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

DOCTORAL DISSERTATION

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

糸の力学的特性を考慮した **3** 次元よこ編布構造のシミュレーションに関する研究

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Chapter 1 Introduction

1.1. Background theory of research

The textile materials are not only used in apparels, now extensively used in technical textiles. So it is an important role to know about the nature and properties of the textile materials to be utilized in different fields in order to acquire aspects according to their end uses. There are generally three methods to make fabric namely; weaving, knitting and non-woven technologies. According to the different technologies, there will be different structures of fabrics and consequently different properties of the fabrics will be get. Knitting is a method of a fabric making the threads by interloping in series. According to the direction of thread passages, knitting can be divided into weft and warp knitting. Weft knitting is widely used in apparels, especially underwear and sports athletes, also used in industrial and technical fields, and in also composite areas because of their peculiar deformability and extensibility especially in course-wise direction.

There are variety of weft-knitted patterns such as plain, rib, miss, and tuck stitches and so different properties in the finished fabric. To analyse their behaviour and properties, their structure become an important factor. The simplest form of the weft knitted fabric is plain stitch. Many researchers have been trying to describe the weft-knitted loop structure in various ways. Pierce's described the basic weft-knitted loop structure for plain stitch by defining three elements needle loop, sinker loop and loop leg regarding as needle loop and sinker loop as a semi-circular and loop leg as a straight [32]. Other researchers tried to describe the knitted loop model by modifying in various ways of Pierce's model. Their models are especially describing in the loop length in order to design the knitted structure depending on its parameter and to express the visualizing of knitted structure as a real one when comparing. Kurbak described three-dimension knitted loop model defining that needle loop and sinker loop as an elliptical curves and loop leg as a helical shape. He also described the model for widthwise curling of plain knitted fabrics and spirality plain knitted fabric [13,14]. Many researchers have been trying to express 3-dimension loop model in various ways, most of them are used with complicated formulae to implement the model with some properties.

The simulation of the cloth models are implemented using with CAD system and some platforms such as 3D Max, C++, etc. When making the simulation of the textile models, some researchers supposed the model as a continuous and some as a discrete type. There are some papers making the 3-dimension of loop model using loop parameters as an input data, and constructing the loops with the reference points along the loop length, connecting these reference points by NURBS curves or spline curves in order to represent three dimension of surface of the loop model. The main assumption of constructing yarn model is to combine the yarn cross-section along the along the central axis of the yarn [24]. When modelling the textile materials, the particle models (energy based model) and elasticity based model (continuum models) are generally used. The cloth models are expressed as sets of discrete vertices (particles), aligned to form the cloth surfaces at the yarn intersections and their position and motion is determined by a mass-spring system. Elasticity based models are implemented using some equations to describe the deformation of the particles aligned on the cloth surface [25].

In recent years, mass-spring system has been utilising widely in the simulation of textile research areas because of their simple implementation and their possible applications for a large panel of deformations. By using mass-spring system, it can be able to express the deformation behaviour of textile materials applying the specified types of springs. The springs can be connected to the corresponding nodes or mass-points and then Newton's laws govern the dynamics of the model, and the system can be solved by solving Ordinary Differential Equations via numerical integration over time [6]. When a force is applied to the particles in the model over a specified time step, it produces a resulting acceleration for each particle. The change of acceleration will also give change in velocity which causes the new position of the particle [26].

The mechanical properties of knitted fabrics are very important for designing and preparing in textile industries to produce new products with the specified end-uses. The knitted fabrics are easy to deform and so its deformation behaviours are very important in determining its mechanical properties. The deformation behaviours or the dimensional changes of the knitted fabrics can be defined as increasing dimension in one direction while decreasing in other direction [8]. The deformation behaviour of the knitted fabric under tensile in course direction can be divided two phenomena, the first one is straightening of the curved yarn in the knitted structure up to its jamming condition and the second one is the elongation of the yarn materials [20]. The plain knitted fabric will be show less elongation in the wale-wise direction than in the course-wise direction because wale-wise jamming will occur sooner than course-wise jamming.

There are some theories used for bending including Euler-Bernoulli theory, Timoshenko bending theory, etc. to predict bending behaviour of the materials. They are especially suitable for small deformation. Because of large deformation nature of the textile material, pure bending developed by Livesey and Owen is suitable in which uniform curvature throughout the bending test is applied.

After studying some simulation for weft knitted structure, some can be expressed geometric structure of knitted fabric by CAD system, some described the knitted structure representing the unit cell analysing with constraint formulae based on the yarn parameters using FEM (Finite Element Analysis). In this paper we tried to express the mechanical properties of the plain weft-knitted model using the properties of simulated yarn model.

1.2. Conventional research

The knitted loop geometry is essential key point to continue further simulation for determining of behaviours and properties of knitted fabrics. Many geometrical models have been coming out by researchers to describe the loop model in various, most of them are emphasizing on its structural parameters. Choi and Lo described a new mathematical model of plain knitted fabric in which the yarn is curved with nonlinear properties and the model was constructed with the parametric equations along the central axis considering loop width, loop height, loop overlapping distance, fabric thickness and yarn diameter. He considered the energy of a deformed loop based on the tensile, bending and torsional moduli of yarn and curvature of yarn along its axis .Their model can express the geometrical dimensions and also low stress mechanical properties of plain knitted fabric. They also point out the dimension behaviours depending on the relaxation of knitted fabrics [29].

Kurbak constructs the model for plain knitted fabric and he expressed width wise curling of the model depending on the radius of curvature of loop parts; needle loop, loop leg and sinker loop. He expressed the curling model with the relationship of radius of curvature and torsion of the loop model. Kurbak also described the model for spirality in weft- knitted fabric due to the twist effect on the loop arm and expressed three dimensions (x, y, z coordinate points) of the loop model separated into eight regions.

Todays knitted fabrics are widely used in various fields because of its unique and stretchy behaviour. The yarns in woven fabric are nearly immobile, leading to an almost inextensible sheet with limited deformations in the yarn structure. In contrast, the interlocked loops in a knit material deform and slide readily, leading to a highly extensible sheet with dramatic changes in small-scale structure as the material stretches [23].

The behaviour of weft-knitted fabric under tensile is strongly restricted by its loop formation. When a tensile load is applied on it, the loops change their initial configuration of loop form in order to accommodate the applied load. In this case, small loads cause large deformations which is the typical behaviour of a low stiffness material [20].

Kawabata developed the instruments for basic mechanical properties for textile materials such as tensile, bending, shearing, compression and surfaces properties. The mechanical properties of the fabric are discontinuous, inhomogeneous, and anisotropic. For cloth simulation, geometric deformation is related to the energy function by the material properties of the cloth and it is very difficult for solving the material properties of cloth [30]. There is no model describing deformation behaviour of weft-knitted fabric in visual effects and its properties for both loading and recovering processes. In the simulation of woven fabrics, mass-spring systems are mainly applied to express for the visual behaviours in the computer screen. In most cases of woven fabrics simulation, the intersection of warp and weft threads are taken as point and connecting with some kinds of spring among these points to show the deformation behaviour and analysing force, torsion and bending rigidity and energy derived on these points. In the simulation of weft knitted fabrics, most are used elastica theory and analyse on the interlacing point of the knitted loop structure. Especially there is no weft knitted model which can describe the deformation behaviour by changing the construction of knitted structure under some basic mechanical conditions and its mechanical properties.

1.3. Purpose of my research and Construction

There are some geometrical weft-knitted models but they were mainly focused on the structure of the knitted loop shape for various stitches such as plain, rib, tuck and miss stitches. Therefore, those models can be applied only in the determination of prediction of designs for the production. Actually, the properties of the products are the most important factor in the production processes and so the model which can express its properties become the main role for the textile fields. So, I constructed 3-dimensional weft-knitted model which can express its deformation behaviours and mechanical properties under the tensile conditions. When constructing the model, I considered firstly to express the yarn model representing the real one and so the model was constructed with the same amount of the fibres consisting in the real yarn.

I expressed deformation of the behaviour of the model by using mass-spring system and also the mechanical properties of the model related to their deformation conditions.

The yarn model was constructed considering an idealized helical yarn structure which can express twist in the yarn. At first, one cross section was made by mass points which can represent the amount of fibres in the real yarn. The two dimensions of the cross section was adjusted in order to be matched with the dimension of the cross section of the real yarn. After that the required amount of cross section was determined in order to express one twist length of the real yarn. Then three dimension of the yarn model was constructed by rotating all of the cross-sections along the axis of the yarn. As a result, the yarn model was obtained with expressing its twist structure because of different positions of mass points from one cross section to next section along the yarn axis.

Two kind of springs were connected within the mass points to evaluate the mechanical properties of the yarn model. The spring connected between the two mass points was defined as a tension spring and the spring connected within the three mass points was defined as a bending spring. And also, the spring for mutual repulsion force in the mass points was considered according to the condition in the extension of the yarn model. Then, the properties of the yarn model were determined its tension and strain to evaluate the yarn model.

After that, it was considered to describe the geometric structure of loop model with the cross section models. In here, kurbak's model was applied to express the geometric structure of the loop model. The idealized helical yarn structure was also maintained in the loop model. Therefore, all of the cross sections were rotated to maintain its yarn structure which are the same as in the yarn model but conform to the loop geometric structure. After constructing the loop model, plain weft-knitted fabrics was described by repeating the loop model in the wale and course direction according to the wale and course spacing.

In the chapter 3, the construction change of the loop model under the tensile condition for both wale and course direction was expressed. In this case, some hypothesis were made to describe the construction change of the loop model. The deformation of the knitted structure in the tensile condition was considered into two phenomena. The first one was the curved yarn in the loop structure will be approximately straighten and the second one was the yarn deformation or elongation up to the breaking condition. The construction change of loop structure (or) position change of cross section was described as a first step in here. The position change of the cross section was expressed by using some formulae in the simulation program.

The tensile properties of the loop model was described by means of the properties of the yarn model. By changing the position of the cross sections, strain values were determined in both loading and recovering processes in the simulation program. And also, the tension values of the model were determined depending on the curvature change of the yarn model under the tensile condition of the loop structure.

In the chapter 4, the bending condition of the loop model was described based on the change of curvature and position in bending. The loop model was bent within the positive and negative curvatures. The change of position of the loop model while bending was determined depending on the curvature of the model. The model can show its bending condition in both face-side and back-side of the weft-knitted loop structure. By simulation, the values of curvature of the model while bending condition can be determined by using formula. And also, moment or bending force of the model was determined.

In the chapter 5, the model was evaluated by simulation the tensile condition in the course direction. By inputting the parameters, the model was expressed its extension up to the specified limit of strain value and then it would be recovered to its original position. The obtained result of tension and strain by simulation was compared with the experimental result.

Chapter 2 Construction of 3-dimension simulated yarn model

2.1. Basic considerations for the yarn structure model

The mechanics of fibre properties in the yarn structure are essential key in the determination of the properties of the fabric. Generally, the properties of fibre are mainly due to fibres elongation, bending and compression of fibres. The nature of bending in fibres follow the elastic material model. There will be friction force within the fibre that holds the fibre in the yarn structure. Most of the fibres have their initial elastic recovery and so, their stress-strain curve is linear within its elastic limit. For these reasons, it was considered that to construct the yarn model with cross sections of mass points along the yarn. And also, some kind of springs were considered to apply in the yarn model in order to determine the properties of the yarn model.

2.2. Geometric structure of yarn

Generally, the geometry of fibres inside the yarn is commonly described by the idealised helical yarn structure. There will be fibre layers within the yarn structure with the helix angles. But the helix angles from layer to layer will be differ. Therefore, it supposes that the positions of the fibres in the yarn have different helices with the common axis of yarn. Figure 2.1 shows different positions of fibre in the yarn. If the distribution of the positions of fibres are known, it may be applied in the determination properties of the yarn model. Therefore, the idea for connecting within the different positions of the fibres was defining the position vectors of each fibres and connecting them.

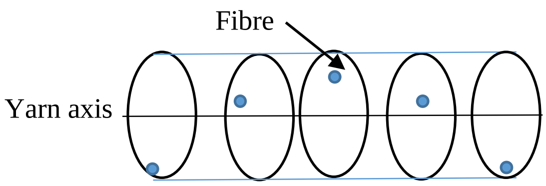
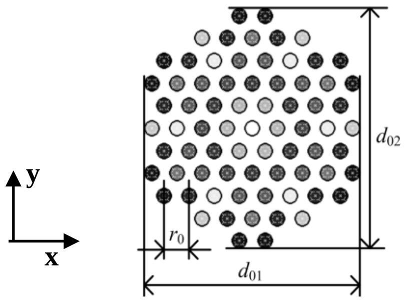


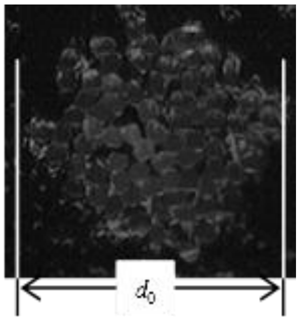
Figure 2.1. Different positions of fibres in the idealised geometric yarn structure.

2.3. Construction of 2-dimension cross-section model

In here, the yarn model was considered to be constructed with the cross-sections along the length of yarn and so the first idea was to make the model of cross-section. When the textile material is examined its cross-section, it can be seen that many fibres or filaments composed in the yarn structure. For that reason, the cross-section model was considered to make with the same mass points or fibres consists in the real yarn. In order to construct the cross-section model, the multifilament polyester yarn was firstly examined its cross-section under the microscopic view as shown in Figure 2.2 (b). The dimensions of the polyester yarn and its filament were also examined. Then the cross-section model was made by mass-points which represent the fibres in the polyester yarn in cross-section. One of the mass points was put in the centre of the model and others were put around its central mass point. After setting the mass points, the distance among these mass points were adjusted to be equal with the diameter of the polyester multifilament yarn.



(a)



(b)

d_0 = fineness of polyester yarn.

d_{01}, d_{02} = 2-dimensions of cross-section model.

r_0 = distance between the two mass-points.

Figure 2.2. (a) Adjusted dimension of one cross-section. (b) Cross-sectional image of polyester yarn.

2.4. Determination for the specifications of yarn model

To construct the yarn model, the length of the model was determined depending on the polyester multifilament yarn. One twist length of polyester multifilament yarn was considered to be construct the yarn model. The number of turns per meter of polyester multifilament yarn was 182 and so the length of yarn model was determined as 5.49 mm which is equal to one twist. And then the required amount of cross-sections for the one twist length of yarn model was determined as follows;

Number of twists per meter of polyester filament yarn = 182.

Length of yarn model for one twist = 1/182 = 5.49 mm.

Dimension of 2D cross-section model in x- coordinate = 285 μm.

The required model for one twist length of yarn = 5.49/0.285 = 19.2 ≈ 20.

Therefore, 20 cross-section models were required to construct the yarn model.

2.5. Consideration the geometrical structure of yarn model

In the production of the textile yarn, twist is exerted along the length of yarn in order to maintain the fibres binding together in the yarn structure and also contribute to the strength of yarn. Twist is generally expressed as turns per unit length of yarn, i.e., turns per inch or turns per metre. The direction of twist can be expressed as right-hand twist (sometimes referred to as Z- twist) and left-hand twist (sometimes referred to as S-twist).

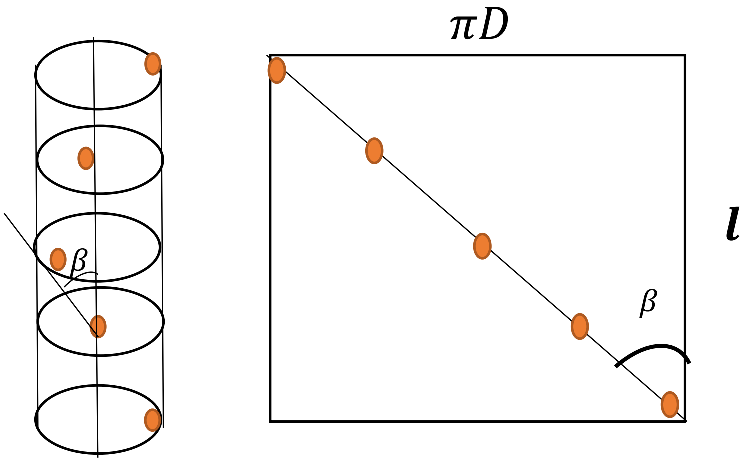


Figure 2.3. Twist angle in the idealised helical yarn structure.

