3-Dimension Simulation for Loop Structure of WeftKnitted Fabric Considering Mechanical Properties of Yarn

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3- Dimension Simulation for Loop Structure of Weft-Knitted Fabric Considering Mechanical Properties of Yarn

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Abstract: The three-dimension weft- knitted loop model was constructed using the simulated yarn which was made by mass-spring system. The simulated yarn was constructed with the cross-sections consisting of the mass-points connected by the springs within the mass-points. In the simulated yarn, two types of springs were used to describe tensile and bending behaviour of the model. The geometrical knitted loop structure was constructed by setting the cross-sections of the simulated yarn in the loop model considering with the loop parameters. The mechanical properties of the loop model under the tensile condition were expressed by using some formulae considering with the construction of the knitted structure.

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1. Introduction

The mechanical properties of knitted fabrics are important both for apparel and technical textiles. The knitted fabric shows different properties comparing with the woven fabrics because of its interloped structure. Many researchers have been trying to attempt for describing the geometrical loop structure and also its mechanical properties by some simulation methods. Popper indicates that the knitted fabric develops its mechanical behaviour from its structural behaviour combining with the tensile properties of yarn [5]. Shanahan and Postle describe the initial load-extension properties of the plain-knitted structure in the course direction and, they concluded that the resistance to extension was due to change in the yarn configuration within the knitted loop, with no slippage, extension or lateral compression of the yarn [6]. And also, De Jong and Postle applied a general energy analysis method for the deformation properties of the plain-weft-knitted structure. They expressed that the major mechanism related to the ability of fabric extension was the freedom of yarn movement within the structure [7]. J. M. Kaldor *et.al.* described yarn level cloth model and they expressed shape of deformation of weft-knitted structure considering some properties on the loop of yarn [8]. Y. Li and L. Yang proposed three dimensional simulation of weft knitted structure based on surface model [3]. Their model can express the result of close to the image of actual fabric, but not including the properties of the fabric [3]. In this paper, we tried the three dimension of weft-knitted loop structure model for plain weft-knitted fabric using with mass points and springs. Then the tensile properties of the model was simulated by changing the construction of the knitted structure considering the mechanical properties of yarn. Comparing above those models, the particular feature of our simulation model was able to expressing the tensile properties of weft-knitted structure in both loading and recovering processes.

There are basically two methods for the simulation of cloth; namely; geometrical models and physically-based models. Physically based models are realistic and easy to implement compared to the geometric models. Among all the methods, the simplest and the mostly preferred method is the mass-spring system. This is a kind of particle system, in which the set of particles are interconnected by springs. Fabric simulation partially relate to the

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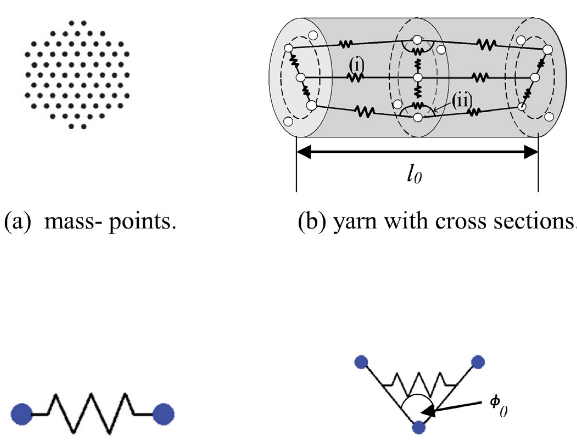
expression of the movement and deformation of a piece of fabric by mimicking how that fabric would react in the real world [18]. Consequently, the mechanical properties of fabric derive from the change or deformation of the fabric and hence the deformation way of fabric plays an important role in determining its properties. Therefore, we considered the deformation way of plain weft-knitted structure under tensile and bending conditions and we used some formulae to express the deformation of the model. The deformation of the knitted fabric under the tensile can be considered into two parts, the first is deformation of the knitted loop structure up to the jamming condition and the second is yarn deformation or yarn stretching after jamming condition [16]. Actually the fabric is made of yarn (except non-woven structure) and so the properties of yarn is the first important factor determining in the properties of fabric and its behaviour. The second one is the geometrical structure of loop which causes different properties such as extension and bending. For these reasons, the yarn was firstly simulated and its properties were examined. After that, the simulated yarn was transformed into the loop structure.

