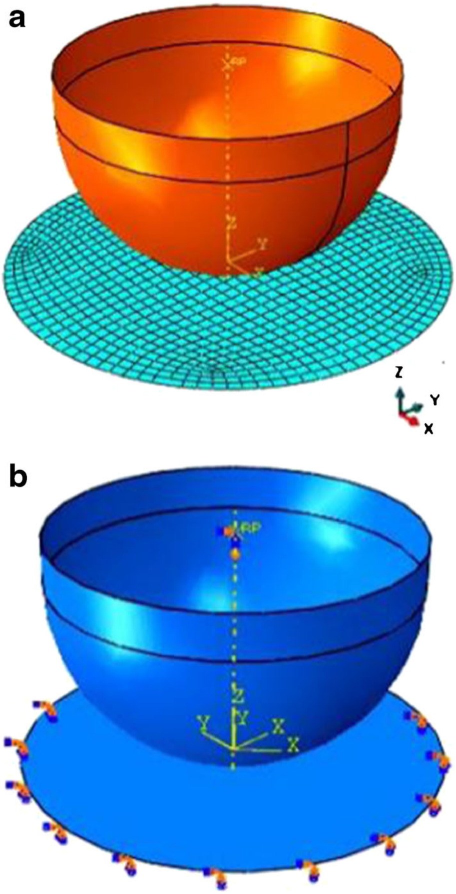


Figure 4 shows the 1×1 rib fabric elongated in weft direction and the calculated stress–strain of the fabric with the curve that has been fitted on it.

$D_{11}^{1\times1\,Rib}$ is obtained by derivation of the fitted curve as follows:

$$D_{11}^{1\times1\ Rib} = -3.1644{*}\varepsilon_1^2 + 0.4306{*}\varepsilon_1 - 0.0055 \tag{3}$$

Figure 5 shows the 1×1 rib fabric elongated in warp direction. The calculated stress–strain of the fabric during tensile test along the wale direction has been fitted on the experimental curve.

$D_{22}^{1\times1\,Rib}$ is obtained by derivation of the fitted curve as follows:

$$D_{22}^{1\times1\ Rib} = 2499.45{*}\varepsilon_2^4 - 872.92{*}\varepsilon_2^3 + 104.394{*}\varepsilon_2^2 - 0.8654{*}\varepsilon_2 - 0.1678 \tag{4}$$

$D_{66}^{1\times1\,Rib}$ is also obtained by using the results of meso scale modeling of the shear test that has been shown in Fig. 6.

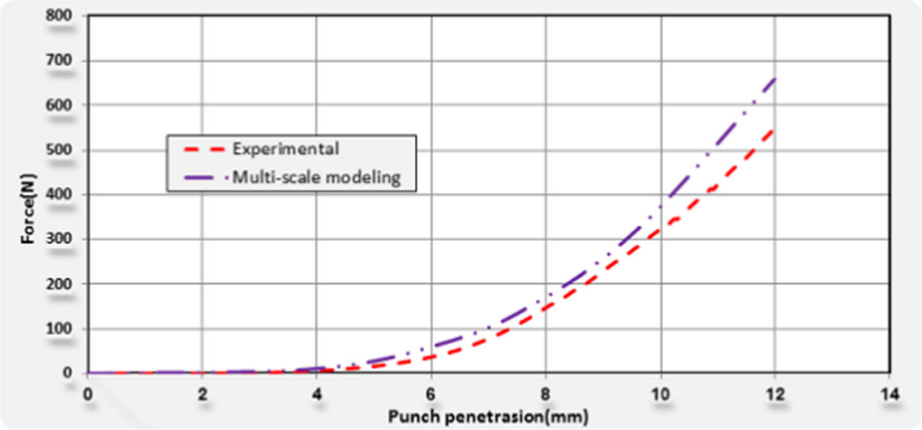


Fig. 12 Comparison between results of multi-scale modeling and the experimental data of bagging test of biaxial knitted fabric

Derivation of the fitted curve is:

$$D_{66}^{1\times1\ Rib} = 44238.6*\gamma_{12}^5 - 143170*\gamma_{12}^4 + 69524*\gamma_{12}^3 - 14667.3*\gamma_{12}^2 + 1222.18*\gamma_{12} + 25.521 \tag{5}$$

where γ_{12} is shear strain. According to proposed method by Peng et al. [26], following assumptions are also considered:

$$D_{12}^{1\times1\ Rib} = D_{21}^{1\times1\ Rib} = 0.02\min\left(D_{11}^{1\times1\ Rib}, D_{22}^{1\times1\ Rib}\right) \tag{6}$$