In the yarn structure, there will be twist angle between a tangent to the helix formed by the fibre and yarn axis. Figure 2.2 shows twist angle formed between the outer layer and yarn axis. By unrolling the surface layer, the fibres will be the hypotenuse of the right-angled triangle as shown in Figure 2.2. According to the figure, the twist angle β can be expressed as

$$tan\,\beta = \frac{\pi D}{l}$$

where, D : Diameter of yarn,

l : Length of yarn formed by one complete turn of twist,

In here, $1/l$ is equivalent to turns per unit length of yarn and so twist angle can be expressed as;

$$tan\,\beta \propto D \times \text{ turns per unit length}$$

In the measurement of linear density of yarn, the diameter is proportional to $1/\sqrt{count}$ in the indirect system and therefore twist angle becomes;

$$tan\ \beta \propto \frac{turns\ per\ unit\ length}{\sqrt{count}}$$

Finally, the relationship between yarn twist and yarn count can be expressed as;

$$\text{turns per unit length} = \text{K} \times \sqrt{count}$$

In here, K is referred to as "twist factor" or "twist multiplier" and is directly proportional to the tangent of the twist angle.

In the construction of yarn model, twist was considered to express by setting the cross-sections with rotating one turn around the yarn axis so as to be the positions of fibres become hypotenuse on the yarn axis in each layer. By this way, the yarn model can be expressed its twist factor.

2.6. Construction of 3-dimensional simulated yarn model

After constructing the cross-sections, the 3-dimension yarn model was constructed by setting all the cross-sections along the length of one twisted yarn. The yarn model was considered to be constructed describing the twist on its structure and this was expressed by setting from one cross-section to the other section rotating with some degree along the length of the yarn model (z-axis). When the cross-sections were rotated with an angle, their initial positions were also changed into the new positions in the x, y coordinates and this was calculated according to the formula (2-1).

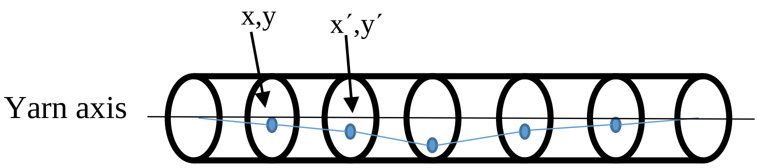
$$\left.\begin{aligned} x' &= x\cos\theta + y\sin\theta \\ y' &= x\sin\theta - y\cos\theta \end{aligned}\right\} \quad (2\text{-}1)$$

x,y : position of mass points in one section.

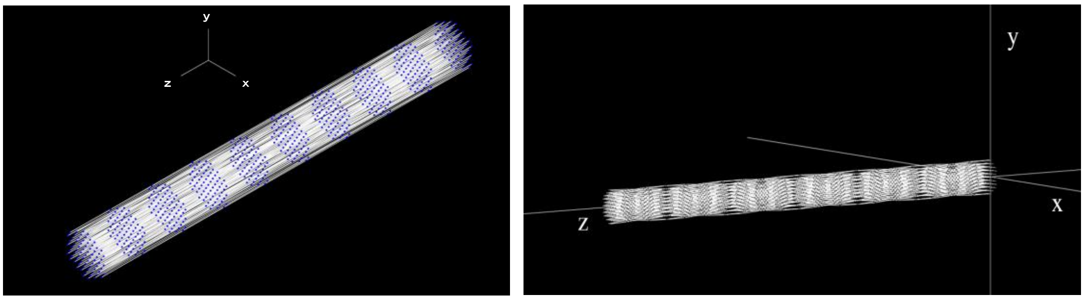
x′,y′ : position of mass points in next section.

θ : angle from one section to next section.

In here, an angle was determined by 2π/number of cross-section models in one twist of length of yarn. As a result, the straight yarn model can be constructed with the insertion of twist on the yarn model by connecting some kind of springs among the mass points. In the yarn model, the same mass point in the cross-sections will be form with an inclined angle at different coordinate points that can be represent twist on the yarn structure as shown in Figure 2.4 (a). Figure 2.4 (b) shows the graphic image of the simulated yarn model.



(a) Different positions of the same mass point in the cross-sections along the length of yarn.



(b) Images of simulated yarn model.

Figure 2.4 Simulated yarn model with twist.

2.7. Type of springs used in the simulated yarn model

The three kind of springs were used to connect within the mass points in the yarn model. The objects of connecting with the springs was to express the behaviour of the yarn model under tensile and bending conditions and calculate the properties of the yarn model such as force and strain. Hooke's law was applied in these connected spring to determine properties of the yarn model. The tension spring was connected between every the same two mass points of the adjacent cross-sections. Figure 2.5 shows connecting of the tension spring between the same two mass points of adjacent sections. By using Hooke's law, the elastic energy on each mass point can be calculated according to the formula (2-2).

$$E_1 = {}^1/_2 \; k_1 x^2 \text{ , ---------------- (2 -2)}$$

Where, E_1 : Elastic energy.

k_1 : Spring constant.

x : Stretched length.

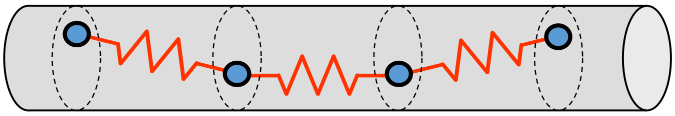


Figure 2.5. Connection of tension spring between the same mass points.

In order to express the bending properties of the yarn model, the springs were connected among the every three same mass points of continuous cross-sections along the length of yarn. Figure 2.6 shows connection of the bending spring among the three mass points of continuous cross-section. By applying formula (2-3), the elastic energy can be calculated acting on each mass point.

$$E_2 = {}^{1}/_{2}\ k_2\, \theta^2 \ , \text{--------------}\ (2\text{- }3)$$

Where, E_2 : Elastic energy.

k_2: Spring stiffness.

θ : Bending angle.

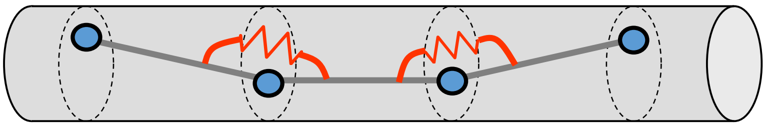


Figure 2.6. Connection of bending springs among three mass points.

There were another factor to be accounted while pulling the yarn model in the simulation program, it was found that the mass points became overlapping each other because the dimension of the cross-section became reduced while pulling and so the repulsion force was considered to apply between the mass points in order to avoid overlapping within the mass points. For the spring, the repulsive force will be outcome when the spring length is shorter than its original length. So, the repulsive force was applied when the dimension of the cross-section was smaller than its original dimension as shown in Figure 2.7. The condition of repulsion was depicted in Figure 2.7. In Figure 2.7 (a), there would not be applied repulsion force between the mass points whereas in Figure 2.7 (b), there would be applied repulsion force between the mass points to avoid overlapping within the mass points when pulling the yarn model. As shown in Figure 2.7, when the yarn model was pulled, the cross-sections in the yarn model became smaller in dimension and the mass points would be touched and so the repulsion force was accounted among the mass points and the elastic energy due to repulsion was calculated from those springs according to the equation (2-4).

$E_3 = 1/2\ k_3\ (r - r_0)^2$ -------- (2-4) if the dimension of cross-section is smaller than its original size,

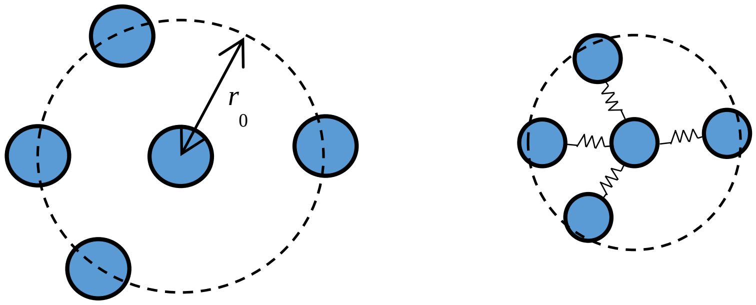
$= 0$ if the dimension of cross-section is equal or bigger than its original size.

Where, E_3 : elastic energy.

k_3: coefficient of mutual repulsion between the mass points.

r_0 : distance between the mass points before pulling.

r : distance between the mass points after pulling.



(a) No repulsion between the mass points. (b) Repulsion between the mass points.

Figure 2.7. Repulsion force within the mass points in the cross-section.

Another considering factor in the yarn model was friction between the fibres or mass points when the yarn model was pulled with the velocity. In here, we considered that textile fibres have viscoelastic properties and so there would be friction when in deformation the yarn model and this can be expressed by the damper. In physics and engineering system, damping can be mathematically modelled using force and velocity of the object but opposite in direction. Therefore the friction between the mass points in the cross-sections when the yarn model was being pulled with the velocity was expressed by the equation (2-5). Figure 2.8 depicts the friction force acting on the mass point because of pulling velocity.

$$F = -cv \text{ ------------------ } (2 - 5)$$

Where, F : Friction force.

c : Coefficient of viscosity.

v : Velocity of the yarn model.

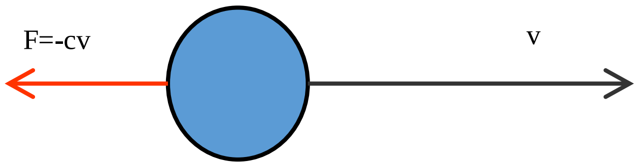


Figure 2.8. Friction force in the mass point.

2.8. Determination of the force on the mass point

After determining the elastic energy, the force acting on the mass point can be expressed according to the relationship between the conservative forces and elastic energy as follows;

$$dU = -F_x \, dx$$

where, dU : change in elastic energy,

F_x : force acting on the point,

dx : displacement of point.

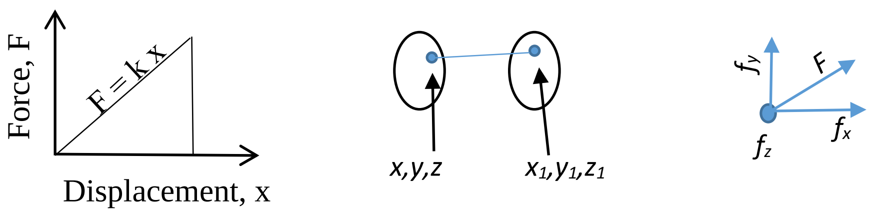


Figure 2.9. General description of force acting on the mass point.

After getting the force acting on each mass point, the force acting on each mass point in three dimensions can be generally expressed as;

$$f_x = F \times \frac{dx}{d} \;,\; dx = x_1 - x$$

$$f_y = F \times \frac{dy}{d} \;,\; dy = y_1 - y$$

$$f_z = F \times \frac{dz}{z} \;,\; dz = z_1 - z$$

$$d = \sqrt{dx^2 + dy^2 + dz^2}$$

where, x, y, z : Coordinate points of mass.

f_x, f_y, f_z : Force acting on the mass point.

2.9. Measurement of tensile properties of polyester multifilament yarn

In order to evaluate the simulated yarn model, the multifilament polyester yarn was examined its tension-strain diagram by using the machine TESILON RTM-100. Some of the specifications of the multifilament polyester yarn were described as shown in Table 2.1. The number of tests was made ten times using the machine parameters of initial tension 9.81cN, speed of pulling with 50 mm per minute, and strain value 0.2. From the experiment result of stress-strain curve of polyester multifilament yarn, the values of spring were examined dividing into two regions; elastic and plastic area. Then these values were applied in the simulation program to determine the mechanical properties of the yarn model.

Table 2.1. Specifications of the polyester multifilament yarn.

Polyester multifilament yarn					
Twist coefficient, K	Number of twists, N	Fineness, T_d [tex]	Yarn count [Nm]	Number of fiber	Fiber diameter, d_f [μm]
33.8	182	33.3	30	72	20.7

2.10. Simulating the yarn model

By the experiment, the stress-distortion diagram of the polyester multifilament yarn was obtained. The value of strain obtained from these graph was applied as a limited strain value in the simulation program of the 3-dimension yarn model and consequently tension of the yarn model was calculated. At the start of the simulation, the pulling velocity was defined as the same velocity of the experiment, and coefficient of viscosity of the mass point and the stiffness of tensile and bending spring were also defined. The simulated yarn model was acted a tensile along the z-direction by velocity and in this condition the extension of the yarn model was described by moving each mass point in all the cross sections. By integrating Newton's second law of motion, the movement of the mass points was described. To do the simulation for the extension of the yarn model, the following steps were made.

1. The change of position of each mass point due to its changing velocity with the time was determined by considering in the x, y, z positions.

2. The force acting on each mass point due to change of position was determined by using Hooke's law. The force was considered in 3-dimension.

3. After getting the force acting on each mass point, the new position of each mass point connected with the spring was determined by integrating Newton's second law of motion considering in x, y, z positions. By this way, the extension of the yarn model when pulling was expressed by constructing C++ program with OPEN GL method. Figure 2.10 depicts the change of position of mass point connected with the spring due to its pulling velocity.

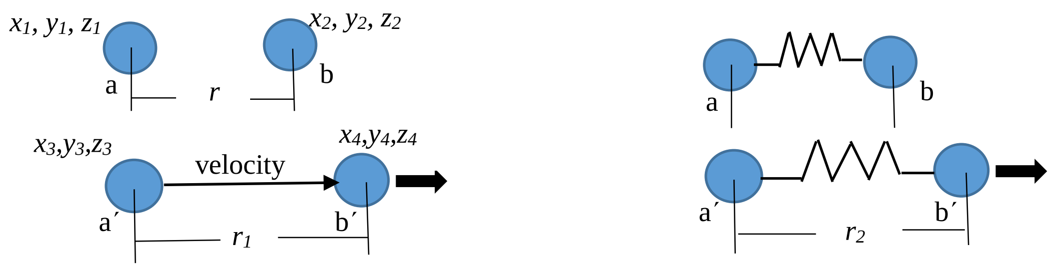


Figure 2.10. New position of mass point in pulling.

According to the Figure 2.10, change of the position or extension of the mass points due to its velocity was calculated in 3-dimension as followings;

$$r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \text{ ------------(2 - 6)}$$

$$r_1 = \sqrt{(x_4 - x_3)^2 + (y_4 - y_3)^2 + (z_4 - z_3)^2} \text{------------(2 - 7)}$$

From these equation (2-6) and (2-7), the extension can be expressed ,

$$x = r_1 - r \text{ -----------(2 - 8)}$$

By Hooke's law, the force acting on the mass point can be expressed,

$$F = k\,x \text{ -------------(2 - 9)}$$

By integrating Newton's second law, the change of position of the mass point connected with the spring was determined as follows;

$$F = m\,a \text{ --------------(2 - 10)}$$

$$v = F/m \times dt \text{ ---------(2 - 11)}$$

$$r_2 = v \times dt \text{ -----------(2 - 12)}$$

By this way, the yarn model was expressed its movement behaviour when it was pulled at one edge of the yarn model. When the yarn model was under tensile condition, its initial state and extension or change of new positions were determined. And also tensions in the spring were determined.

Figure 2.11 shows the results of simulation and experiment of tensile properties of polyester multifilament yarn. It can be concluded that the simulation result of yarn model was approximately near to the experimental results.