2. Making the simulated yarn

In order to construct three dimension weft knitted model, the yarn was firstly constructed by mass points and springs. The simulated yarn was constructed with the cross sections along its length, and each cross section consists of the mass-points connected with the springs. In here the mass-points were considered as fibre. Figure 1 shows the components used in the simulated yarn model. The



(a) mass- points. (b) yarn with cross sections.

(b) extension spring. (d) bending spring.

Fig. 1 components used in simulated yarn model.

tension spring was connected between the two mass points and the bending spring was connected among the three mass points.

All the cross-sections were allocated according to x, y, and z coordinates to make the simulated yarn. Twist was expressed in the simulated yarn by connecting the springs between the adjacent sections with an inclined angle acoording to the formula (1). Figure 2 shows the diffferent positions of the same mass point in every cross section because of the inclined angle.

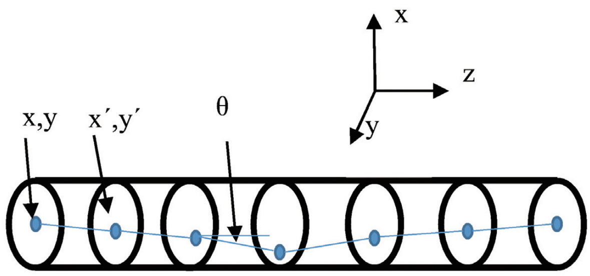


Fig. 2 different positions of same mass point between the adjacent sections along the yarn axis.

$$\left.\begin{aligned} x' &= x\cos\theta + y\sin\theta \\ y' &= x\sin\theta - y\cos\theta \end{aligned}\right\} \qquad (1)$$

x, y : position of mass points in one section.
x', y' : position of mass points in next section.
θ : angle between from one section to another section.

After constructing the yarn model, it was simulated by defining with the tensile velocity in the simulation program, it will be moved, and the elastic energy and strain values in the yarn model were calculated according to the spring applied in the yarn model as shown in Figure 1 by the following formulae. The value for the spring constant was determined by the stress-strain curve of the yarn examined by the experiment, and the measured values were applied in the simulation program.

For the tension spring,
$t_1 = 1/2\, k_1 (l - l_0)^2$
t_1 : elastic energy.
k_1 : spring constant.
l : extended length.
l_0 : initial length of yarn.

For the bending spring,
$t_2 = 1/2\, k_2 (\phi - \phi_0)^2$
t_2 : elastic energy.
k_2 : spring constant.
ϕ : angle among three mass points in tensile condition.
ϕ_0 : angle among three mass points in initial condition.

$$\text{strain}, \varepsilon = \frac{l - l_0}{l_0}$$

And also the friction among the mass points or fibres was also determined when pulling by the following formula.

$$F = cv$$

F: friction force among the fibres.
c: coefficient of friction.
v: tensile velocity.

In here, coefficient of friction and tensile velocity were defined at the start of the simulation program.

2.1 Modification of Pierce model

There are some geometrical models of knitted loop structure firstly developed by Pierce and nowadays Kurbak, Choi and Li, *et. al.* In here ,we used the modified geometrical knitted loop structure developed by (Fukuta *et. al.*) who made the knitted loop structure based on the loop parameters and connecting with the spline curve between the anchoring points (1 to 6) in the loop as shown in Figure 3.

