Investigation into the Geometrical Loop Effect on Tensile Behavior of Single Bar Warp-Knitted Fabric Using Finite Element Method

Marzieh Javadi Toghchi and Saeed Ajeli

***Abstract*—In this study, the finite element modeling with considering the two-dimensional Elastica curve is used. Then, a twisted shape of Elastica iss investigated through applying a pair of equal unbalancing twisted torques to the ends of the elastic rod. In the loop model, the implicit method, nonlinear geometry, elastic properties and three-dimensional beam element are used. Implicit method is accurate and a simple method for problems of structural complexity without intervention of time. Finally, the proposed model is used as overlap and legs of the warp-knitted single bar fabric structure and uniaxial tensile behavior of the fabric in the low strain is modeled using ABAQUS software. The explicit method is used in the fabric simulation based on complexity, connection and interaction of the parts in the simulated fabric and the nonlinear geometry, elastic properties and three-dimensional beam element is used in fabric simulation like the loop model. The results of the actual fabric test under low strain with theoretical model are compared. The model results are more consistent with the results of experiments conducted at lower strain on the fabric.**

Key words: Single bar warp-knitted fabric, uniaxial tensile, three-dimensional Elastica, finite element method.

I. INTRODUCTION

DETERMINATIONof the loop form is the key issue in knitting technology. The loop modeling and loop dimensional properties are very important to predict the knitting dimensional characteristics and some of its properties such as tensile behavior.

The first model of warp-knitted loop has been offered by Alison. He divided the loop into four independent parts including the head of the loop that is considered as half-circular, legs and the under lap that is considered as a straight line [1]. Leaf studies on the buckling of perfect elastic rod have had a great effect on the loop modeling in 1958. He obtained the ratio of maximum height of the buckled elastic rod (Elastica) to its maximum width under two equal pressure loads (P) and the couple of C as is shown in Figure 1 is irrespective of the material or the length of the rod [2].

The warp-knitted loop model based on the physical shape of the yarn in the fabric structures and the Elastica theorem is suggested by Grosberg [3]. It is noted that the synthetic yarns are popularly used in knitted fabrics and the fabrics are heat set; so the loop study is noticed in dry relaxation condition. Raz investigated the relation between the stitch density and the run-in yarn in the knitted fabric for loom-state condition in 1980 [4].

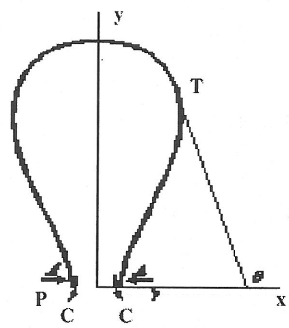

Fig. 1. The Elastica curve [2].

Recently, the image processing tools are used in loop shape simulations. In one research, the warp-knitted fabric microstructure is captured and analyzed in the fabric plane and the cross-section plane by Goktepe in 2002, so; the loop characteristics are measured of the microscopic specimens [5]. The loop structure was modeled by using analytical method in another study in 2007. The proposed model is a combination of the three-dimensional model of warp-knitted microstructure and mechanical analysis of warp-knitted fabric units [6]. Vassiliadis proposed a new model based on the assumption of the ideal elastic yarn and the elastic energy minimization of the relaxed knitted fabric [7].

It was noted that fabric geometry is an essential factor in prediction of fabric mechanical behavior. One of the warp-knitted fabric mechanical properties is tensile behavior that is studied by many researchers. Dabiryan and Jeddi suggested a 3D straight line model for double-guide-bar warp knitted fabrics in 2011. They obtained some geometrical parameters of seven most common warp knitted structures theoretically [8]. In another study, the variation of unit cell geometry under uniaxial tension in the range of the elastic deformation was investigated and applying Castigliano's theorem, strain and initial modulus of fabrics were found by them [9].

In the present study, the three-dimensional model loop for warp-knitted fabric is proposed considering Elatica shape using finite element method and then a single-bar warp knitted fabric is simulated under uniaxial tensile force and the three-dimensional model of loop is used as the overlap and legs of this simulated fabric.

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Finite element method (FEM) is a numerical method that has been used for physical problem analysis with partial differential equations or an energy theorem. In the finite element method, the considered structure is replaced with small elements and the small elements are analyzed [10]. The finite element method should be used in cases where solving problems with analytical methods is difficult and the geometry or the boundary conditions are complicated. The finite element method is used in this study to model the single loop method and simulate the collection of loops beside each other because of the warp knitted fabric's complexity.