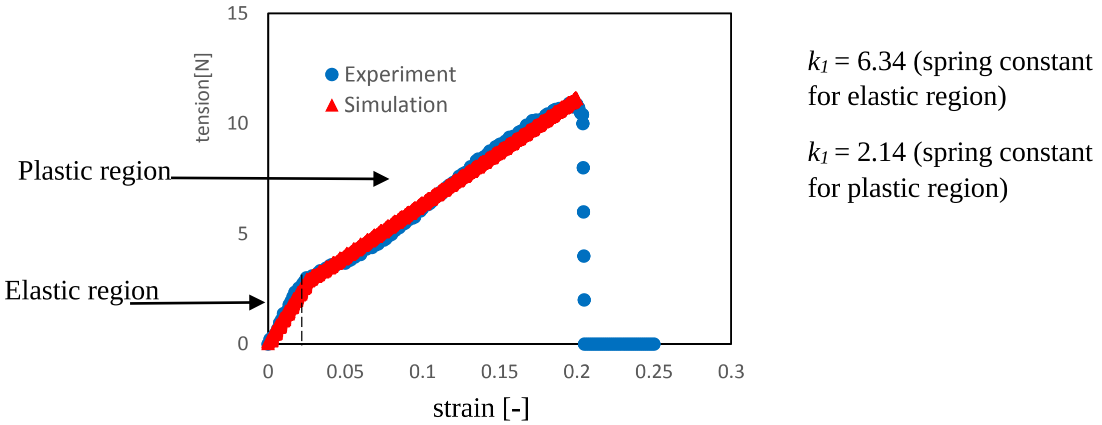


Figure 2.11. Results of simulated yarn model and experimental yarn in tensile properties.

In the simulation of the yarn model in tensile condition, it can show the extension of the yarn mode behaviour until reaching the limitation of strain (input data), it will stop at that limited strain data and go back to its original position until the strain was zero.

2.11. Flow chart of simulation of yarn model

The aspects of simulation for the yarn model was shown by the flow chart diagram as sown in Figure 2.12.

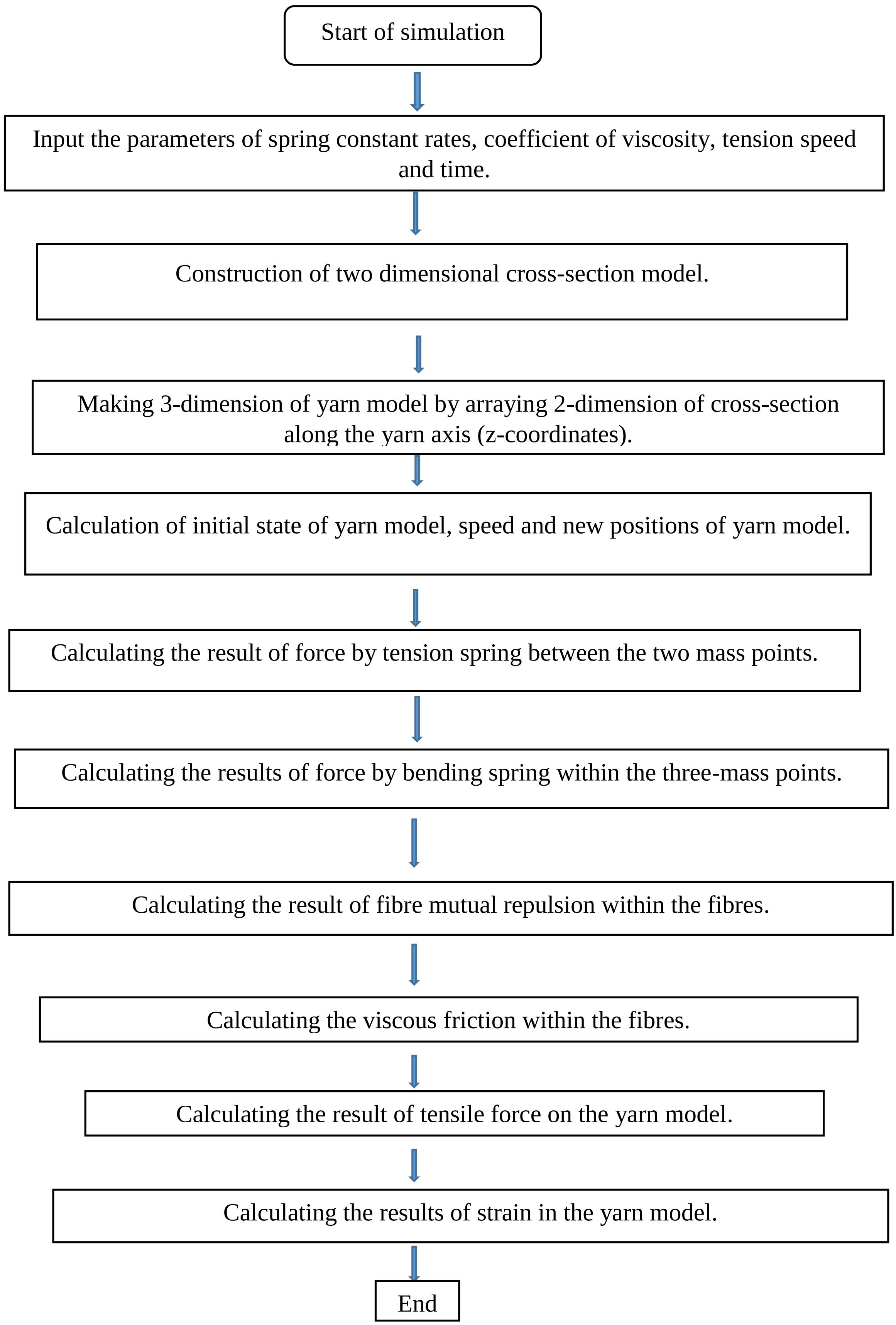


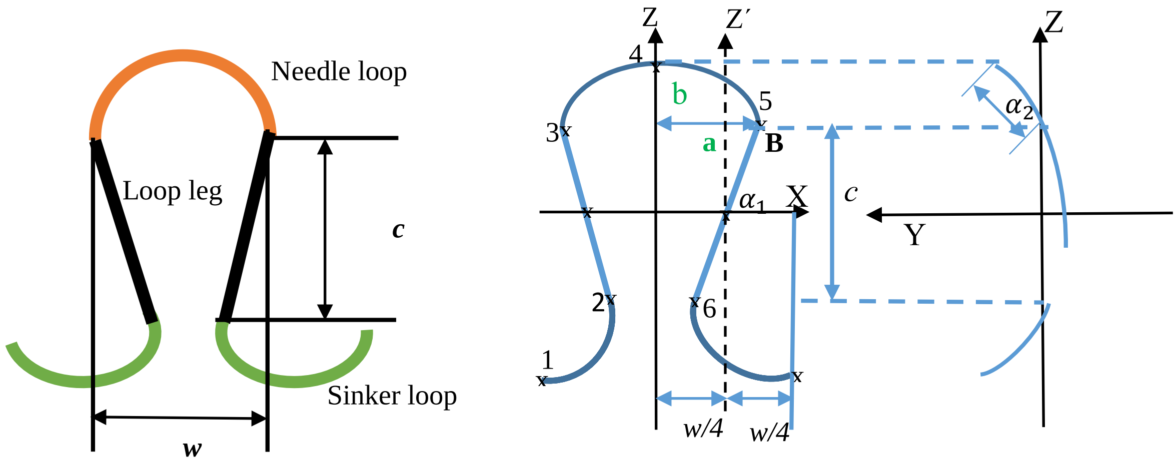
Figure 2.12. Flow chart of simulation aspects for yarn model.

2.12. Geometrical loop structure of model

To construct the yarn model into the loop structure, it was needed the geometric loop structure which can be used in the determination of the properties of the loop structure. There are many weft-knitted geometrical loop structure model by Pierce, Munden, and Kurbak etc. The loop structure can be defined its parameters such as wale spacing (*w*), course spacing (*c*), yarn diameter (*d*) and its loop length (*l*) as shown in Figure 2.13 (a). The relationship between the parameters are described in equation (2-13) by Pierce.

$$\left.\begin{aligned} \text{Course spacing, } c &= 3.4643d \\ \text{Wale spacing, } w &= 4d \\ \text{Loop length, } l &= 16.6d \end{aligned}\right\} \quad (2\text{-}13)$$

In here, Kurbak's model was applied to construct the simulated loop model in order to avoid the friction at the contact point of yarn within the loop structure. Kurbak's model described the upper and lower parts of the loop in the form of elliptical curves and the arm of the loop as a helical shapes wrapping over elliptical cylinders which are arranged parallel to the wale direction. Because of these assumptions, there were helix angles along the central loop axis. Figure 2.13 (b) shows the central loop axis of Kurbak's model with its geometric structure.



(a) (b)

where, c : course spacing.

w : wale spacing.

a : major radius of upper elliptical curve of loop head.

b : minor radius of upper elliptical curve of loop head.

α : helix angle.

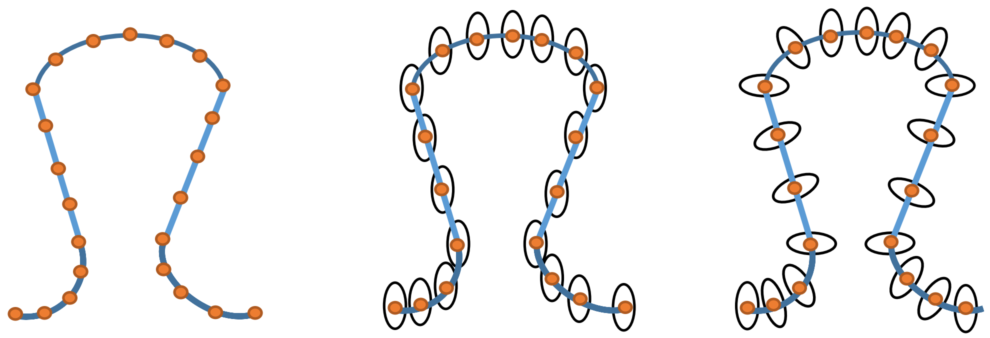
Figure 2.13. (a) Basic loop structure and its parameters. (b) Geometric structure of Kurbak's model with its central loop axis.

The elliptical shape of the upper part of loop (loop head) was formed with the helix angle (α_1) with the horizontal axis (y-axis) which is directed towards the fabric thickness direction as shown in Figure 2.13 (b). This helix angle would be perpendicular with both sides of the fabric width (x-direction) at the point B.

2.12.1. Considering the structure of yarn model to loop model

Firstly, the yarn model was constructed according to the idealised helical yarn structure using the cross sections model. The properties of yarn model was described according to the positions of mass points in the yarn structure. In here, the properties of loop model was to be expressed depending on the properties of the yarn model. Therefore, the yarn structure was considered to maintain in the loop model. The main idea for maintaining the yarn structure in the loop model was to construct the cross sections perpendicular with the yarn axis.

At first, the coordinates of the sections were determined with the centre of the mass points along the central loop axis as shown in Figure 2.14 (a). All the sections were set on its centre of the mass points and then the sections were rotated in order to be perpendicular with the yarn axis (or) central loop axis as shown in Figure 2.14 (c). By this way the loop structure was constructed considering with the yarn structure.



(a) Loop structure with coordinates of centre mass points.

(b) Loop structure with cross sections.

(c) Loop structure with inclined cross sections.

Figure 2.14. Setting the cross sections along the central loop axis.

There are some methods to construct the image of knitted loop structure using in CAD (computer aided design) system. Some researchers implemented the image of loop structure by solid work, 3D-max studio and C++ program etc. In here, Kurbak's loop model was expressed by the way of method of Fukuta Yuka. Modified loop structure of Fukuta Yuka can be designed the loop structure by C++ program using with OPEN GL method.

2.13. Construction of the loop model

The loop model was constructed based on the principle of Kurbak's model. In order to be the elliptical shape in the upper and lower parts of the loop model, from every one cross section to next section were inclined so as to form perpendicular with the yarn axis. Figure 2.15 shows an inclined angle forming in the elliptical shape of the upper part of the loop. Therefore, in order to express the elliptical shape of the loop model in the upper and lower part of the loop model similar to Kurbak's model, from one section and next section was inclined in the z-y plane and z-x plane.

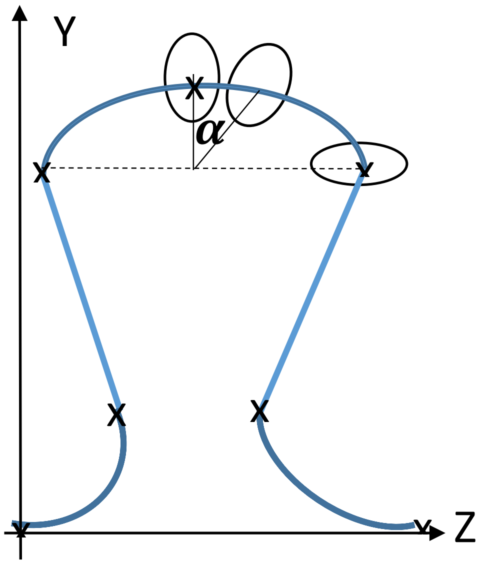


Figure 2.15. An elliptical angle formed in the upper part of loop model.

To be constructed the loop model, the length of the loop was firstly calculated using with and then the required amount of cross-section models was determined. When constructing the yarn model, twist was considered to be expressed and this was implemented by rotating all the cross-sections around the yarn axis. Similarly, twist was also considered in the loop structure and it can be expressed by rotating every cross section to next section with the angles in the z-y plane and z-x plane. Therefore the inclined angle θ was an important factor constructing the loop model. The angle θ firstly calculated in the z-y plane and z-x plane by the formula (2-14) as shown in Figure 2.16. All the mass points were inclined by the corresponding inclined angle θ, and their new positions were calculated by the formula (2-15) and (2-16). By this way, the loop model was constructed considering the yarn structure in the loop form.

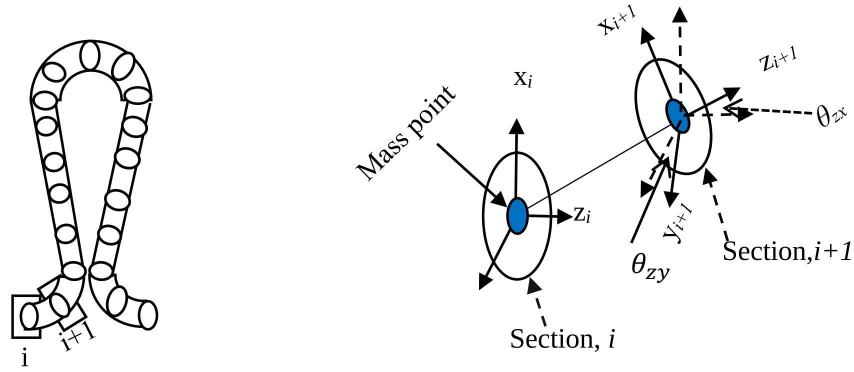


Figure 2.16. An inclined angle of section in the loop form.

The inclined angle, θ for each mass point for every section in z-x plane and z-y plane was calculated as follows;

$$\left.\begin{aligned} \theta_{zx} &= tan^{-1}\ \frac{x_i - x_{i-1}}{z_i - z_{i-1}} \\ \theta_{zy} &= tan^{-1}\ \frac{y_i - y_{i-1}}{z_i - z_{i-1}} \end{aligned}\right\} \qquad 2\text{-}14$$

After calculating the inclined angle for each mass point in the cross-sections, all the mass points were inclined in the z-y plane and z-x plane by their corresponding angle θ and consequently the new positions of the all mass points were also calculated according to the formula (2-15) after inclining in z-y plane and formula (2-16) after inclining in z-x plane.

$$\left.\begin{aligned} z' &= z\ cos\ \theta_{zy} + y\ sin\ \theta_{zy} \\ y' &= -\ z\ sin\ \theta_{zy} + y\ cos\ \theta_{zy} \end{aligned}\right\} \qquad 2\text{-}15$$

Where, θ_{zy} , θ_{zx} : An inclined angle for z-y and z-x plane.

z' : New position of the mass point in z-coordinate.

y' : New position of the mass point in y-coordinate.

$$\left.\begin{aligned} z'' &: z'\ cos\ \theta_{zx} + x\ sin\ \theta_{zx} \\ x' &: -\ z'\ sin\ \theta_{zx} + x\ cos\ \theta_{zx} \end{aligned}\right\} \qquad 2\text{-}16$$

where, z'' : New position of the mass point in z-coordinate.

x' : New position of the mass point in x-coordinate.