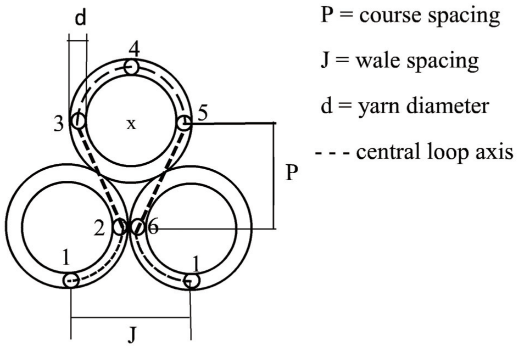


Fig. 3 modified Pierce loop model

2.2 Transformation of simulated yarn into loop model

After making the simulated yarn, it was transformed into three dimension loop model. In the simulated yarn, all the cross sections were set up along the z- axis (straight form). In the loop model, every one section to another section were inclined with the angle along the central loop axis (as shown in dotted line in Figure 3) in z-x plane and z-y plane. So, the two inclined angles were calculated according to the formula (2) and (3).

$$\theta_{zx} = tan^{-1} \frac{x_i - x_{i-1}}{z_i - z_{i-1}} \quad (2)$$

θ_{zx}: an inclined angle of section in z-x plane.
x_i : position of the section in x-coordinate.
z_i : position of the section in z- coordinate.

$$\theta_{zy} = tan^{-1} \frac{y_i - y_{i-1}}{z_i - z_{i-1}} \quad (3)$$

θ_{zy}: an inclined angle of section in z-y plane.
y_i : position of the section in y-coordinate.
z_i : position of the section in z- coordinate.

Figure 4 shows the transformation of the simulated straight yarn into the loop structure with an inclined angle. After transforming the loop model, it was connected along the course direction according to wale spacing and connected along the wale direction according to the course spacing as shown in Figure 5.

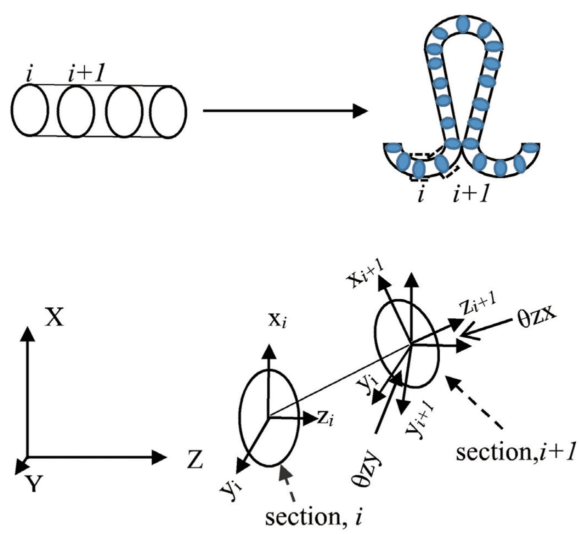


Fig. 4 transformation of yarn into loop model with an inclined angle.

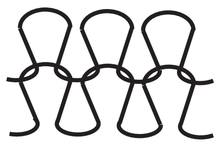


Fig. 5 connected loop structure.

2.3 Deformation of loop model under tensile in course direction

After constructing the loop model, it was considered to express the deformation of model when it was exerted by tensile in the course direction. At that condition, the model will be changed the dimensions in the course and also in the wale direction. The model will be extended in the course direction and compressed in the wale direction because of its structure. In order to simulate the deformation of model under tensile in the course direction, the following assumptions were made.

- the weft knitted loop structure would be compressed in wale direction about half of its loop height i.e., the same amount of course spacing, and
- the weft knitted loop structure would be deformed on both sides from the centre of loop in the opposite directions as shown in Figure 6.

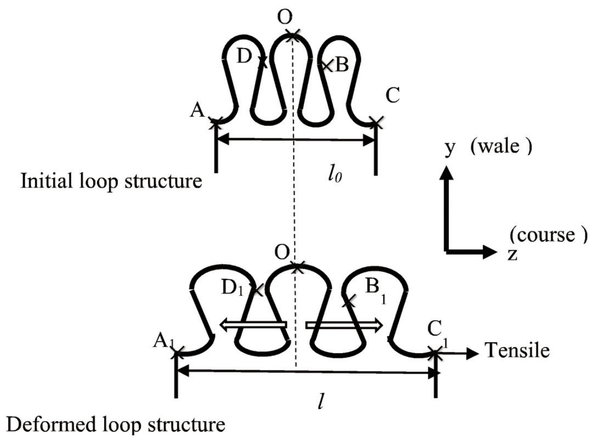


Fig. 6 deformation of loop structure under tensile in the course direction.