II. MATERIALS AND METHODS

A. *Single-bar warp-knitted fabric loop's shape*

Unless the real loop shape is close to three-dimensional form due to needle forces during the knitting action and loop forming that causes the yarn bending and the yarn perpendicular twisting to the yarn plane, loop geometry is considered in two-dimensional shapes in the most previous loop models. In the present study, the loop shape is investigated in the warp- knitting structure and it is tried to attain the suitable loop model in three-dimensional form to predict the real loop geometry in the fabric. The single bar warp-knitted sample of fabric with 75 denier flat polyester yarn was knitted on the LIBA tricot machine. The real shape of loop in the real single-bar warp-knitted fabric structure is shown in Figure 2. As it is shown in Figure 2, the ends of the loops are twisted and the loop gets a three-dimensional shape.

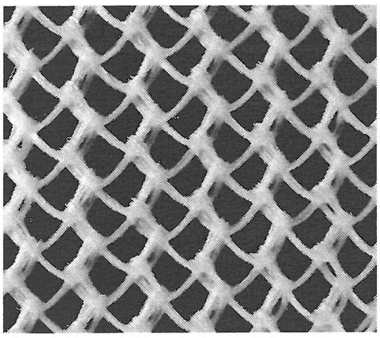


Fig. 2. The technical face view of the 1×1 single-bar warp-knitted fabric.

B. *Uni-axial tensile test method*

The uni-axial tensile test and the force-displacement analysis are implemented on the warp-knitted fabric specimen along the wale direction. The tensile tester device (*Zwick model 1446*) that is operated based on CRE (constant rate of elongation) method is employed for the uniaxial tensile test. The rate of elongation is set on 100(*mm/min*). The specimens' lengths are considered 100*mm* and their widths are considered 40*mm* under the standard conditions and the five samples are used for each test.

The samples are analyzed at low-strain conditions and the amount of elongation that is applied to them is considered before achieving the edges curling due to the fabric edges curling. The movements of the fabrics are captured using digital camera during the uni-axial tensile behavior test. The initial state of the fabric sample and after the 30% strain fabric sample form is shown in Figure 3. One of the force-displacement curves of the fabrics is shown in Figure 4.

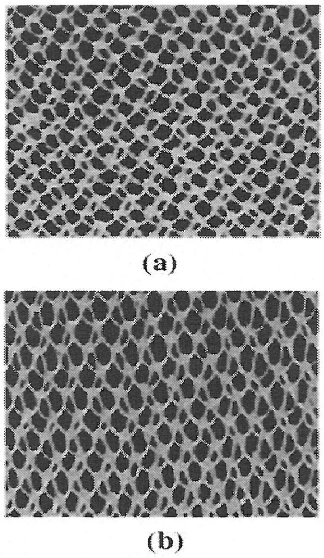


Fig. 3. The fabric views in a-initial state, b- the 30% longitudinal strain.

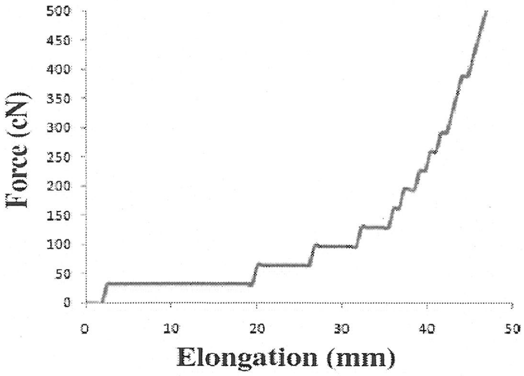


Fig. 4. The force-displacement curve of one of the samples.

III. THEORETICAL MODEL

A. *Three dimensional FEM loop's Model*

The real images of the loops in the knitted fabric structures show that the yarn during the loop formation is twisting besides the bending and the three-dimensional shape of loop is created. In this study, the two-dimensional Elastica shape is analyzed in the first phase and then the twisted torques at the ends of the rod is employed to predict the real shape of the loop.

In another study that has been done about weft-knitted loop modeling, the three-dimensional shape of the loop is modeled using the pair of twisted torques that are applied in the opposite directions of each other at the ends of the Elastica [11].