After setting the cross-sections perpendicular with the yarn axis, the 3-dimension of loop model was obtained and in here z- coordinate represents course direction, y- coordinate represents wale direction and x- coordinate represents thickness direction of the loop model.

Figure 2.17 shows the image of simulated loop model. The simulated loop model can represent the knitted fabric loop structure because it was constructed according to the wale and course spacing.

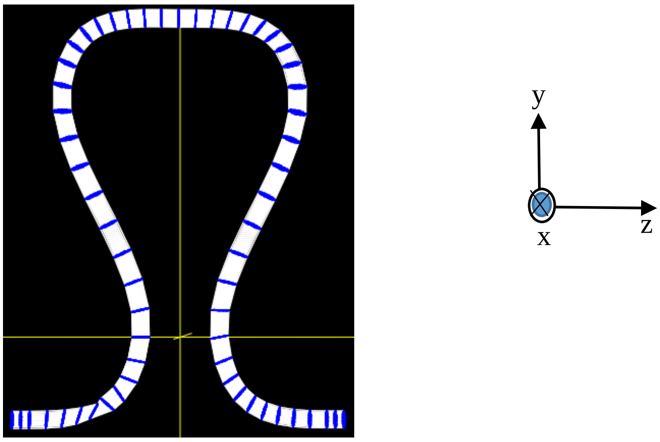
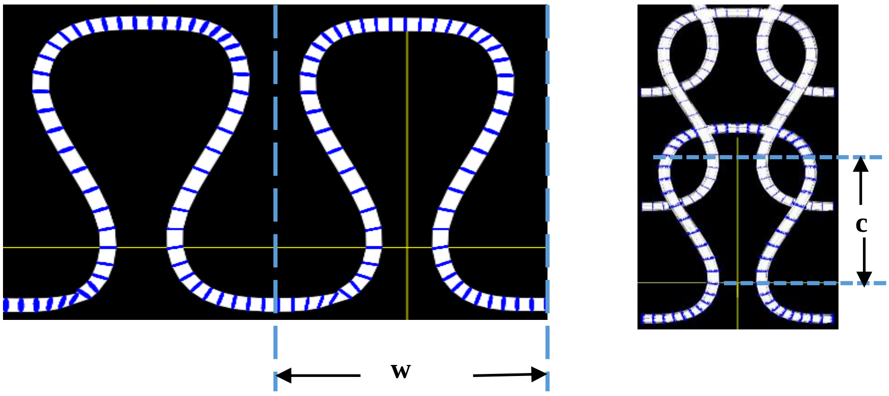


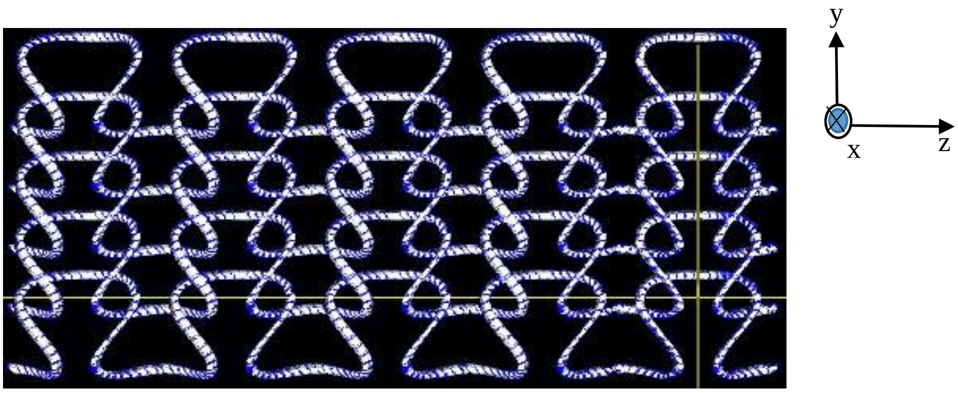
Figure 2.17. Simulated model of loop structure and its coordinate system.

After constructing the loop model, it was considered to express the weft-knitted structure of plain stitch. The weft-knitted structure is constructed by interloping of thread in the direction of the weft (i.e., filling direction in the weave structure). In the weft-knitted fabrics, there are technical face-side and back-side according to the surface of knitted structure. There are various weft-knitted structure such as plain, rib, tuck, and miss. Of these, the plain stitch is a basic structure for the weft-knitted fabric. The appearance of the technical face-side and back-side is different in the plan weft-knitted structure showing that the face-side is smoother than back-side. Because of its different surface structure, the plain weft-knitted fabric shows unbalanced form which leads to edged-curling.

In here, weft-knitted fabric for plain structure was constructed using the three dimension of the loop model. The plain weft-knitted model can be constructed according to the wale spacing (w) and course spacing (c). Therefore the plain weft-knitted fabric structure was constructed by repeating and connecting the loop model according to the wale spacing in the course direction and course spacing in the wale direction. Figure 2.18 shows simulated weft-knitted loop structure model for plain stitch.



(a) Connected loop model according to the wale and course spacing.



(b) Plain weft-knitted model.

Figure 2.18. Simulated weft-knitted loop model for plain stitch.

Chapter 3 Deformation behaviour and properties of the model in tensile condition

3.1. Considering in the deformation of plain weft-knitted structure for tensile condition

The weft-knitted loop structure for plain fabric was examined in order to simulate its deformation behaviour under the tensile condition. The weft-knitted structure of plain fabric can be stretched easily once the tensile force are acted on one edge of the fabric and this may be because of an equally opened space within the loop structure. The tensile behaviour of weft-knitted fabrics are strongly restricted by its loop structure. While the tensile force is acted on one edge of the fabric, the deformation of the loop structure will be start due to the curved yarn become straightening until reaching to the jamming condition and after that the deformation is mainly due to yarn deformation. When weft-knitted loop structure deforms under the tensile condition, the loop will be extended in one dimension while being compressed in the other dimension as shown in Figure 3.1.

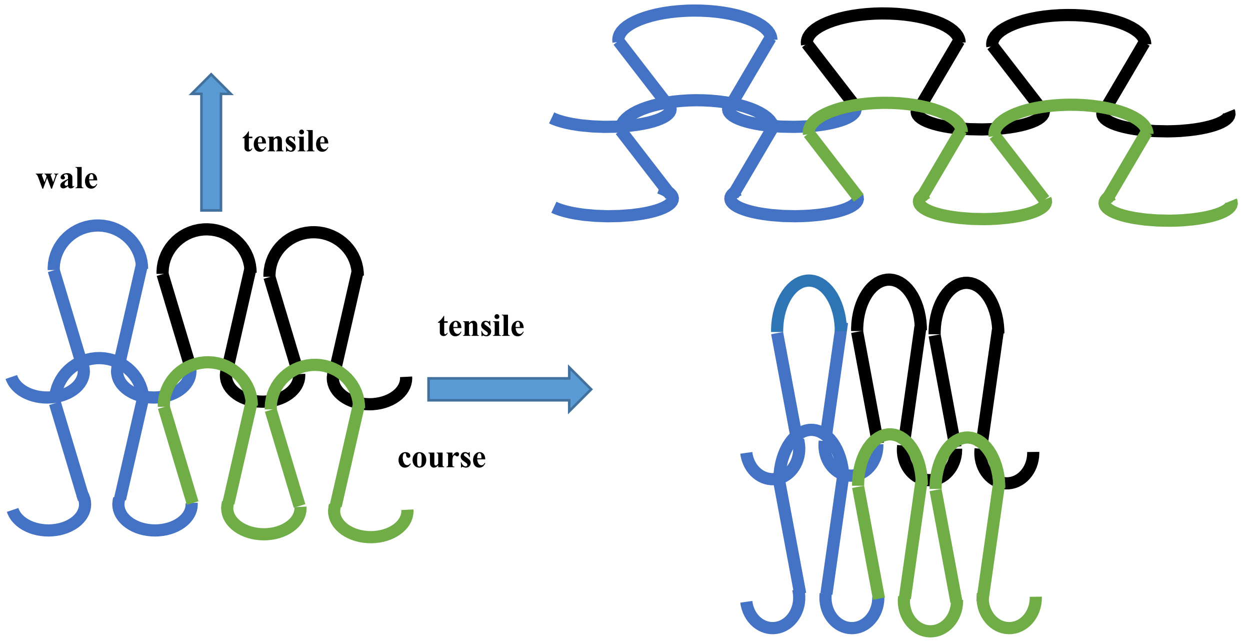


Figure 3.1. Deformation of plain weft-knitted fabric.

From these above reasons, the knitted loop model was considered to be simulated its deformation behaviours during acting the tensile force by changing its dimensions increasing in one direction whereas decreasing in other direction depending on its knitting construction.

3.2. Deformation of loop model under tensile in the course direction

When the knitted loop model was under tensile in the course direction, the extension of the loop structure will be in the course direction and compression in the wale direction. It was supposed that the curved yarn in the loop will become gradually straightening until it reach the jamming condition. In here, how much extension of the loop model according to its knitted structure in the course direction was defined by how much the loop model can compress in the wale direction and that amount was considered depending on the knitting construction. According to the loop structure of weft-knitted fabric, hypothesis was made that it can compress about its course spacing or half of its loop height (*H/2*) as shown in Figure 3.2. Another assumption for the deformation behaviour of the weft-knitted loop structure under tensile in the course direction was the extension of the fabric would be extend on both sides from the centre of the length of the tested sample. Therefore, in order to express the extension of the weft-knitted model on both sides from its centre, all the mass points in the cross-sections were equally moved from the centre of the knitted model according to its wale and course direction or y and z positions.

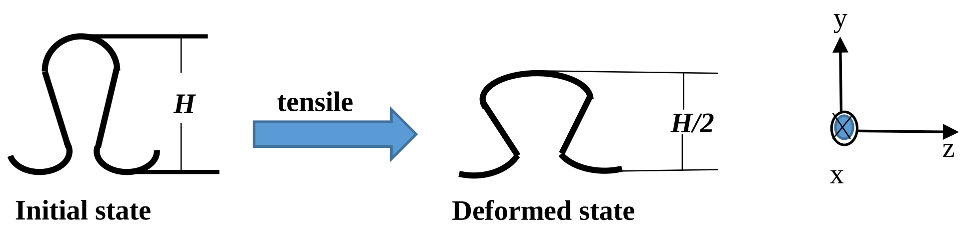


Figure 3.2. Deformation of loop structure according to its course spacing.

The weft-knitted loop model was firstly simulated using wale spacing, course spacing, yarn diameter, and number of loops in the wale and course direction. By this way the knitted fabric loop model was obtained and the positions of all the mass points were determined according to x, y, z coordinates in this initial state. When one edge of the model was pulled with some velocity, it will show the extension behaviour in the course direction or z-coordinate in the simulation program. Therefore, change of the positions or movement of each mass point in the course direction (z-coordinates) was calculated according to the formula (3-1). In Figure 3.3, m_1, m_2, m_3 are the same mass point but different in positions due to its increasing velocity while pulling in the course direction. Referring to the Figure 3.3, the change of position of mass points in the cross-section along the course direction was calculated as;

$$m_i = m_{i-1} + v \qquad (3\text{-}1)$$

m_i : new position of mass point in z-coordinate due to increased velocity.

m_{i-1} : old position of mass point in z- coordinate.

v : pulling velocity.

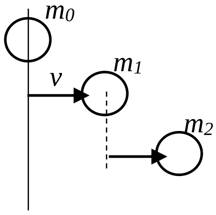


Figure 3.3. New position of mass point due to changing velocity.

Actually all the mass points in the cross-sections were located in the loop form, it was considered to move all the mass points equally when tensile loading along the course direction according to the loop form. Therefore, after calculating new positions of each mass point due to its increased velocity, the positions of all the cross sections were also calculated depending the length of knitted loop model in z-coordinate (course direction) by the formula (3-2).

$$B_i = B_{i-1} \times r \text{ --------------- } (3\text{-}2)$$

B_i : extension of the section in the course direction (z-coordinate) according to the loop form.

B_{i-1}: initial length of section in the course direction (z-coordinate) according to the loop form.

r : length ratio in the course direction.

Figure 3.4 shows the deformation of loop structure for tensile in the course direction, extension of the loop structure from its centre to both ends. Referring to this Figure, new position of the section B_1 can be calculated as follows according to the formula (3-2). In the Figure 3.4, (*A*) and (*B*) mean the sections at the edge of the loop model, (*O*) means the central section, and (*B*) and (*D*) mean the sections locating in the loop form.

$$B_1 = B \times OB/OC \qquad (3\text{-}3)$$

B_1: Extended length from section B to B_1 in z-coordinate.

B: Length from section O to B in z-coordinate.

OB : total length between the section O to B in z-coordinate.

OC : total length between the section O to C in z-coordinate.

By this way, new positions of the all mass points in the cross-section were moved equally in the course direction (z-coordinate) in order to express the extension behaviour of the loop model when it was pulled with the velocity at one edge in the course direction.

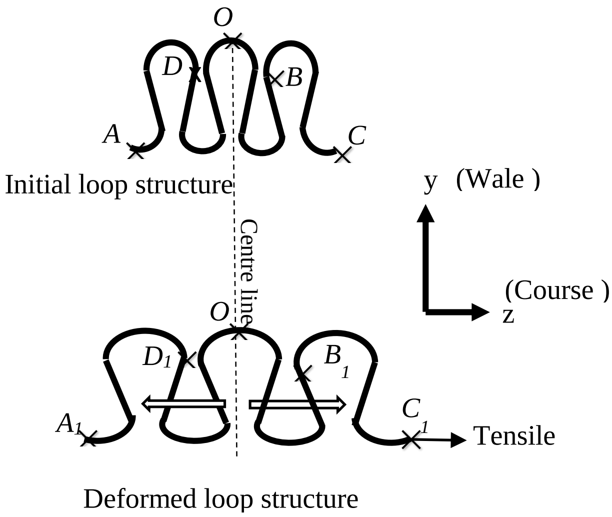


Figure 3.4. Deformation of loop structure pulling in the course direction.

In the tensile condition, the loop model would be extend to both sides according to the increased velocity and it would stop at its limitation of loop structure, and then the loop model would be recovered to its original position with the same velocity. So, change of position of the each mass point was calculated according to the formula (3-4) in the recovering process. And then the new positions of all the sections in the loop form were calculated by the formula (3-5).

$$m_i = m_{i+1} - v \text{ -------------- } (3\text{-}4)$$

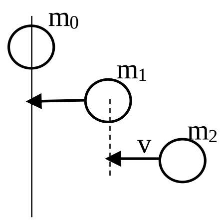


Figure 3.5. New position of mass point due to changing velocity to its original position.

$$B_i = B_{i+1} \times r \text{ --------------- } (3\text{-}5)$$

3.2.1. Compression of the loop model under tensile in the course direction

While the loop model was extended to the course direction (z-coordinate), it was also compressed in the wale direction (y-coordinate) at the same time. In order to express the compression behaviour of the loop model, the mass points in the loop model were also changed in the wale direction. The compression of each mass point in wale direction was expressed by changing its y-coordinate position according to the changing of its z-coordinate position (course direction). At first, the position of the mass points in the initial state were calculated in x, y, and z positions while constructing the knitted loop model. From these coordinates, the position vector of each mass point were calculated according to the formula (3-6). While pulling the loop model with the velocity, the compression amount of each section were determined. Then the compression of the whole knitted fabric model was determined. By this way, the loop model was expressed its deformation by means of discrete deformation of the sections in the loop model.

$$R = \sqrt{x^2 + y^2 + z^2} \qquad \text{--------} \ (3\text{-}6)$$

R = position vector of mass point.