When the weft knitted model was exerted by tensile with a certain tension speed at one edge in course direction, all the sections in the model will be moved equally in the course direction according to the formula (4).

$$B_i = B_{i-1} \times r \quad (4)$$

B_i : position of the section i, in z-coordinate.
r : length ratio.

Figure 6 shows the deformation of loop structure with its sections under exerting tensile in course direction. In the figure, A and C are the edge of the sections, O is the central section, and B and D are the sections in the loop. According to the Figure 6, change of the position of the section B in the course direction (z-axis) can be expressed referring to formula (4) as;

$$B_1 = B \times OB/OC$$

In here, B was the position of the section B in z-coordinate and OB/OC also referred to length ratio in z-coordinate. By this way all the sections in loop were moved equally in the course direction (z-axis).

While the sections in the loop were extending in the course direction (z-axis), they were also compressed simultaneously in the wale direction (y-axis). For example, change of position of the section B in wale direction (y-axis) was expressed as shown in figure 7, by y'.

By changing the positions of all the sections in z and y directions, the model was expressed the deformation behaviour when the tensile exerts in the course direction. Finally the loop model was examined its mechanical properties in the simulation program by defining with the tensile speed in the course, the model will be moved or changed its positions and consequently, the values of tension and strain in the model were determined by the following formulae. In order to get the value of spring constant, the single yarn was examined its tensile properties by experiment and stress-strain curve was obtained. Then, the value of spring constant was determined from this curve in term of function of strain and this relation was applied in the simulation program.

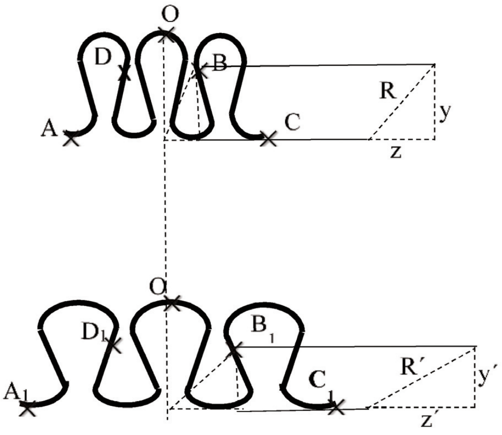


Fig. 7 change of position of the section B in course direction (z-axis) and wale direction (y-axis).

$$\varepsilon = \frac{l - l_0}{l_0} \qquad \sigma_i = k_3 \times \varepsilon$$

ε : strain. σ_i : tension on the loop model.
l : extended length. k_3 : spring constant.
l_0 : initial length.

2.4 Deformation of loop model under tensile in wale direction

When one edge of the loop model was exerted by tensile in the wale direction, the deformation will be occurred in both wale and course direction. The loop model will be extended in the wale direction and compressed in the course direction. In order to simulate the deformation of the model under tensile in wale direction, the following assumptions were also made.

- the weft knitted loop structure would be compressed about half of wale spacing in the course direction, and
- the weft knitted loop structure would be deformed from both sides of edge to the centre of the loop structure in the opposite directions as shown in Figure 8.

When the weft knitted model was exerted by tensile with a certain speed at one edge in the wale direction, all the sections in the model will be moved equally in the wale direction according to the formula (5).

$$B_i = B_{i-1} \times r \quad (5)$$

B_i : y-coordinate of section i.
r : length ratio.

