Part A: English Edition

Journal of Textiles and Polymers

Vol. 10, No. 3, 13-21, July 2022

ORIGINAL PAPER

Straight-Line Loop Models for the Basic Structures of Weft Knitted Fabric (Plain, Rib 1×1, and Interlock)

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Received: 9 June 2022, Accepted: 11 October 2022

***Abstract*- Considering the importance of straight-line model in fabric cells to model their mechanical properties, straight-line models have been developed to fulfill the geometry of plain, rib 1×1, and interlock weft knitted fabrics in 2D and 3D states. To verify the generated models, these fabrics were produced in three densities. The loop lengths of the produced fabrics were precisely measured and compared with the loop lengths calculated by models. The results showed that the straight-line model is capable of predicting the loop length of these fabrics.**

***Keywords*: plain weft-knitted fabric, rib 1×1, interlock, straight-line model, loop length**

NOMENCLATURE

d	Yarn diameter
d'	The image of thread diameter on horizontal axis
C	Course spacing
W	Wale spacing
l_{1p}, l_{2p}	Length of segment of stitch head for plain weft knitted
l_{3p}	Length of stitch shank for plain weft knitted
l_{4p}, l_{5p}	Length of segment of stitch feet for plain weft knitted
l_{3bp}	Length of stitch shank of plain weft knitted from the side view
$l_{2p\ 3D}$	Length of segment of stitch head for plain weft knitted in 3D situation
$l_{3p\ 3D}$	Length of stitch shank for plain weft knitted in 3D situation
L_{Tp}	A loop length of plain weft knitted
l_{1fR}, l_{2fR}	Length of segment of stitch head for front needle bed loop for rib 1×1
l_{3fR}	Length of stitch shank of front needle bed loop for rib 1×1
l_{4fR}	Length of stitch feet of front needle bed loop for rib 1×1
l_{1bR}, l_{2bR}	Length of segment of stitch head of back needle bed loop for rib 1×1
l_{3bR}	Length of stitch shank of back needle bed loop for rib 1×1
l_{4bR}	Length of stitch feet of back needle bed loop for rib 1×1
$l_{1fR\ 3D}$ $l_{2fR\ 3D}$	Length of segment of stitch head of front needle bed loop for rib 1×1 in 3D situation
$l_{3fR\ 3D}$	Length of stitch shank of front needle bed loop for rib 1×1 in 3D situation
$l_{4fR\ 3D}$	Length of stitch feet of front needle bed loop for rib 1×1 in 3D situation
$l_{1bR\ 3D}$ $l_{2bR\ 3D}$	Length of segment of stitch head of back needle bed loop for rib 1×1 in 3D situation
$l_{3bR\ 3D}$	Length of stitch shank of back needle bed loop for rib 1×1 in 3D situation
$l_{4bR\ 3D}$	Length of stitch feet of back needle bed loop for rib 1×1 in 3D situation
θ_{1p}, θ_{2p}	Angles of stitch head for plain weft knitted
θ_{3p}	Angles of stitch shank for plain weft knitted
φ_{1p}	Angles of stitch shank for plain weft knitted out of plane
φ_{1fR}, φ_{2fR} φ_{3fR}	Angles of front needle bed for rib 1×1 out of plane
φ_{1bR}, φ_{2bR} φ_{3bR}	Angles of back needle bed for rib 1×1 out of plane
l_{1fI}, l_{2fI}	Length of segment of stitch head for front needle bed loop of interlock
l_{3fI}	Length of stitch shank of front needle bed loop for interlock

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l_{4fl}	Length of stitch feet of front needle bed loop for interlock
l_{1bl}, l_{2bl}	Length of segment of stitch head of back needle bed loop for interlock
l_{3bl}	Length of stitch shank of back needle bed loop for interlock
l_{4bl}	Length of stitch feet of back needle bed loop for interlock
$l_{1fl\,3D}$, $l_{2fl\,3D}$	Length of segment of stitch head of front needle bed loop for interlock in 3D situation
$l_{3fl\,3D}$	Length of stitch shank of front needle bed loop for interlock in 3D situation
$l_{4fl\,3D}$	Length of stitch feet of front needle bed loop for interlock in 3D situation
$l_{1bl\,3D}$, $l_{2bl\,3D}$	Length of segment of stitch head of back needle bed loop for interlock in 3D situation
$l_{3bl\,3D}$	Length of stitch shank of back needle bed loop for interlock in 3D situation
$l_{4bl\,3D}$	Length of stitch feet of back needle bed loop for interlock in 3D situation

I. INTRODUCTION

Due to the complexity of fabric structures, their structure analysis is facing problems. Different methods such as force method, energy method, and finite element method have been used to investigate fabric mechanics [1-4]. On the other hand, knitting loop geometry is a key element in analyzing knitted fabrics structure. In the theoretical investigations of the dimensions of the knitted fabric, more emphasis is placed on determining the loop shape. The fabric dimension, on the other hand, is directly related to the dimensions of a unit cell defined by joining similar points of the loops in adjacent wales and courses [5].