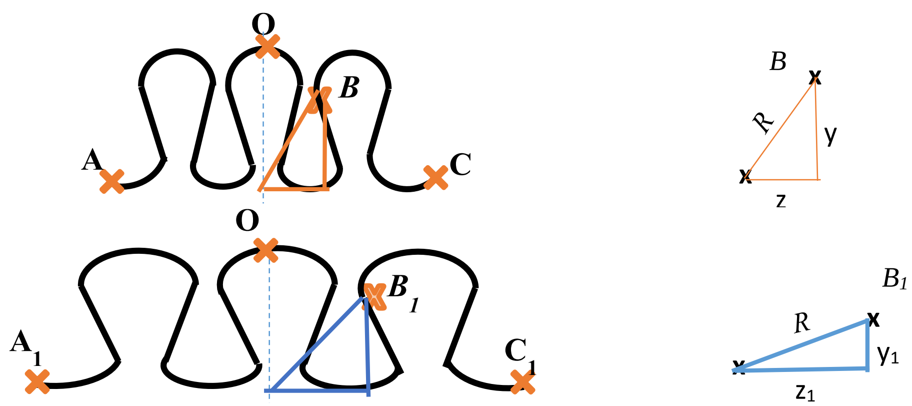


Figure 3.6. Position of mass points in the loop form.

Referring to the Figure 3.6, the positions of the mass point *B* and B_1 in the initial state and extended state were calculated in Cartesian coordinate system and consequently, the position vector *R* was calculated. According to the Pythagoras theory, the compression amount of section *B* to B_1 was determined as follows;

$$dy = y - y_1$$

Where, dy : compression amount of section in the Y- direction.

3.3. Deformation of loop model under tensile in the wale direction

In order to simulate the deformation of the loop model while it was under tensile in the wale direction, it was considered that the loop model would be extended in the wale direction and compressed in the course direction. So, how much extension of the loop model in the wale direction was defined by how much the loop model can be compressed in the course direction according to the loop construction. In here, hypothesis was made that the loop structure can be compressed about half of its wale spacing (*w/2*) as shown in Figure 3.7. Another assumption was considered that the whole loop model would be compressed to its centre from both ends. All the mass points were considered to be moved equally to its centre for the deformation under tensile in the wale direction.

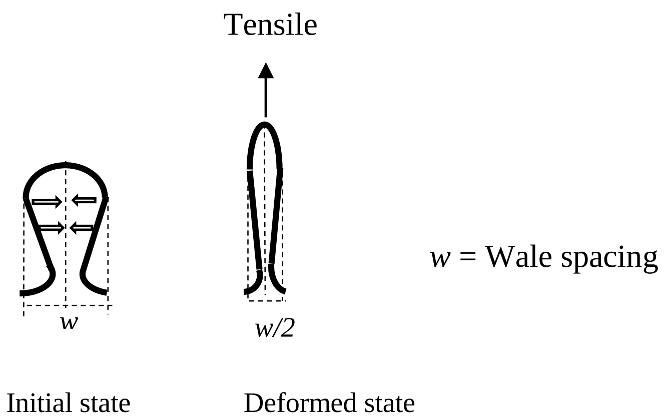


Figure 3.7. Compression of loop structure under tensile in the wale direction.

3.3.1. Extension of the loop model under tensile in the wale direction

The weft-knitted loop model was firstly simulated using wale spacing, course spacing, yarn diameter, and the amount of number of loops in the wale and course direction. In the initial state of weft-knitted model, the positions of all the mass points were calculated according to the x, y, z coordinates. Then it was considered to move all the mass points from its initial state to deformed state according to increasing velocity in the wale direction. In order to express the extension behaviour of the loop model in the wale direction, the positions of all the mass points in the loop model were changed in the wale direction (y-coordinate). When one edge of the loop model was pulled with some velocity, change of the positions or movement of each mass point in the wale direction (y-coordinates) was calculated according to the formula (3-7). Referring to the Figure 3.8, the change of position of mass points due to its velocity in the cross-section along the wale direction was calculated by formula (3-7). By this way, the new positions of each mass point due to its increasing velocity in the wale direction were determined in the simulation program. In the Figure 3.8, m_1, m_2, m_3 are the same point but different in positions due to its increasing velocity while pulling in the wale direction.

$$m_i = m_{i-1} + v \qquad (3\text{-}7)$$

m_i : new position of mass point in y-coordinate due to increased velocity.

m_{i-1} : old position of mass point in y- coordinate.

v : pulling velocity.

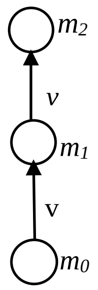


Figure 3.8. New position of mass point due to changing velocity.

After determining the new positions of each mass point in the wale direction, the next step was to move all the mass points equally along the wale direction. Figure 3.9 depicts movement of the mass point (*B*) under tensile in the wale direction. The deformation of the loop structure was extension in the wale direction and compression in the course direction. So the extension or new positions of each mass point in the wale direction (y-coordinate) were calculated by the formula (3-8).

$$B_i = B_{i-1} \times r \text{ --------- } (3\text{-}8)$$

B_i : extension of the section in the wale direction (y-coordinate) according to the loop form.

B_{i-1}: initial length of section in the wale direction (y-coordinate) according to the loop form.

r : length ratio in the wale direction.

Referring to the Figure 3.9, the section (*B*) would be extended in the wale direction while under tensile in the wale direction and this was expressed by the formula (3-9).

$$B_1 = B \times h/H \text{ --------- } (3\text{-}9)$$

Where, h : length of the section (*B*) from the bottom of the sinker loop in y-coordinate.

H : total length from the bottom of the sinker loop to the top of needle loop of the model in y-coordinate. By applying formula (3-9) for each section and their corresponding length ratios, all the sections in the loop structure were extended equally in the wale direction while the loop model was under tensile in the wale direction.

3.3.2. Compression of the loop model under tensile in the wale direction

While the loop model was extended to the wale direction (y-coordinate), it was also compressed in the course direction (z-coordinate) at the same time. The compression of each mass point in the course direction was expressed by its z-coordinate position according to the changing of its y-coordinate position (course direction). The compression of all the mass points were limited according to the wale spacing. All the mass points were compressed into the centre of the wale spacing as shown in Figure 3.7. At first, the positions of all the mass points in the initial state were calculated and then change of the position in z-coordinate or the new position of the mass points were determined by the formula (3-10). By this way all the mass points in the loop model were compressed until the loop structure became half of the wale spacing.

$$B_i = B_{i-1} - z_0/4 \text{ ---------- (3-10)}$$

B_i : position of the section in z-coordinate.

z_0 : half of the wale spacing.

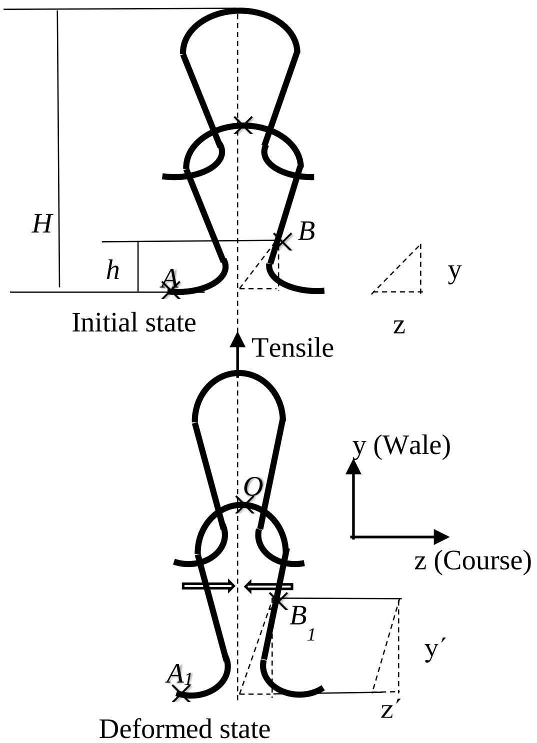


Figure 3.9. Deformation of loop structure under tensile in the wale direction.

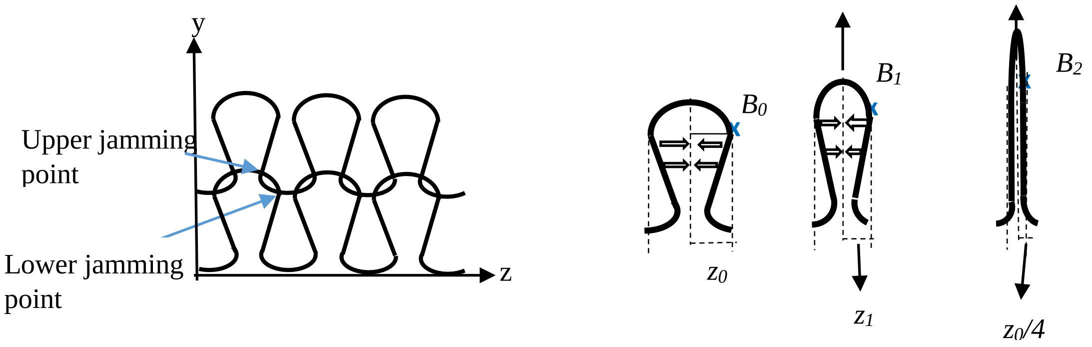


Figure 3.10. Compression of the mass point in the z-coordinate.

Referring to the Figure 3.10, the compression or new position of the section (*B*) can be calculated by using formula (3-10) as follows;

$$B_1 = B_0 - z_0/4$$

The section (*B*) would compress in the course direction until it reaches to the centre of the wale spacing with the limited compression amount of $z_0/4$. By applying the formula (3-10), all the sections were compressed equally to the centre of the wale spacing while the model was under tensile in the wale direction.

The loop model would be extend to the wale direction until it reach its limitation of the loop structure and then stop, and it will again recover to its original structure. Similarly for the extension of the model in the wale direction, its new positions while the loop model was recovered, were calculated according to its velocity by the formula (3-11) and all the mass points in the loop structure were equally moved to their new positions according to the formula (3-12).

$$m_i = m_{i-1} - v \text{ --------------- } (3\text{-}11)$$

$$B_i = B_{i+1} \times r \text{ --------------- } (3\text{-}12)$$

Finally, the loop model can be expressed its deformation behaviour while the loop model was under tensile in the wale direction visually in the simulation program.

3.4. Determination of tension in the loop model

The tensile properties of weft-knitted fabrics can be said that it is due to the bending deformation of loop structure and due to the stretching deformation of yarn. Therefore, the total tension acting in the loop model can be expressed as;

$$\sigma = \sigma_b + \sigma_s$$

Where, σ: Tension acting in the loop model.

σ_b: Tension due to the deformation of loop structure.

σ_s: Tension due to the stretching of yarn.

In this step, the loop model was considered to change its knitted-construction structure and so, the tension was considered according to the bending deformation of loop model. The stretching deformation of the yarn would be considered in the next step. In here, the properties of the loop model was described depending on the properties of the yarn model. Therefore, the tension due to the deformation of the loop model was described considering change of curvature in the yarn model according to the dimension of loop structure.

Making the loop structure can be said that the bending of the straight yarn. In this condition, the flexural rigidity is an important factor in the transformation of yarn to loop structure and also in the determination of the properties of the loop structure. When the loop structure was changed under the tensile condition, the curvature of each section in the yarn were also changed. Therefore, the tension in this condition was expressed depending on the change of curvature of each section under the tensile condition. The curvature was considered within the every three sections and so, the tension was expressed according to the bending spring as follows;

$$\sigma_b = k_2 \times k'$$

k_2: The spring value for bending spring.

k': Difference curvature of each section under the tensile condition.

In here, the value of spring k_2 was determined from the bending properties of yarn by means of experiment. The bending rigidity and its curvature were considered as an important factor effecting on the tensile properties of knitted fabric. The value of spring k_2 was determined from the relationship of equation (3-13) as follows;

$$M = B\,K + 2HB \qquad (3\text{-}13)$$

Where, M : Bending moment per unit length,

B : Bending rigidity per unit length,

K : Curvature,

$2HB$: Moment of hysteresis per unit length.

From this relationship, the spring value k_2 was determined depending on the curvature of each section as follows;

$$k_2 = \frac{M}{k}$$

k : Curvature of each section under the tensile condition.

In here, the curvature of each section under the tensile condition was determined using the principle of camber and bow dimensions. Figure 3.11 depicts the determination of curvature of each section according to the cam and bow system. The radius of curvature of each section under the tensile condition was determined as follows;

$$r = \frac{b^2 + 4\,c^2}{8c}$$

where, r : Radius of curvature of each section.

(bow) b : Length between (i) and ($i+2$) section.

(camber) c : Length between centre of the bow and middle of the section ($i+1$).

After determining the radius of curvature of each section under the tensile condition, the curvature acting on each section was determined as;

$$k = \frac{1}{r}$$

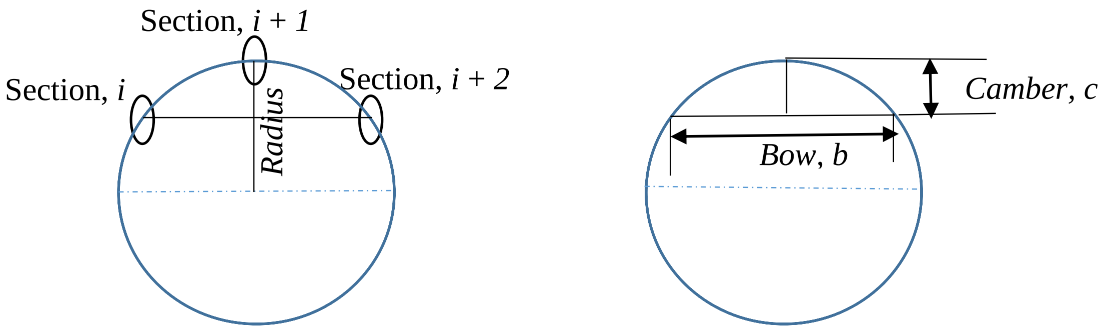


Figure 3.11. Dimensions of cam and bow system used in determination of curvature of each section.

According to the loop shape structure, there will be initial tension in the yarn model at the initial state of tensile condition. The tension will be gradually changed under the tensile condition depending on the curvature change of each section. As mentioned above, the properties of the loop model was described by means of properties of the yarn model, the actual tension in the yarn model was determined in order to express the tension of the loop model. Figure 3.12. depicts initial tension and different tension acting on each section in the yarn model according to their curvature under the tensile condition. The actual tension acting on each section in the yarn model was determined as follows;

$$\sigma_a = \sigma_i - \sigma_0$$

Where, σ_a : actual tension acting on the section.

σ_i : tension action on the section under the tensile condition.

σ_0 : initial tension of section.

(a) Initial tension of section in the yarn model. (b) Tension of section under the tensile condition.

Figure 3.12. Tension of section in the yarn model with their curvatures.

3.5. Determination of strain value in the loop model

The strain value of the loop model was determined considering the dimensional changes of x, y, z coordinates of the loop model under the tensile condition. When the dimensions of the loop model were changed under the tensile condition, its strain values in the respective dimensions were determined. Then the resultant strain values of the loop model were determined considering dimensional changes of the loop model as follows;

$$e = \sqrt{e_x^2 + e_y^2 + e_z^2}$$

e_x : Strain value acting on the loop model under the tensile condition in the x-coordinate.

e_y: Strain value acting on the loop model under the tensile condition in the y-coordinate.

e_z: Strain value acting on the loop model under the tensile condition in the z-coordinate.

e: Resultant strain acting on the loop model.

3.6. Flow chart of simulation of loop model

The aspects of simulation for the loop model was shown by the flow chart diagram as shown in Figure 3.14.