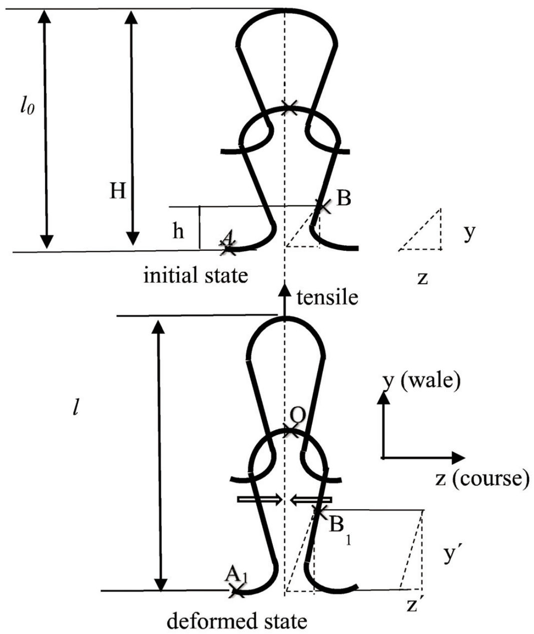


Fig. 8 deformation of loop structure under tensile in the wale direction.

According to the Figure 8, change of the position of the section B in the wale direction (y-axis) can be expressed referring to formula (5) as;

$$B_1 = B \times h/H$$

In here, B was the y-coordinate of section B and h/H referred to the length ratio. By this way, all the sections in the loop were moved equally in the wale direction (y-axis). At the same time, all the sections in the loop will be compressed to the course direction (z-axis) until the limitation to half of the wale spacing (w/2), from both sides of the loop structure to the centre as shown in Figure 9.

By changing z and y coordinate points of all sections, the model was expressed the deformation behaviour when the tensile exerts in the wale direction.

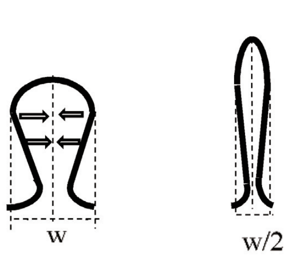


Fig. 9 compression in course direction.

2.5 Bending the model

In order to simulate the model for bending in both wale and course direction, the principle of pure bending was used because of large deformation of textile materials. In bending, the model was considered to be bent on both face-side and back-side bending in course direction and wale direction referring to the KES (Kawabata Evaluation System) system. Therefore the model was bent between a certain amount of positive and negative curvatures. In the simulation of bending, one edge of the model was supposed to be fixed and the other end was bent between a certain amounts of curvatures. Therefore, the curvature of one edge of model was firstly defined. When the model was increasing in bending i.e. changing the curvature of the model, all the sections in the model will also be changed theirs curvature and consequently their positions will also be changed. Figure 10 shows change of curvature of the sections in pure bending showing that the curvature of edge of the section (A) will be changed while bending and consequently the other sections (like section B) will also be changed. So, the following steps were made in the simulation procedure to express the bending of model.

- At the start of the simulation, the curvature was defined to be bent the model and this was the curvature at the edge of the model such as the curvature of the section A', A'', etc. in the Figure 10. In order to express the positions of the edge of the model, the formula (6) was used for course bending and formula (7) for wale bending respectively,
- While bending the model, the positions of non-edge of the sections, (e.g., B in the Figure 10) will also be changed into B' and in order to express these change of the position, the curvatures of non-edges of the sections were firstly determined (i.e., K') and then the change of positions of non-edges of the sections were calculated by the formula (8) for course bending and formula (9) for wale bending respectively,
- The curvatures of non-edges of the sections in the model were determined by the formula (10) for course bending and formula (11) for wale bending respectively,

When the model was bent in the course and wale, it was considered different curvatures in the model, the first was the curvature of the section at the edge of the model, and the second was the curvature of the other sections in the model.