According to the complexity of the analytical method, the two-dimensional and three-dimensional forms of the warp-knitted loop are modeled using ABAQUS software that works based on finite element method. To accomplish this, the elastic rod is created and then the properties of the structure are defined in property module in the ABAQUS environment. The analyzed material is considered polyester because the knitted fabric specimen has been made of polyester yarns. The material is assumed to be perfect elastic and homogeneous with the circular cross-section. Three dimension 2-node linear Timoshenko beams element (B31) are considered for this analysis. This type of element is chosen due to small ratio of cross-section radius to rod length. The 60 elements covered the structure perfectly. The smaller element size has no good consequences on accuracy and is time consuming in this step and in the warp-knitted fabric simulation in the next step. It is noted that the larger size of elements cannot cover the structure completely.

Two steps are defined in this issue. The first step is defined to model the two-dimensional Elastica shape based on Leaf theorem applying two equal pressure loads (P) and the couple of (C) and the second step is defined to twist the ends of it and turns it into the space. The Static General method is used in the both steps. It's noted that, The Static method is implicit, accurate and easy to use and understand [12].

Now; the forces are exerted in the load module. As mentioned earlier, the two equal pressure loads and the couple are applied to the ends of the elastic rod for modeling the two-dimensional Elastica shape in the first step. Then the pair of equal unbalancing twisted torques is applied to the ends of the elastic rod to twist the arms of two-dimensional Elastica and turns it into the z direction in the second step. The amount of this rotation is considered $\pi/2$ radians at each end. It is noted that, the boundary conditions are considered for the ends of the elastic rod in the initial state and the motions are restricted along the other directions for the end points of the elastic rod in both steps. Finally, the model is analyzed and the results are shown in the visualization module.

The primary elastic rod and the two-dimensional Elatica and the three-dimensional final shape of the Elastica are shown in Figure 5. The Figure 5-a shows the initial elastic rod and the two-dimensional modeled Elastica in ABAQUS environment based on Leaf theorem and the Figure 5-b shows the initial elastic rod and the three-dimensional Elastica shape by adding a pair of equal unbalancing torques at the ends of the rod.

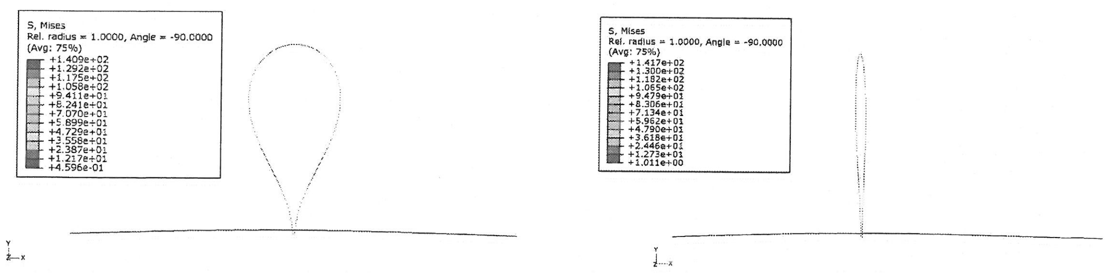
As it is seen in this figure, the Elastica changes under out-of-plane twisting is clear. The two-dimensional Elastica turns in out of *x-y* plane direction (toward *z* direction) under the twisting torques and the obtained shape is similar to the loop position in the warp-knitted fabric structure. The maximum stress is imposed on the ends of the three-dimensional form of Elastica in the ABAQUS analysis. The two side points that obtain the maximum distance along *x* direction from each other in two-dimensional Elastica shape (*x-y* plane) and so the maximum amount of displacement is exerted to them toward *z* direction applying the twisting torques.

B. *Warp-knitted fabric simulation using proposed loop's model*

The three-dimensional proposed model of loop could be used for single-bar warp-knitted structures' modeling under different conditions like tensile behavior. The single-bar warp-knitted structure is created in ABAQUS considering the three-dimensional proposed loop model as the overlap and the legs of the loop beside angular straight lines as underlap. It is noted that the created structure is based on real geometry dimensions of single-bar warp-knitted fabric. The specimen is generated tracing the yarn path in the microscopic image besides using course and wale spacing of the warp-knitted fabric in the ABAQUS environment.