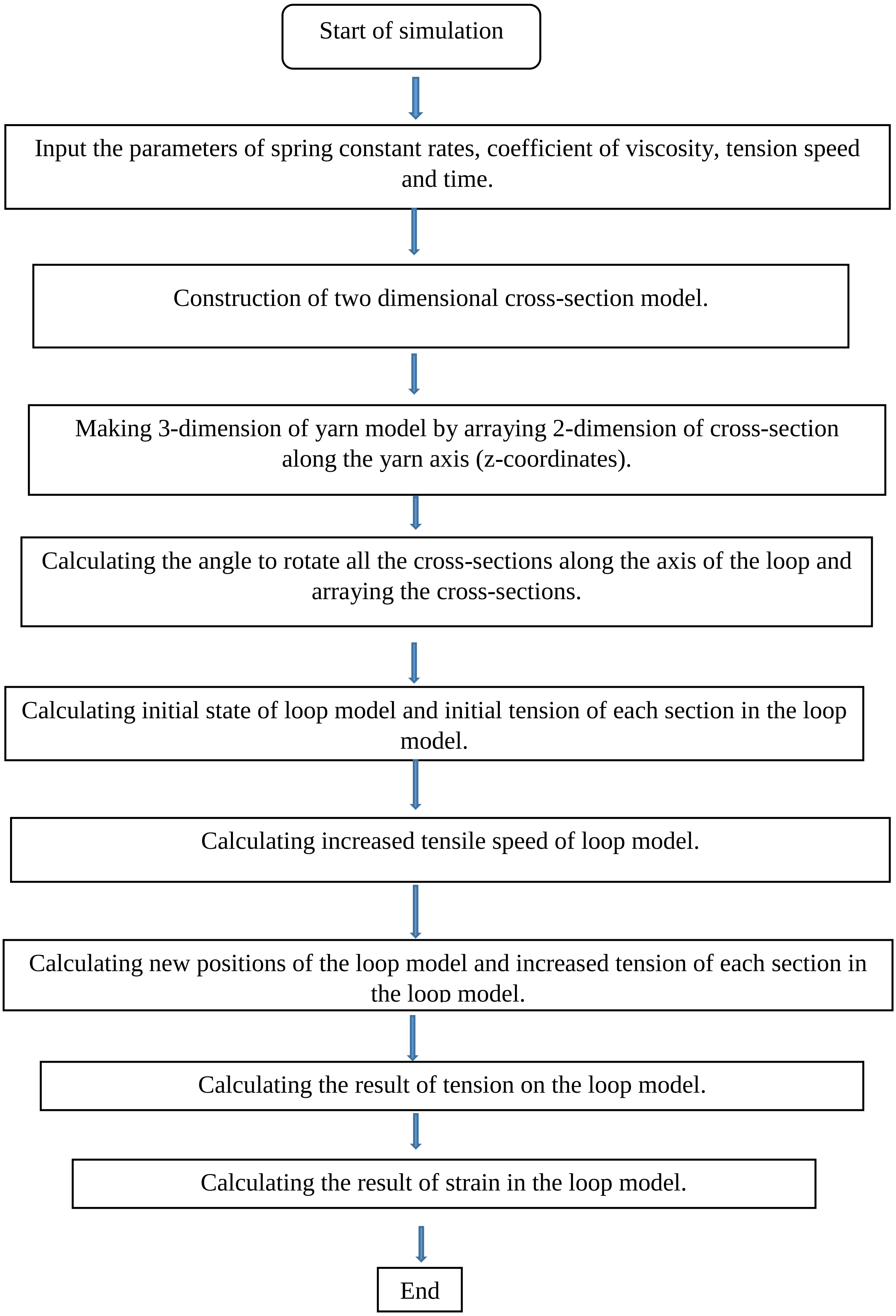


Figure 3.13. Flow chart of simulation aspects for tensile the loop model.

Chapter 4 Deformation behaviour and properties of the model in bending condition

4.1. Bending the model

The loop model was considered to be bent in both face side and back side. One of the edge of the loop model was considered to be fixed and the other edge of the model was considered to be gradually increased bending. In order to express this behaviour of bending, the positions of all the sections were considered to be changed according to their curvatures in bending.

4.1.1. Bending the loop model along the course

When bending the loop model along the course, it was considered to change the dimensions in the course (z-coordinate) and thickness (x-coordinate) according to its 3-dimension. The dimensions of the model in the wale (y-coordinate) was not changed while in bending. The loop model was bent within the +2.5 and -2.5 curvatures. As shown in the Figure 4.1, one edge of the loop model was bent in various curvatures and the other parts of the loop model were also with the different curvatures at the same time.

Before the bending condition, the loop model would be in the straight form and at that initial condition, the curvature of all the sections were zero. And then the loop model was bent using the certain amount of the bending speed which turn in gives the edge of the curvature of the loop model in the simulation program. When the edge of the curvature of the loop model was changed, the curvature of the other sections in the loop model were also changed. By this way, the loop model was bent between the curvature of (+2.5) and (-2.5). In order to express the behaviour of the loop model in the bending along the course condition, the following procedures were made to express the sections in the loop model with the different curvatures and different new positions during bending;

1. The curvatures of the edge of the section in the loop model were firstly defined.

2. And then the curvature of non-edge of the sections in the loop model were determined according to the formulae.

3. By using the curvature of the edge and non-edge of the sections, the new positions of all the sections were determined.

By this way, the behaviour of the loop model bending along the course were simulated in the program. The curvature of the edge of the sections during increasing in bending conditions were defined in the simulation program by inputting the bending speed. Then the change of the positions or new positions of the edge of the loop model in the x and z-coordinates were determined by the formula (4-1).

$$\left.\begin{aligned} x &= \frac{1-\cos k}{k} \\ z &= \frac{\sin k}{k} \end{aligned}\right\} \quad 4\text{-}1$$

z : New position of mass point in the edge according to its curvature.

x : New position of mass point in the edge according to its curvature.

k : Curvature of the section at the edge.

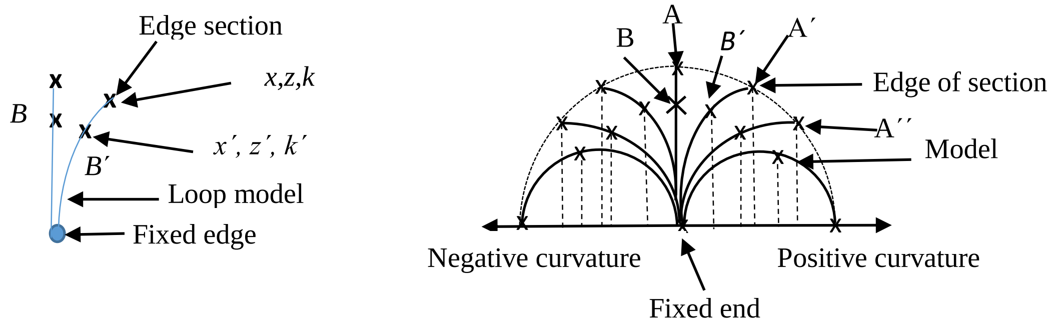


Figure 4.1. Different curvatures and new positions loop model in bending.

The different curvatures and their new positions of the other mass points in the loop model were calculated by the formula (4-2) and (4-3).

$$K' = K \times l / \mathrm{L} \qquad (4\text{-}2)$$

K' : Curvatures of the non-edge of the mass points.

K : Curvature of the edge of the section.

l : Length of the mass point from one edge to the desired section in the course-direction (z-coordinate).

L : Total length between the two edges of the sections in the course-direction (z-coordinate).

After calculating the curvatures of non-edge of the mass-points (K'), the change of positions or new positions of the mass point in the course (z-coordinate) and thickness (x-coordinate) was calculated by the formula (4-3).

$$\left.\begin{aligned} x' &= \frac{1-\cos K'}{K'} \\ z' &= \frac{\sin K'}{K'} \end{aligned}\right\} \quad 4\text{-}3$$

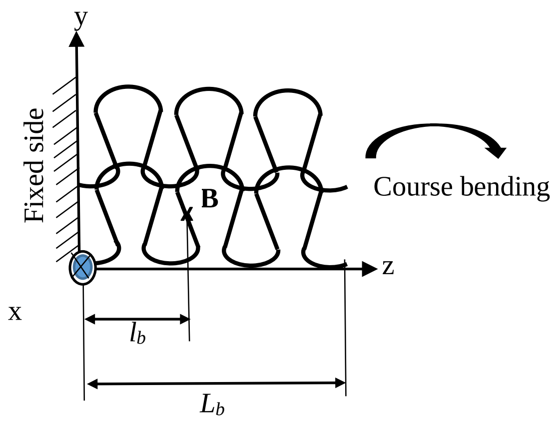


Figure 4.2. The required lengths for the determination of curvature in bending the loop model.

Referring to the Figure 4.1 and 4.2, the change of position or new position of the mass-points B′ when bending the course can be determined as follows;

For the new position of *B′*,

$$K' = K \times l_b/L_b$$

$$x' = \frac{1-\cos K'}{K'}$$

$$z' = \frac{\sin K'}{K'}$$

In here, *K* was the edge of the curvature of A′ in Figure 4.1 which was defining by means of bending speed in the simulation program. While the model was being gradually bending in the simulation program and consequently the change of curvature of non-edges of the model and their new positions were determined according to the respective formulae. By this way, the loop model can be shown its bending condition in the course within the positive and negative curvatures. In the simulation of the model, it was the straight form at the initial condition which was no curvature and then it will be bent gradually according to the positive curvature up to the limit i.e., +2.5 in the simulation program. When the model was its limited positive curvature, it will stop and move back to the initial condition. After that it will be bent gradually according to the negative curvature up to the limit i.e., -2.5 in the simulation program. When the model was its limited negative curvature, it will stop and move back to the initial condition. By this way, the model can be simulated both face-side and back-side bending.

4.1.2. Bending the loop model along the wale

When bending the loop model in the wale, it was considered to change the dimensions in the wale (y-coordinate) and thickness (x-coordinate) according to its 3-dimension. The dimensions in the course (z-coordinate) was not changed while in bending. The loop model was bent within the +2.5 and -2.5 curvatures.

At first the loop model was in its initial position and the curvatures of all sections in the model was zero at that condition. After that the loop model was bent within the positive and negative curvatures with the values of (+2.5) and (-2.5). In order to express the bending condition of the model, change of their positions or new positions were determined according to the formulae. In the simulation, the curvature of edge of the model was defined and also the position of the edge of the model was determined according to the formula (4-4).

$$\left.\begin{aligned} x &= \frac{1-\cos k}{k} \\ y &= \frac{\sin k}{k} \end{aligned}\right\} \quad (4\text{-}4)$$

In order to determine the new positions of non-edge of the model while bending, the curvature of non-edge of the sections were firstly determined by the formula (4-5).

$$K' = K \times h / \mathrm{H} \qquad (4\text{-}5)$$

K' : Curvatures of the non-edge of the mass points.

K : Curvature of the edge of the section.

h: Length of the mass point from one edge to the desired section in the wale-direction (y-coordinate).

H : total length between the two edges of the sections in the wale-direction (y-coordinate).

After determining the curvatures of non-edge of all sections in the model, their new positions while in bending were determined by using their respective curvatures according to the formula (4-6).

$$\left.\begin{aligned} x' &= \frac{1-\cos K'}{K'} \\ y' &= \frac{\sin K'}{K'} \end{aligned}\right\} \quad (4\text{-}6)$$

Referring to the Figure 4.1 and 4.3, the change of position or new position of the mass-points B′ when bending the wale can be determined as follows;

For the new position of B',

$$K' = K \times h_b/H$$

$$x' = \frac{1-\cos K'}{K'}$$

$$y' = \frac{\sin K'}{K'}$$

By this way, the loop model was expressed its changing positions while in bending conditions.

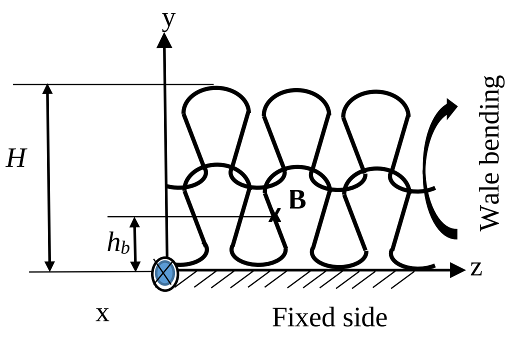


Figure 4.3. The required lengths for the determination of curvature in bending the loop model.

4.1.3. Determination of tension in bending the loop model

The tension of the loop model was determined by their change of curvatures while bending and spring value according to the formula (4-7). As mentioned before, the properties of the loop model was described by means of properties of yarn according to the loop structure. The spring constant was derived from the moment-curvature graph of the yarn bending test examining by the experiment and this value was applied.

$$\sigma_b = k_2 \times k' \qquad (4\text{-}7)$$

σ_b : Tension of the loop model in bending.

k_2: Spring value.

k' : Difference curvature of each section under the bending condition.

4.2. Bending test of sample by KES system

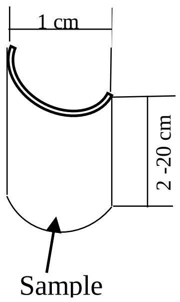
In the KES system, the bending test is done based on pure bending between the curvatures of (+2.5) and (-2.5) with the constant rate of curvature 0.50 (cm^{-1})/sec. The effective dimension

Figure 4.4. Pure bending tester of KES-F2.

of the specimen is 2.5 cm long and 1 cm in width mounted vertically to prevent the effect of gravity influencing the experiment. One end of the specimen was clamped in one chuck and another end was also clamped in the movable chuck which rotate within (+2.5) and (-2.5) curvatures. The system can bent the sample both face side and back side in both wale and course direction within the specified curvatures and the resultant curve is recorded by means of curvature and bending moment. The two characteristic values are used to define the bending properties of the fabrics, namely; B and 2HB. The former means bending rigidity per unit length and the latter is moment of hysteresis per unit length. Bending rigidity (B) represents the resistance of fabric against flexion. Bending hysteresis (2HB) demonstrates the ability of a fabric to recover after bending and the smaller the (2HB), the better the bending recovery of the fabric will be. Figure 4.6 shows the bending property of KES system.

The value of bending rigidity (B) can be determined from slope of the moment-curvature curve (M-K curve) diagram between the positive curvature of (0.5) and (1.5) for face side bending, and between the negative curvature of (-0.5) and (-1.5) for back side bending respectively. And also, the value of bending hysteresis can be determined from the hysteresis width of the moment-curvature curve diagram between the positive curvature of (0.5) and (1.5) for face side bending and between the negative curvature of (-0.5) and (-1.5) for back side bending respectively.

The specimen of cotton fabric with the wale and course density of (6.67 ×8.33) was laid 24 hours at the standard condition prior to testing and set between the two chucks as shown in Figure 4.5. Before testing, the operation was checked its oscillation and balanced condition. After that the operation was started and the face side of the specimen was bent between the positive curvatures and the back side of the specimen was bent between the negative curvatures and the curve was recorded by the recorder as shown in Figure 4.7 and from this curve, the force and curvature of the specimen while bending can be determined.