So, the positions of the model at the edge of the curvature were firstly calculated according to formula (6) for bending in course and formula (7) for bending in wale, and then the positions of the other sections in the model were calculated according to formula (8) for course bending and formula (9) for wale bending. By

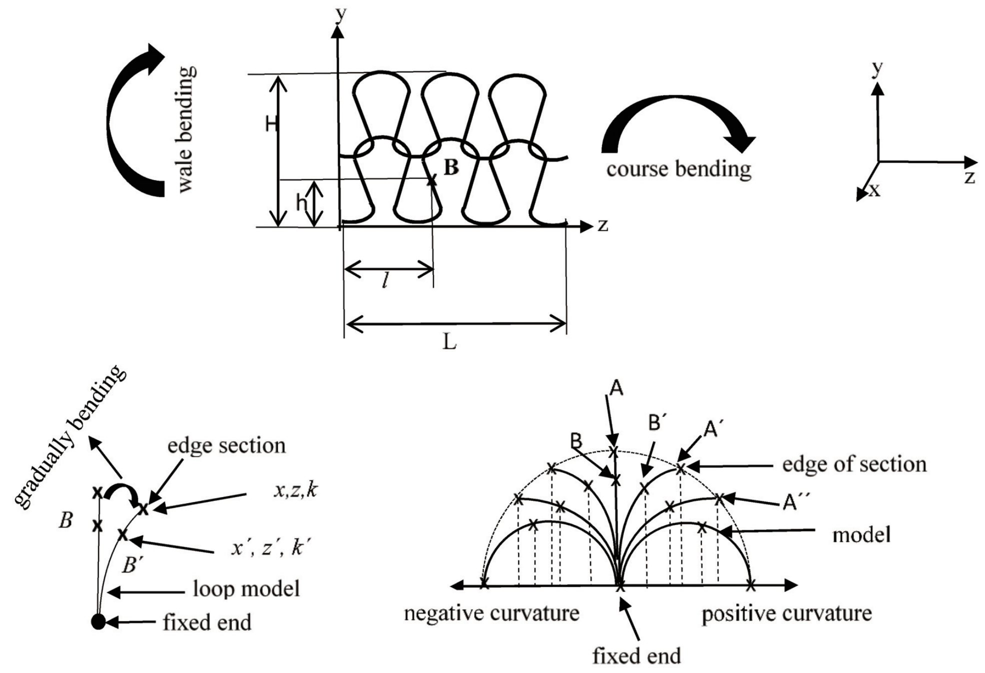


Fig. 10 various curvatures in bending.

this way the model was expressed the change of position in bending condition. The position of the model was changed in x and z (course) axis when bending in course, and changed in x and y (wale) axis when bending in wale.

$$\left.\begin{aligned} x &= \frac{1-\cos K}{K} \\ z &= \frac{\sin K}{K} \end{aligned}\right\} \quad (6)$$

$$\left.\begin{aligned} x &= \frac{1-\cos K}{K} \\ y &= \frac{\sin K}{K} \end{aligned}\right\} \quad (7)$$

where, K = curvature of edge of the section.

$$\left.\begin{aligned} x' &= \frac{1-\cos K'}{K'} \\ z' &= \frac{\sin K'}{K'} \end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned} x' &= \frac{1-\cos K'}{K'} \\ y' &= \frac{\sin K'}{K'} \end{aligned}\right\} \quad (9)$$

where, K' = change of curvature of non-edge of the sections.

For course bending, For wale bending,

$K' = K \times l/L$ (10) $K' = K \times h/H$ (11)

l : length or position between one edge of the mode to non-edge of the section.

L : length or position between the two edges of the model in the course (z-coordinate) direction.

h : length or position between the bottom of the loop model to non-edge of the section.

H : length or position between the top and bottom of the loop model in the wale (y-coordinate) direction.

For example, referring to the Figure 10, change of curvature at the non-edged section B' in the course and wale bending can be calculated as follows;

$K' = K \times l/L$ $K' = K \times h/H$

(for course bending), (for wale bending),

where, K : curvature of edge of the section.

The simulated bending images of the model in the various curvatures were shown in Figure 11. In order to evaluate the model, the way of determination of bending properties will be considered depending on the related factors of curvature of loop structure in the future.