The assigned structure of the knitted fabric in the ABAQUS environment is shown in Figure 6. The assigned structure consists of three loops along the wale and course directions, the under laps connected these loops as a single-bar warp-knitted structure.

The material type of the specimen fabrics is polyester and the polyester fabric properties are assigned to the whole structure in the ABAQUS. The tensile behavior analysis of the knitted-fabric is done using the Dynamic Explicit method in ABAQUS wherein, the time of solution has effective role in the results. Increasing the time of solution causes the time consuming analysis so, the optimum time is the time that causes a faster analysis and more accurate results together. The simplest method for finding the optimum time is the trial and error method



(a) (b)

Fig. 5. (a) The x-y plane views of the initial rod (black color) and the two-dimensional Elastica (rainbow), (b) The x-y plane views of the initial rod (black color) and the three-dimensional Elastica (rainbow).

which is used in this analysis. The time of analysis is considered 0.1 second in which the convergence of the results is obtained.

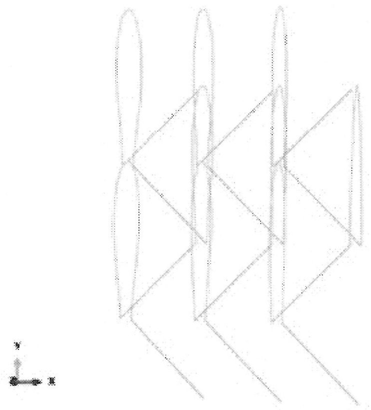


Fig. 6. The assigned structure of the warp- knitted fabric in the ABAQUS.

It is noted that, the assigned parts in ABAQUS should be connected to each other in the Interaction module. Otherwise the ABAQUS software cannot recognize the parts as the continuous structure and applying a little force causes the separation of the assigned parts from each other. The friction between the parts is defined and assigned in this module, too. The initial mechanical properties of the specimen are extracted from the tensile tests and used in the warp-knitted fabric simulation.

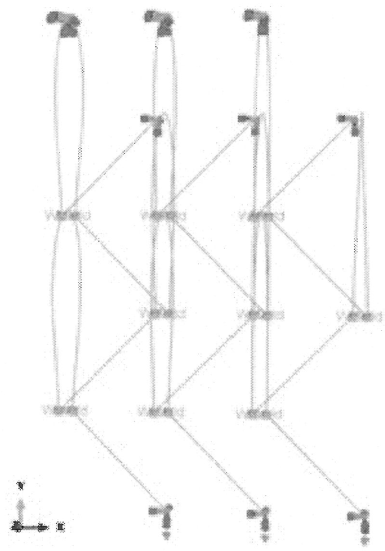


Fig. 7. The load exertion and boundary conditions.

Now, the loads and the boundary conditions are established and applied to the simulated models of the knitted fabric according to the Figure 7. The sample is constrained on one side and pulled using tensile forces on another side along the wale direction according to the tensile test experiments. The amounts of forces in different elongations are obtained.

Then, the kind and the number of the elements are determined and the structure is meshed. The element type is considered three-dimensional linear Beam element (B31) in this analysis, too. The 780 elements covered the structure perfectly. It is noted that the size of elements is considered larger for the underlaps because their structure is simple.

Figures 8, 9 and 10 show the single-bar warp-knitted model at initial state and 20% strain and 40% strain conditions in ABAQUS, respectively.

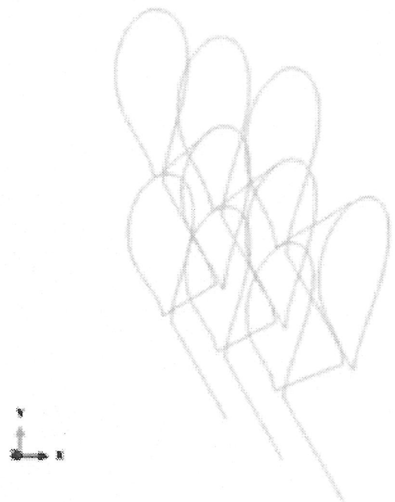


Fig. 8. The perspective view of the initial state fabric.

IV. RESULTS AND DISCUSSION

In this part, the results of 1×1 single-bar warp-knitted tensile tests and its simulation using finite element method are investigated and compared. Their results in different low strains are shown in Table I.