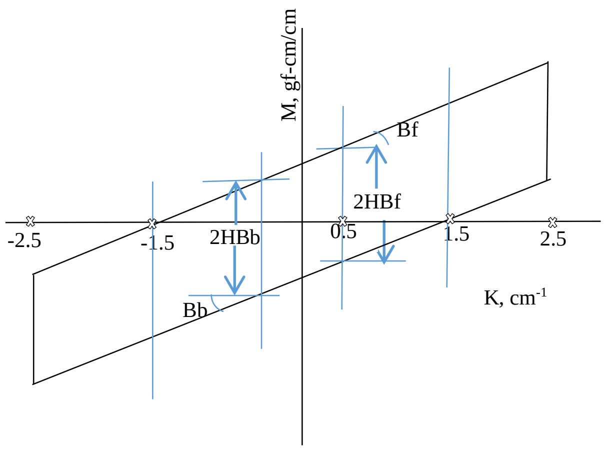
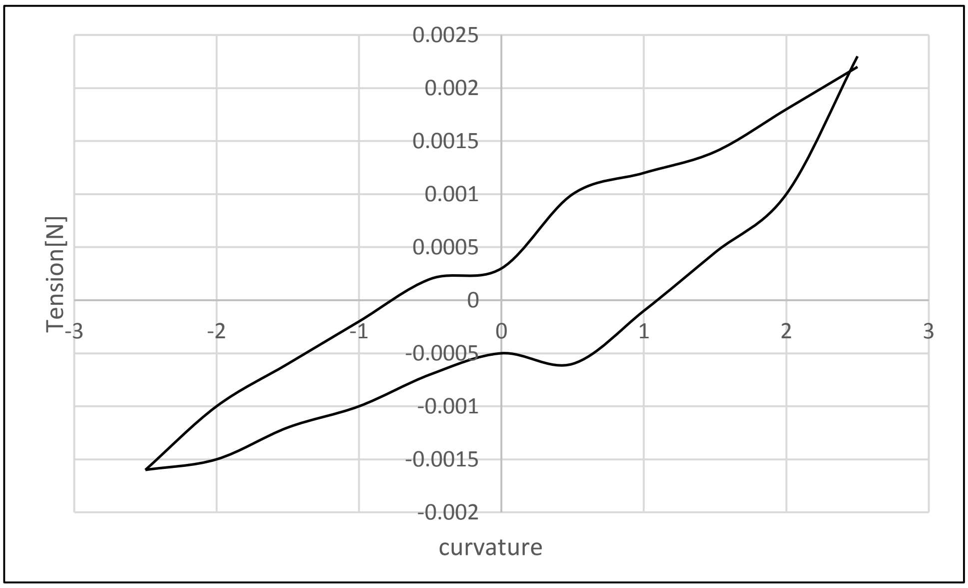
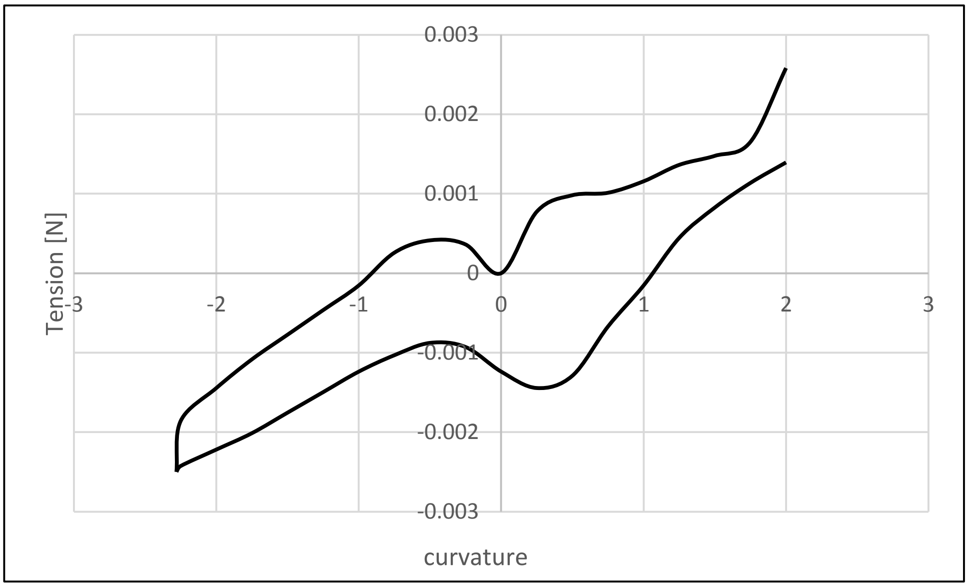


Figure 4.5. Bending property of KES system.

The appearance of the weft-knitted plain fabrics have difference appearance due to its structure forming the rib-like structure on the technical face side which is more smooth-surface than the technical back side. The technical back side has curling appearance so more rough than that of the technical face side. When bending in the technical face side and back side, the moment-curvature curve was difference in appearance in the face side and back side bending and this may be due to the difference surface appearance of the weft-knitted plain fabrics. When setting the sample in the bending tester, some difficulties were encountered because of edge-curling of the sample.



(a) Course bending

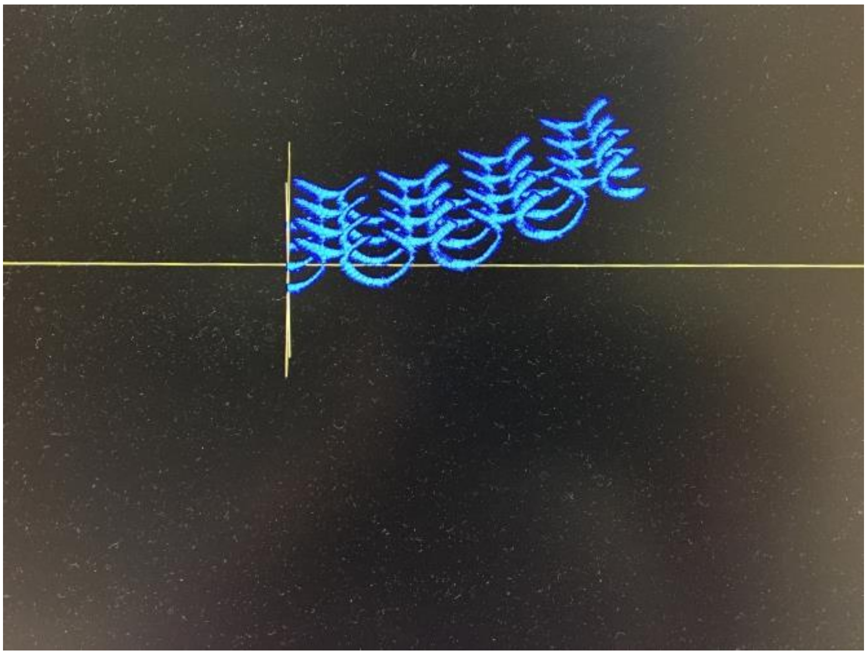


(b) Warp bending

Figure 4.6 Bending curve of the sample by KES system.

4.3. Bending simulation of the loop model

The loop model was simulated for bending within the curvatures of (+2.5) and (-2.5). The parameters of wale and course density, wale and course spacing, warp or course bending and bending speed were defined to simulate the model. By starting the simulation, the loop model showed its bending from one edge that was edge of curvature of the loop model. The loop model will be bent gradually within the specified curvatures. While bending the loop model, it was considered to maintain the construction of the yarn structure. Therefore, the cross sections were considered to be perpendicular while the loop model was being gradually bending. This was implemented by using based on the quaternion formula which can be applied for the rotation of three dimensions. The images of simulation of loop model were shown in Figure 4.7 and 4.8.



Simulation parameters
-wale density (6.67/cm)
-course density (8.33/cm)
-yarn count (559.86 dtex)
-curvature (+ 2.5 to – 2.5)

Figure 4.7. Image of course-bending simulation of loop model.

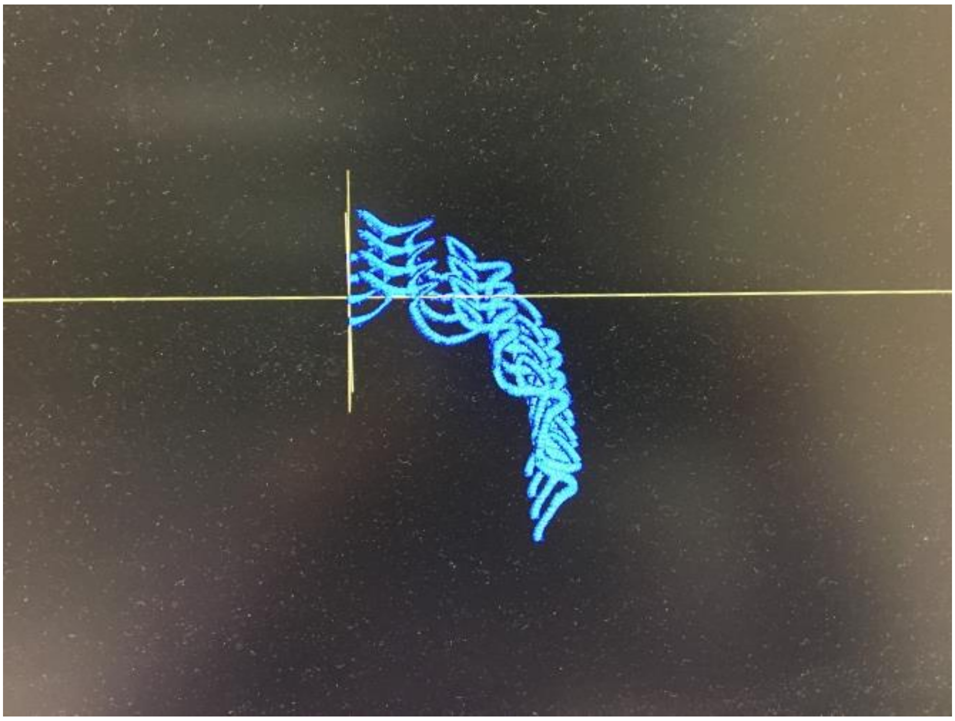


Figure 4.8. Image of course-bending simulation of loop model.

4.4. Flow chart of simulation of loop model for bending

The aspects of simulation for the yarn model was shown by the flow chart diagram as shown in Figure 4.9.

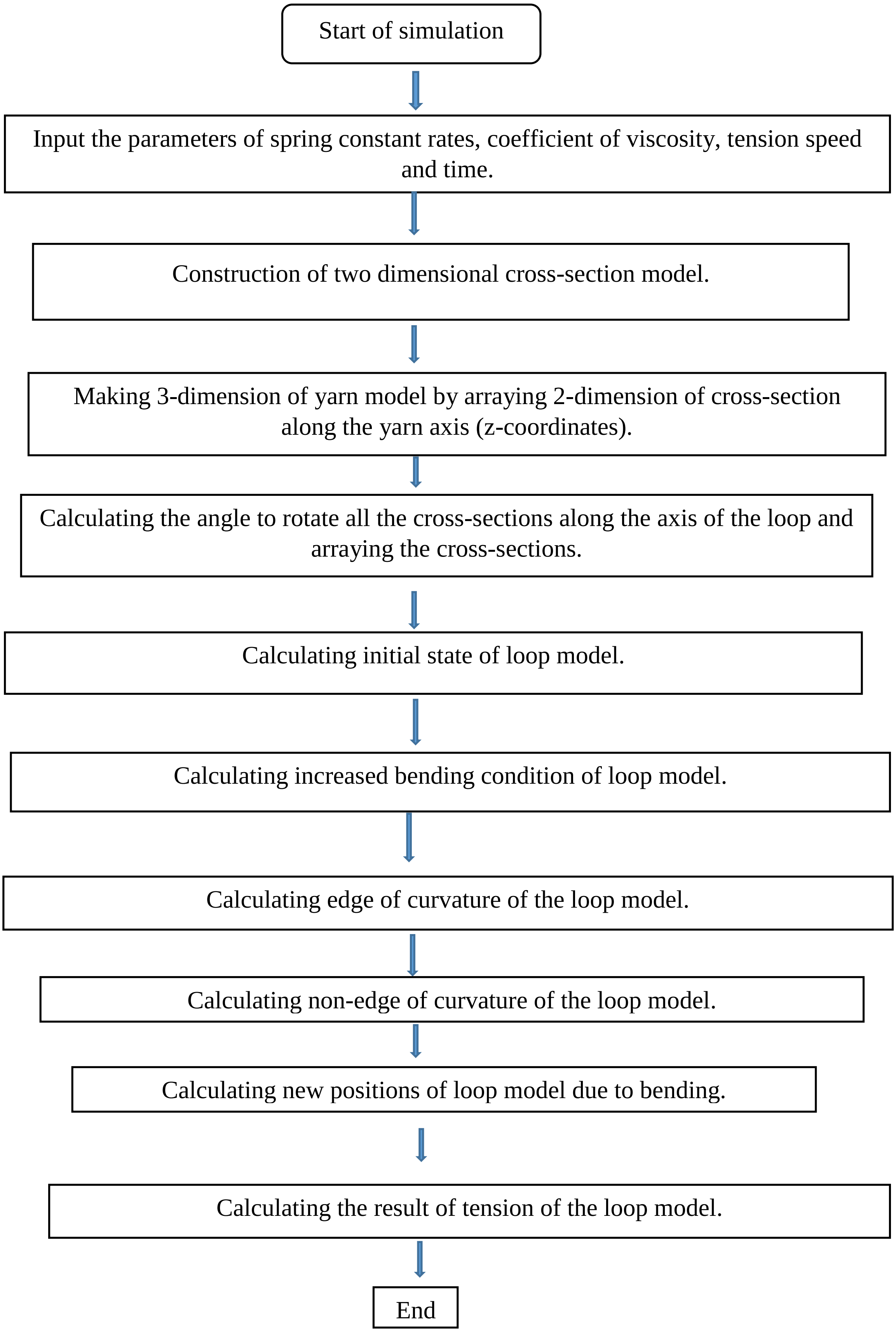


Figure 4.9. Flow chart of simulation aspects of loop model for bending.

Chapter 5 Evaluation of the loop model

5.1. Evaluation with Kawabata Evaluation System (KES system)

Kawabata evaluation system is widely used for the determination of mechanical properties of fabrics although it is intended for determination of hand values of fabrics. The main groups of properties used in KES system are tensile, bending, surface, and shearing. In the tensile test, the specimen (20cm×5cm) is applied the tensile force in one direction to the maximum limit of 500 gf/cm using the constant strain rate with 4.00×10^{-3} /sec. The three characteristic values are used to define the result of the tensile properties of the fabric namely; linearity (LT), Tensile energy per unit area (WT), and Resilience (RT). Tensile linearity describes the elasticity of the fabric; the higher the (LT) value the stiffer is the material. Tensile energy (WT) is the work done during stretching of the fabric, and a greater tensile energy value shows a higher tensile strength of the fabric. Tensile resilience (RT) indicates the ability of the fabric to recover the work done after it is being elongated. Higher tensile resilience of the fabric means higher ability to recover the work done after being elongated.

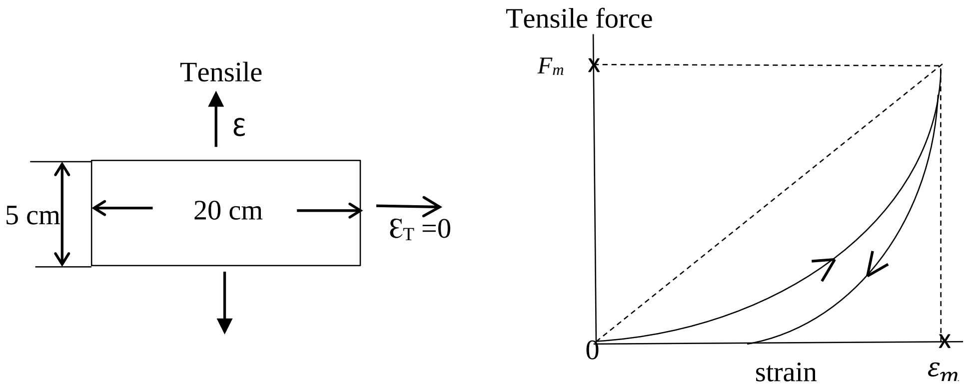


Figure 5.1. Tensile test in KES system.

In here,

$$WT = \int_0^{\varepsilon} F d\varepsilon$$

ε = tensile strain,

F = tensile force per unit width. (gf/cm),

$$LT = \frac{WT}{\frac{1}{2}F_m\,\varepsilon_m}$$

F_m = maximum value of force.

ε_m = maximum value of strain.

$$RT = \left(\frac{WT'}{WT}\right) \times 100$$

WT' = recovering energy per unit area and it can be defined as

$WT' = \int_0^{\varepsilon_m} F' d\varepsilon$

F' = tensile force in recovering process. (gf/cm)

The cotton knitted fabric of plain stitch (590.5 dtex) was tested to evaluate the loop model. The specifications of the model was as shown in table 5.1. The material was cut into 20×20 cm to be tested. The sample was put in the standard condition (20̊ C and 65%R.H) about 24 hours prior to making experiment. The sample was mounted in the Tensile testing instrument (KES-FB 1) and 20 g of pre-tension was applied on the sample before starting the operation. The specimen was cramped by two chucks of 20 cm long by setting the course direction of the sample perpendicular to the chucks so as to measure the tensile properties in the course direction. Before testing, the operation was checked its oscillation and balance.