3. Results and Discussion

The simulated yarn was constructed with the same amount of number of fibres in the actual yarn. Some kind of springs were connected among these mass-points (fibres) to express the deformation behaviours. So, the simulated yarn can be regarded as the real yarn. Some formulae were used to evaluate the simulated yarn with the real yarn by stress-strain curve. In order to evaluate the simulated yarn model, the polyester multifilament yarn (333.33 dtex/72 filaments) was firstly examined by the TESILON RTM-100 machine and its stress-distortion diagram was

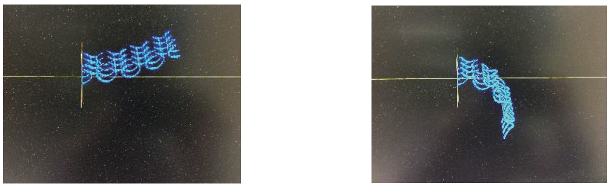


Fig. 11 images of simulated model when bending in various curvatures by simulation program.

obtained, and from these graph, the spring constant was determined by dividing the elastic region and plastic region in the stress-distortion diagram. And then these obtained values were applied as the value of spring constants (k_1 = 6.34 N and k_2 = 2.41 N) in the simulation program to evaluate the yarn model. After simulating the result of the simulated yarn model and the experimental one was shown in Figure 12 and it was seen that the results were approximately similar.

The next step was transforming the simulated yarn into knitted loop structure. When transforming into loop model, all the sections were changed in position according to the angle along the central knitted-loop structure axis to conform the three dimensional loop structure. By this way, the loop structure was described with the number of cross-sections of yarn consisting of fibres. This loop model was connected along the course-direction and wale-direction to represent the plain weft-knitted fabrics. After that the model was considered to describe change of the behaviours under the tensile and bending conditions. In order to show the dimensional changes of the model in the course and wale direction when tensile exerts on the model, it was mainly considered all the sections were moved equally in x, y, and z-axis respectively. This was successfully done by some formulae used in the simulation program and the initial state and deformed state of the model of cotton weft knitted structure (wale density of 6.67/cm, course density of 8.33/cm, 559.86 dtex of yarn) was shown in Figure 13. The loop model can show its constructional changes from its initial condition to its deformed state by changing its initial curved loop form into approximately linear loop form as shown in Figure 13. The model will move until it reaches its maximum strain limit which is defining at the start of the simulation and then it will be recovered into its initial position. While the model was moving, its tension and strain values can be calculated according to the formulae. The spring constant values, k_3 = 43.805 ($\varepsilon \leq 0.01$) and $k_3 = 94.005 - 0.48942/\varepsilon$ ($\varepsilon > 0.01$) were applied in the simulation program. After simulating the loop model by tensile in the course direction, the results of strain and tension values were obtained and it was compared with the experimental result shown by Figure 14. By simulation, the model can show its value of strain and tension when loading and recovering conditions. In the simulation, the result of tension was higher than the experimental result and it may be the friction at the contact points of loop structure which was not taken into account in the the

Parameters for experiment and simulation

- yarn count (333.33 dtex)

-tensile speed (50mm/sec)

-maximum strain (0.2)

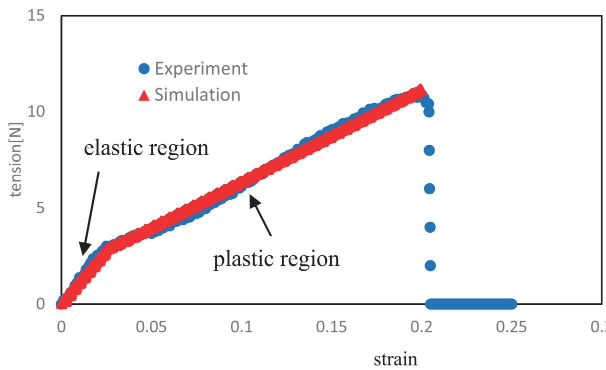
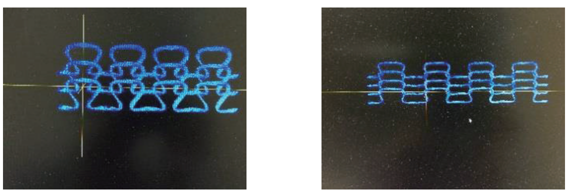


Fig. 12 simulation and experimental result of yarn in tensile condition.