The loop length is one of the basic parameters of a unit cell of fabrics that applies impression on most of the properties of the fabric.

Chamberlain (1926) [6] obtained the relationship between fabric dimensions and the loop length with a series of hypotheses. Pierce (1947) [7] developed the Chamberlain mathematical model and presented the loop length as follows:

$$L = 2c + w + 5.94d$$

Robert and Fletcher (1952) [8] experimentally examined the relationship between Pierce's theory and achieved the following relationship:

$$L = 2c + w + 4.56d$$

Munden (1959) [9], assuming that the loop structure also moves in the Z direction of space, was able to derive four non-dimensional parameters or K values that govern the dimensions of simple knitted fabrics.

Jeddi *et al.* (1999, 2006, 2007, and 2008) [5,10-13] developed theoretical ideal models for simple knitting loop and 1×1 gear structure based on a new approach related to geometrical and physical principles. Analyzes were introduced for two- and three-dimensional models. Ultrasonic waves were then used to reduce the potential energy of the fabrics to obtain the natural or ideal configuration of the knitting loop with minimal energy conditions. They then created this ideal model for the interlock structure and measured the non-dimensional parameters of the fabrics (Uc, Uw, and Us values) and compared them with theoretical values using conventional mechanical relaxation on interlock fabrics.

Dabiryan *et al.* (2019) [14] developed a geometric model for the Queens Cord fabrics, which is used to produce a mechanical model as a set of series and parallel springs. The unit cell of the straight line model was discretized into different segments and geometric relationships were presented for each section of the loop.

In this study, a new approach to predict the structure of plain fabric loops, rib 1×1, and interlock fabric loops, has been presented assuming straight lines. Finally, the proposed model is discussed with real fabric samples.

II. THEORETICAL LOOP MODELS

There are three basic structures in weft knitting (plain, rib 1×1, and interlock structures). Fig. 1 shows these structures along with their real photos.

Considering the deviation of loops, the schematic drawing in SOLIDWORKS 2020 program, shown in Figs. 2-4, can be proposed for modeling the geometry of plain, rib 1×1, and interlock in straight-line structures.

In order to investigate the dimensional properties of the unit cell, the loop length should be first calculated. For this purpose, we suppose that plain knitting has a loop for unit cell, and rib 1×1 and interlock knitting divide the unit cell into two main parts: front needle bed loop and back needle bed loop. In this case, we can say that the length of the unit cell (L) is equal to:

$$L = L_f + L_b \quad (1)$$

where L_f and L_b are the length of the front and back beds loops, respectively.

A. Plain Loop Model

A.1. 2D State of the Model

We suppose that the head of loop is similar to semi-

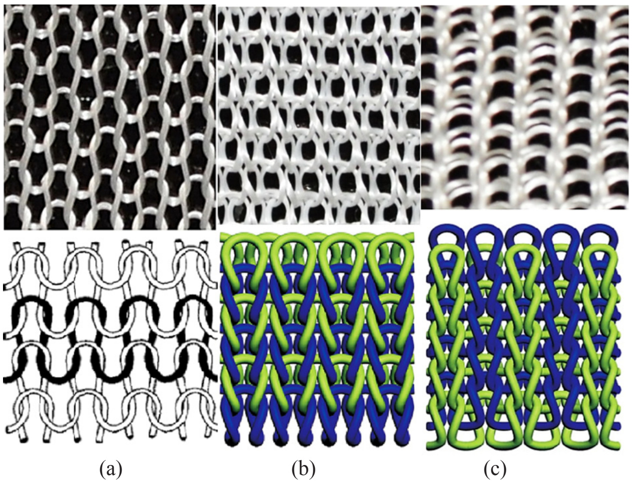

Fig. 1. Basic structures of weft knitted fabrics: (a) plain weft knitted structure [15], (b) rib 1×1 structure, and (c) interlock structure [16].