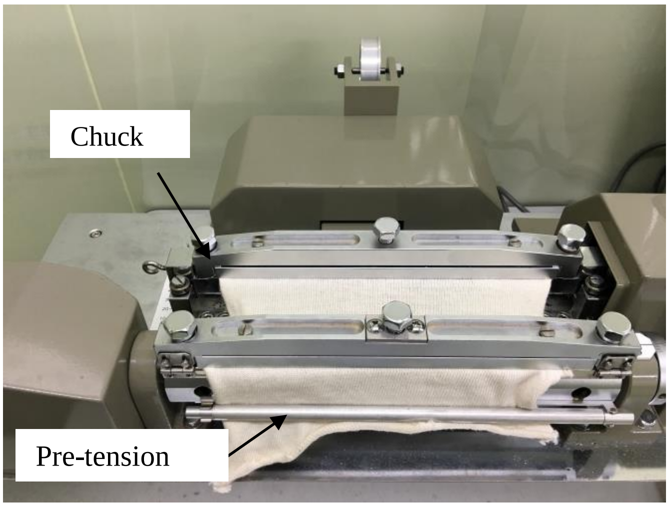


Figure 5.2. Tensile tester of KES-F-1.

By operating the instrument of KES-FB 1, the sample was exerted by a tensile force gradually up to 500gf/cm. The strain rate was kept constant at the 4.00×10^{-3}/sec. After loading the sample to its maximum tensile load, it was recovered again to its original position, and the force-strain curve was recorded by the X-Y recorder as shown in Figure 5.3 and the characteristics values for tensile properties can be calculated.

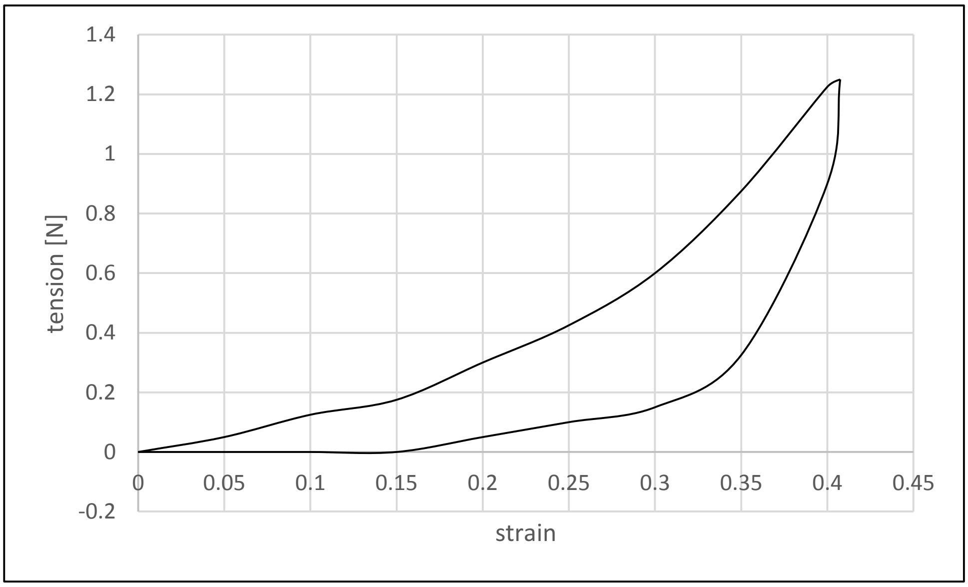
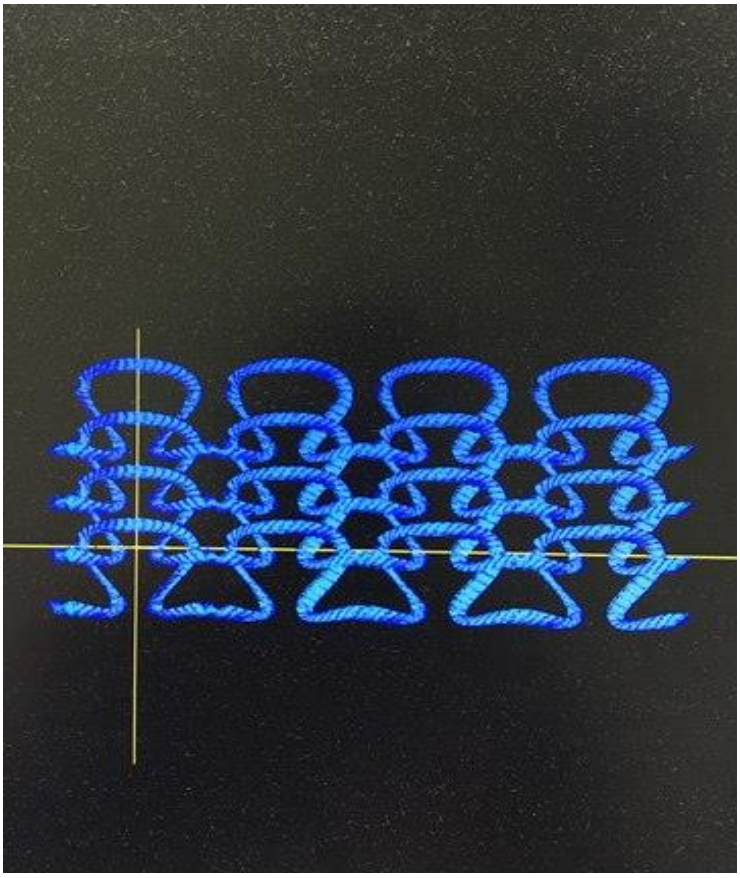


Figure 5.3. Force-strain curve of the sample by KES system.

And also the tensile properties of the loop model was simulated by defining wale density, course density, yarn diameter, wale spacing and course spacing, tensile speed and maximum strain limit. By simulation the program, the model was extended changing its knitted construction up to the specified limit strain value. Then the model would be recovered to its initial strain value (i.e., zero). The values of tension and strain were determined in both loading and recovering processes. Figure 5.4 shows the simulated images of the loop model. The obtained result of experiment and simulation of the sample was compared in Figure 5.5.

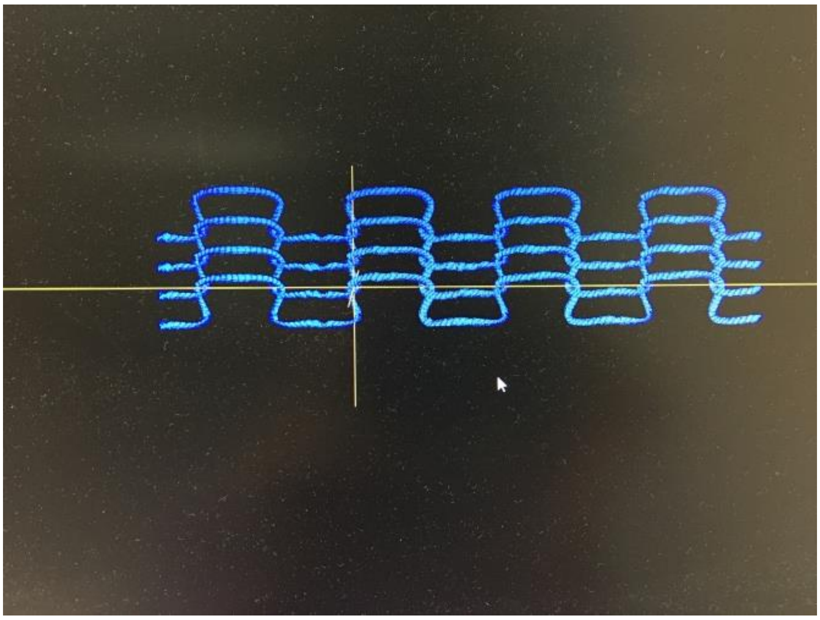
Table 5.1. Specifications of the sample.

yarn count (dtex)	wale density (/cm)	course density (/cm)	wale spacing (cm)	course spacing (cm)	yarn diameter (cm)	loop length (cm)	tightness factor	remark
590.5	6.67	8.33	0.1667	0.1250	0.0417	0.6917	11	plain stitch, slack fabric



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).

(a) Initial state of model.



(b) Deformed state of model.

Figure 5.4. Images of plain weft-knitted model in tensile condition.

At the start of the simulation, by inputting wale and course density, the other parameters such as wale spacing, course spacing, and yarn diameter can be consequently defined according to the formulae. The other input parameters were tension speed, time step, tensile direction (wale or course direction) and also, the limited strain value was put so as to compare the values with the KES system. The loop model was moved or deformed in the simulation program according to the direction of tensile exerting, and from the initial length and extended length of the model, the strain values were determined. When the out-coming strain value of the model was similar to the limited strain value of inputting data, the loop model was stopped and recovered to its initial position.

By simulation the loop model can show its loading and recovering processes by means of its respective tension and strain values. In the KES system, the tension value of the sample was gradually increasing to its maximum force in the loading process and gradually decreasing in the recovering process. There was a hysteresis phenomenon apparently between the loading and recovering process in the KES system. In the simulation the hysteresis effect was little and this may be lack of consideration about the friction within the yarn at the jamming of loop structure in the deformation process which would be considered in the next step.

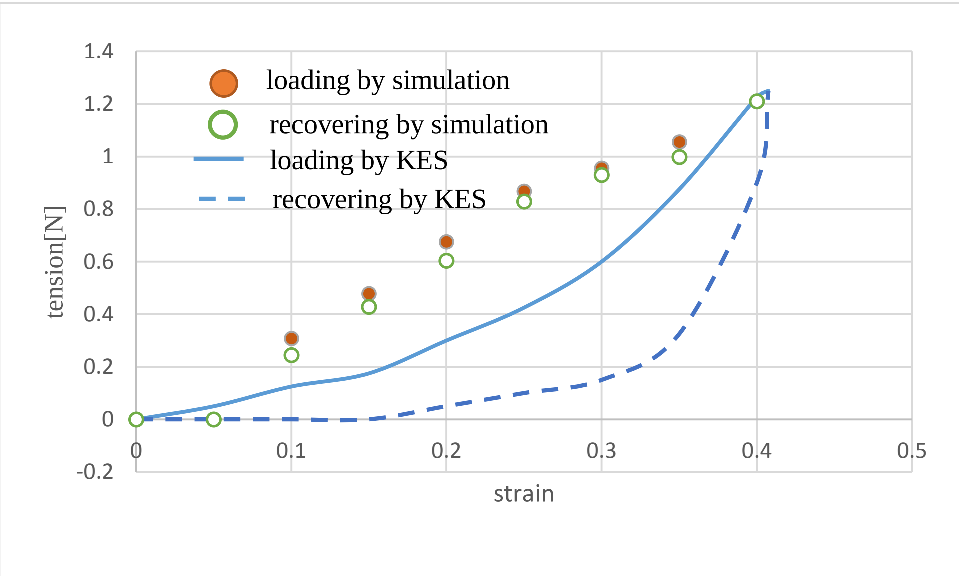


Figure 5.5. Comparison result of simulation and experiment.

Chapter 6 Conclusions

Generally textile materials are variable materials and so the properties of the textile fabrics are also different according to their structures; weaving, knitting and non-woven form. Of these, the knitted fabrics are widely used in apparel and also in the technical textile fields, and so the prediction of the mechanical properties of knitted fabrics become an important role in the production of knitted fabrics with the desired properties for various end-uses. There are many commercial instruments in the textile fields to determine the various properties of the textile materials. In order to produce the products with the desired properties is very important for the textile industries to be fulfil their consumer's requirements matching with the products. There have been still trying many models for weft knitted fabrics; most of the models are intended to predict the designs with the specifications of the knitted fabrics before producing the material in the industry. Some researchers described the mechanical properties of the knitted fabrics by applying with the complex formulae and many constraint factors difficult in practical applications. Therefore, we tried the three dimension loop model for knitted fabric which can show its mechanical properties for both loading and recovering processes under the tensile condition. In here, the mechanical properties of loop model was expressed depending on the mechanical properties of the yarn model.

When constructing the yarn model, it was considered to implement the yarn model with the fibres by examining the cross-section of the yarn. So the yarn model was firstly made with the cross-sections lying throughout the length of the yarn axis. In here, the cross-section was made with the mass-points setting them as the closed-package form by adjusting the dimensions within the mass-points so as to match with the dimensions of the cross-section of the real yarn. In the closed-package structure, all the mass-points were set by touching each other in order to give a hexagonal shape in the yarn cross-section. Some kinds of springs were considered to put within the mass-points so that the yarn model can show its mechanical properties and represent with the real yarn model. And consequently the structure of the yarn model was considered to be converted into the loop form, so the loop can be supposed as the real loop structure and can be determined the mechanical properties of the knitted loop model under deformation conditions.

All the cross-section was made with the mass-points in two dimensions and then all the cross-sections were located along the length of the yarn by changing their positions from one cross-section to the next section so as to appear one twist of the shape along the length of the yarn model. The tension spring was connected between the two mass points and bending spring was connected within the three mass points to determine the result of tension when the model was under the deformation process. After setting all the cross-sections along the length of the yarn axis, the three dimension of the yarn model was obtained. Otherwise, the yarn model can be constructed according to the idealised helical yarn structure. After getting the yarn model, it was simulated to express its behaviour under the tensile condition. The yarn model can show its extension up to the specified strain value and, after that recover to its initial position. By simulation the yarn model, its mechanical properties can be evaluated with the result of experimental one.

The loop model was constructed by considering the yarn structure combined with the geometric structure of the loop model. The loop parameters such as wale spacing, course spacing and yarn diameter can be defined via wale and course density in the simulation program. In the transformation of straight yarn model to loop model, all the cross-sections have to be transformed according to the loop form. In order to do that, all the cross-sections were inclined to be perpendicular along with the axis of the loop model. The two-inclined angles were determined to transform the cross-section to be perpendicular along with the axis of the loop model. By this way, the loop model can be constructed considering with the loop parameters. After getting one loop model, a series of loop can be connected according to the wale spacing and course spacing by defining the amount of number of wales and courses in the simulation program. Finally the three dimension of knitted loop model for plain stitch was obtained.

The loop model was considered to express its mechanical properties in the tensile and bending conditions. In here, we considered to determine the properties of the loop model by means of changing of knitted construction. So, the way of behaviours of the loop model was considered under the tensile condition. When considering the tensile condition of the loop model, the construction of the knitted structure was mainly considered to be changed in order to show its deformation behaviour. In the tensile condition, we considered that the curved yarn would be firstly changed into the straight form i.e., the deformation of the construction change in the knitted loop structure and after that the deformation would be due to yarn deformation according to its properties. In this first step, we considered to simulate the deformation of the loop structure and therefore, some hypothesis were made to express the constructional change of knitted loop structure according to the tensile condition in the wale and course direction. By using some formulae, the loop model can be simulated its construction change of loop structure in the wale and course direction and consequently, the value of tension and strain can be determined from these changes of loop structure model. By simulation, the knitted model can show its deformation behaviour for both lading and also recovering processes, and the values of tension and strain can be determined for both processes.

As mention above, we also considered the loop model to be expressed the way of its bending. The bending behaviour of the loop model was expressed depending on the curvature of loop model while bending. The positions of the cross sections in the loop model was changed according to their change of curvature in bending process.

When evaluating the loop model by simulating its tensile condition in the course direction, the tendency of increasing and decreasing in the loading and recovering processes was the same with the experimental one by KES system. In the simulation, it was found that the tension values were more than that of the experimental result and the hysteresis effect (or) the difference between the loading and recovering processes was not as much as the experimental one. Therefore it can be considered that there would be other factors to be accounted in the constructional changing of the loop structure. In this simulation, we did not considered the friction within the yarn which may be found at the contact point of the interloping of the connected loop or at the jamming condition.

In the conclusion of aspects with this model, the knitted loop structure can be constructed with the structure of the cross-sections of yarn containing the fibres. In this case, the mechanical properties of loop model was described on the properties of yarn model describing the discrete type of the cross sections. The model can be simulated its deformation behaviour with the visual effects. And also, the model can show its mechanical properties in the loading and recovering processes of tensile condition. When using this model, it can be simulated within a short-time by a commercial computer. In the future, we expected that the model can be developed in the determination of mechanical properties of plain knitted fabric considering with some related factors in the deformation of the loop structure in various ways.

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