Simulation parameters

-wale density (6.67/cm)

-course density (8.33/cm)

-yarn count (559.86 dtex)

-tensile speed (0.05mm/sec)

-maximum strain limit (0.4).

Fig. 13 images of simulated model when tensile in course direction by simulation program.

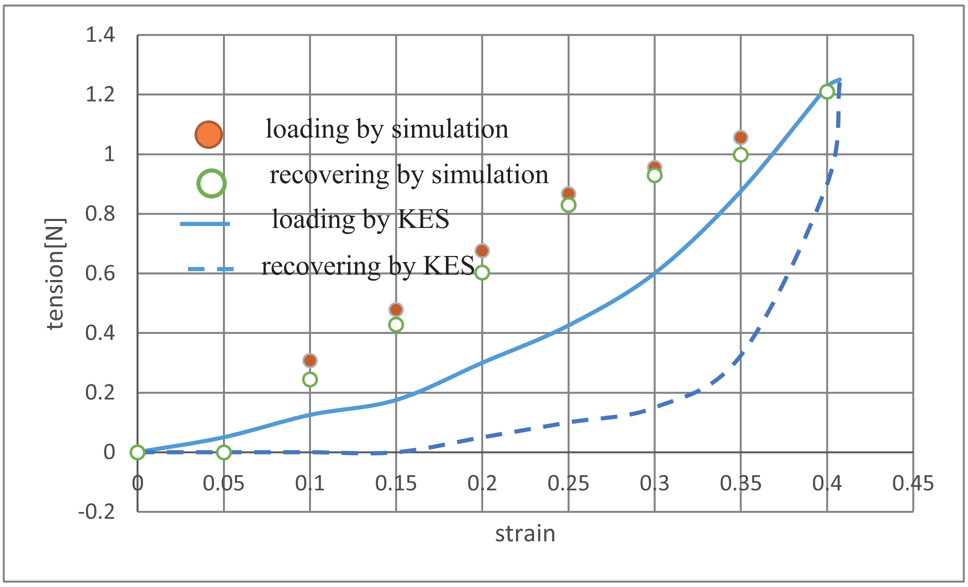


Fig. 14 simulation and experimental result in tensile condition of plain-weft-knitted structure in the course direction.

simulation. The friction within the fibres was considered in the yarn model and so in the simulation of the loop model, the friction may be considered due to fibres, not the contact point of yarn in the loop structure. So, the author expects the model can show its mechanical properties by using proper formulae and considering some related factors concerned with the deformation behaviours by various ways in the future.

4. Conclusions

The three dimension of plain weft-knitted model was constructed. At first the model was made by cross-sections of mass-points (fibres) to represent the straight yarn. In order to implement the simulation, we used the mass-spring system. When simulating the yarn structure, we considered an idealized helical yarn structure and therefore all the cross-sections were put along the yarn axis by varying angle so as to get twist in the yarn. Then the simulated yarn was transformed into the loop structure. In this case, we mainly considered that all the cross-sections in the yarn were perpendicular with along the axis of the loop structure. By connecting the loop model with respect to the wale and course direction, the plain weft-knitted structure was obtained. In order to express the deformation of the model under tensile condition, the change of dimensions of the model was expressed by increasing dimension in one direction while decreasing in other dimension. And also, the bending deformation of the model was expressed considering based on the pure bending principle. In order to simulate tensile condition of the model, the computation time was around 5 minutes for course direction and around 8 minutes for wale direction, and for bending the model the computation time was around 5 minutes respectively. Finally, 3-dimension loop model for weft-knitted structure was constructed. By simulation the model was able to express the tensile properties in both loading and recovering processes. However, there was some differences in the result of simulation and experiment, the authors believe that the model may be improved by modifying the simulation of model with taken into account of the friction at the contact points of yarn within the loop structure.

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