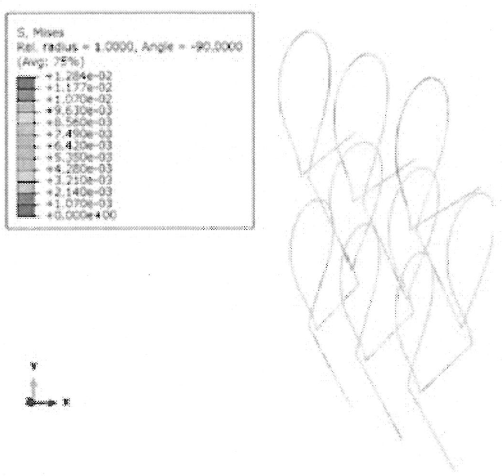


Fig. 9. The von mises stress contours in 20% strain (0.1 sec).

As shown in Table I, the results of model and the results of tensile test using Zwick tensile test device correspond with each other. The model results in lower strain are more consistent with the real fabric results and the percentage of difference between them increases in the higher strains.

Therefore, the provided model is more suitable for the investigation of the knitted fabric conditions in lower strains. The correlation coefficient between model results and experimental results is presented in Figure 11.

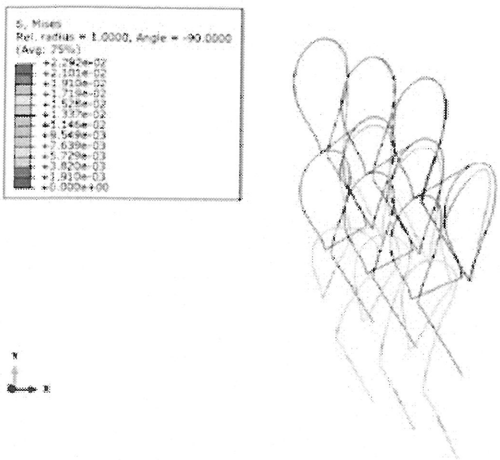


Fig. 10. The initial state (black color) and 40% strain state fabric (blue-green color).

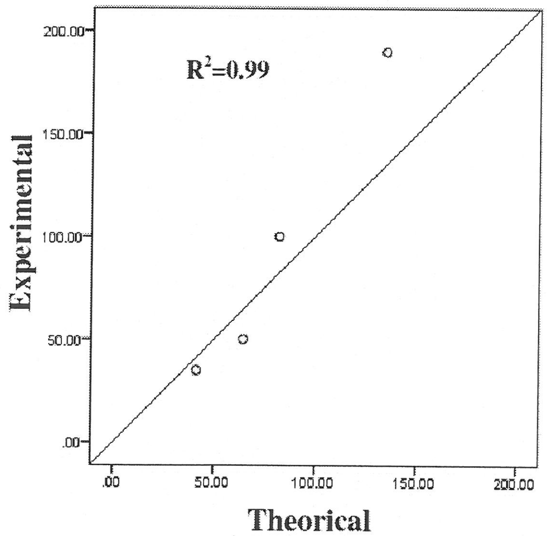


Fig. 11. The correlation between theoretical (FEM) and experimental results.

TABLE I
THE COMPARISON OF THE MODEL RESULTS AND THE EXPERIMENT RESULTS OF THE FABRIC TENSILE BEHAVIOR

Results of ABAQUS Simulation (cN)	Result of tensile stretch tester (cN)	Percentage of elongation (longitudinal strain)
41	35	10%
64.5	50	20%
82.2	100	30%
134.5	190	40%

V. CONCLUSION

The three-dimensional model of loop is proposed to show the real loop situation in the warp-knitted fabric structure.

First, the two-dimensional Elastica is modeled using finite element method based on Leaf loop theorem and the rod is twisted toward z direction by applying the twisted torques at the ends of it. This three-dimensional loop model is suggested to be used in warp-knitted fabric simulation under different load conditions according to the consistency of the loop proposed model with real shape of the loop in the warp-knitted fabric structures. For this purpose, the three-dimensional model of loop is employed as the overlap and the legs in the single-bar warp-knitted structure and the fabric behavior under uniaxial tensile condition along wale direction in low strains is investigated. The results of the models are compared to the experimental tensile test results. The model results in lower strain are more consistent with the real fabric results and the difference between the experiment and model results is increased in the higher strains increases.

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