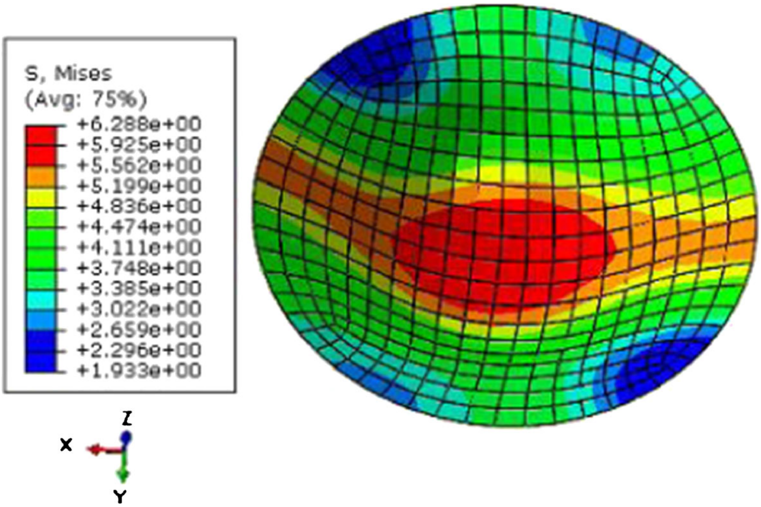


Fig. 13 Mises stress distribution in the formed fabric predicted by continuum model [13]

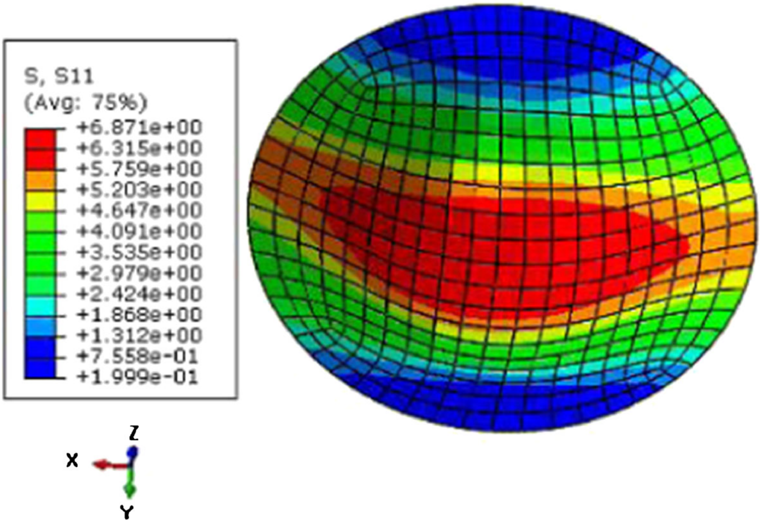


Fig. 14 Distribution of the stress along weft direction [33]

$$D_{16}^{1\times1\ Rib} = D_{61}^{1\times1\ Rib} = D_{26}^{1\times1\ Rib} = D_{62}^{1\times1\ Rib} = 0 \tag{7}$$

3.2.4 The Results of the Meso Scale Simulation of the Biaxial Fabric

In order to calculate each of the components of the stiffness matrix of the biaxial fabric (D^{Re}), the proposed method similar to the previous section is used. For this purpose, the stress–strain curves of the biaxial fabric are obtained via meso scale modeling of the tensile tests in both course and wale directions.

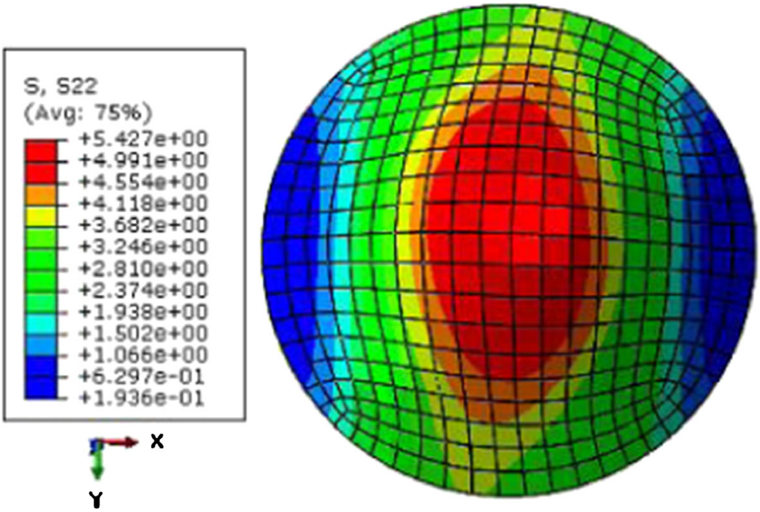


Fig. 15 Distribution of the stress along warp direction [33]

Figure 7 shows the biaxial rib fabric elongated in weft direction. The results show that the calculated stress-strain curve has been fitted on the curve extracted from experimental test.

D_{11}^{Re} is obtained by derivation of the fitted curve as follows:

$$D_{11}^{Re} = -66.422 * \varepsilon_1 + 60.024 \tag{8}$$

Figure 8 shows the biaxial rib fabric elongated in warp direction. It can be observed that the calculated stress–strain curve of the fabric has been fitted on the curve extracted from experimental test.

D_{22}^{Re} is obtained by derivation of the fitted curve as follows:

$$D_{22}^{Re} = -53.706 * \varepsilon_2 + 41.35 \tag{9}$$

Since there is no interlacing between reinforcement yarns, therefore no shear force is exerted to reinforcement yarns:

$$D_{66}^{Re} = 0 \tag{10}$$

According to proposed method by Peng et al. [26], following assumptions are also considered:

$$D_{12}^{Re} = D_{21}^{Re} = 0.02 \min\left(D_{11}^{Re}, D_{22}^{Re}\right) \tag{11}$$

$$D_{16}^{Re} = D_{61}^{Re} = D_{26}^{Re} = D_{62}^{Re} = 0 \tag{12}$$

As previously stated, the parameter K which have a constant value, represent the effect of inserting reinforcement yarns into the fabrics structures on their shear stiffness during tensile loadings. To tune this parameter, the results of meso scale modeling of the bias tensile on the biaxial rib fabric is used here. Figure 9 shows the biaxial rib fabric elongated in bias direction and the calculated stress–strain of the fabric. The parameter K is obtained such that the result of the Eq. 6 is identical with this curve.

4 Results and Disscusions

4.1 Macro Modeling of Bias Tests in Various Directions

To evaluate the accuracy of the proposed constitutive model, tensile tests in 22.5 and 67.5° through the weft direction are simulated and then compared with the experimental results. For this purpose, Abaqus software is used to perform the analysis and the user material subroutine UMAT is used to implement the proposed constitutive behavior. Since the plain stress is mostly expected in these fabrics, in the present test the plane stress analyzing is also taken into account or the shell modeling can be used for doing the modeling. After the model designing, the simulated structure is meshed by 494 reduced integration linear hexahedral shell elements. To solve the task, the implicit numerical method of the Abaqus software is used. The boundary conditions of tensile test are applied to the fabric. To change the fabric direction with respect to the loading condition different material orientations are assigned to the fabric in each modeling. As it is shown in Fig. 10(a and b), there is a good agreement between experimental and modeling results in both directions (22.5° and 67.5°).

The stress–strain curves extracted from modeling and experimental methods show good conformity in 22.5^0 and 67.5^0 directions. This means that the proposed model can successfully predict the tensile behavior of biaxial weft knitted fabric in different directions. The consistency of the numerical and experimental results confirms that the bias properties of the biaxial knitted fabric is depend on the behavior of knit structure while reinforcing yarns determine the fabric properties in both weft and warp directions.

4.2 Macro Modeling of Spherical Deformation

The Abaqus software is used to simulate the bagging test through which the user material subroutine VUMAT is used to implement the proposed constitutive behavior. Due to the plane mode stress of the fabrics as well as the small ratio of fabric thickness to its other dimensions the shell elements are used to model the fabric structure and mechanical behavior. Once the model is designed, a meshing phase is followed. The meshed fabric that is shown in Fig. 11a consists of 1006 reduced integration linear shell elements.

To solve the task, the explicit numerical method of the Abaqus software is used. The boundary conditions of the bagging test as shown in Fig. 11b are applied to the fabric. As can be seen in this figure, the outside edge of the shell model is totally fixed because it refers to those part of the fabric which are in contact with the fixing ring. A definite displacement also is applied to deform the fabric from its original shape.

Figure 12 depicts a comparison between results of the theoretical and experimental data of bagging test for biaxial knitted fabric. The good agreement between the experimental data and the modeling results is observed in this figure. It can be concluded that the multi scale modeling approach can well predict fabric formability.

Figure 13 shows stress distribution in the deformed fabric. It can be seen from this figure that the highest stresses are along the x and y axis. This shows that the stress is tolerated by the parts that the tension and reinforcement yarns are in the same directions. To show a better explanation of this result, stress along weft and warp directions are shown in Figs. 13, 14 and 15, respectively. These figures show that only warp yarns bear stress in x direction (S11) and weft yarns bear stress in y direction (S22).

Comparing the results of multi-scale modeling and experimental data shows that this approach can be used in investigation of the macro behavior of the biaxial fabric with least required inputs.

5 Conclusions

Modeling mechanical behavior of biaxial fabric as a continuum material needs remarkable tensile tests on the fabric in order to achieve some inputs data in terms of the mechanical constants. In this paper to solve this drawback multi-scale numerical model was presented to simulate mechanical behavior of biaxial weft knitted fabrics. The results of modeling fabric tensile behavior in various directions and spherical deformation are in good agreement with experimental measurements. While in the multi-scale simulation only the yarns' properties are needed and remarkable efforts in producing samples and performing experiments are omitted, this type of modeling can well predict fabric tensile behavior in various directions and spherical deformation.

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