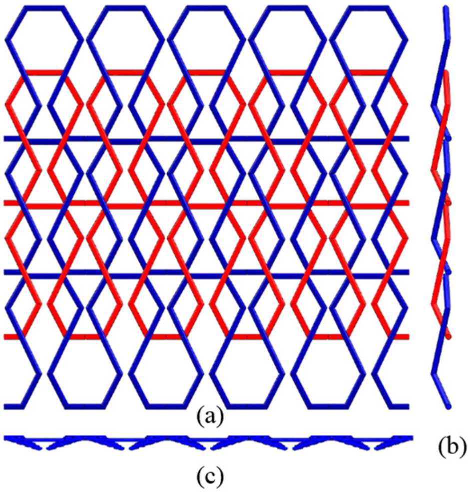

Fig. 2. Plain knitted straight-line structure: (a) front view, (b) side view, and (c) top view.

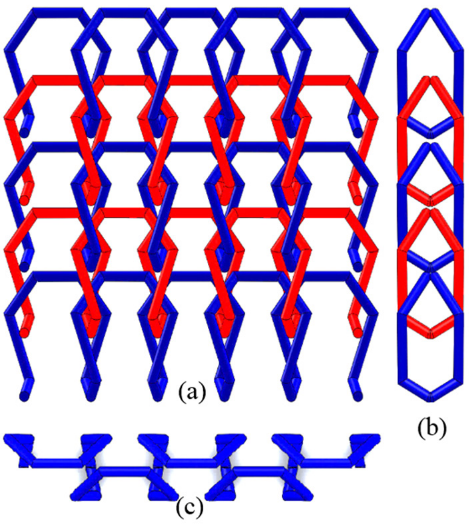

Fig. 3. Rib 1×1 straight-line structure: (a) front view, (b) side view, and (c) top view.

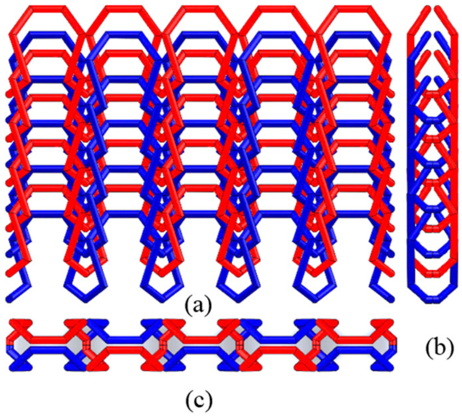

Fig. 4. Interlock straight-line structure: (a) front view, (b) side view, and (c) top view.

hexagonal (Fig. 5). There for l_{1p}, l_{2p}, l_{4p}, and $2l_{5p}$ are equal. If we look closely, we have an equilateral triangle that can be taken as the starting point of our modeling.

$$l_{1p} = l_{2p} = l_{4p} = 2l_{5p} = \left(\frac{W-d'}{2}\right) \tag{2}$$

According to Fig. 5, we have the following equations:

$$\theta_1 = \frac{\pi}{3} \tag{3}$$

$$\sin\theta_1 = \frac{d}{d'} \rightarrow d' = \frac{d}{\sin\theta_1} \tag{4}$$

According to Fig. 6:

$$l_{3p} = \sqrt{c^2 + d'^2} \tag{5}$$

$$\theta_2 = \cos^{-1}\left(\frac{C}{l_{3p}}\right) \tag{6}$$

$$\theta_3 = \frac{\pi}{2} - \theta_2 \tag{7}$$

Finally, the length of loop in 2D state is equal to:

$$L_{2D} = 6l_{2p} + 2l_{3p} = 3(W-d') + 2\sqrt{C^2 + d_2'} \tag{8}$$

A.2. 3D State of the Model

Due to the 3D nature of knitted fabrics, we should calculate the length of all sections in 3D state. A straight line model has been proposed for side view of unit cell, which shows the loops in 3 dimensions (Fig. 7).

As it can be seen in the 3D model, section l_{3p} makes an angle φ_1 with the longitudinal direction. Therefore, their

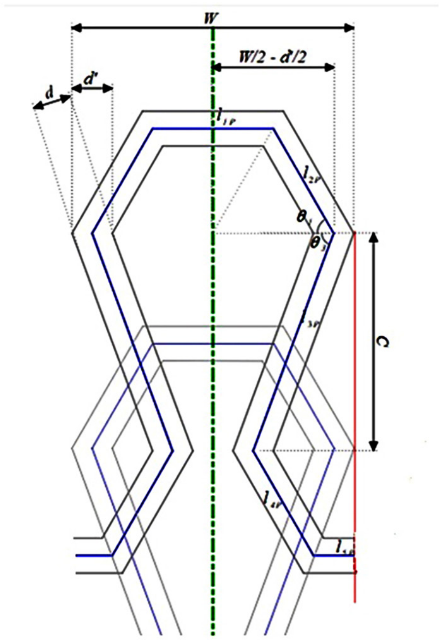

Fig. 5. Unit cell of plain structure.

lengths should be calculated in 3D state. For this purpose, we need to obtain aforementioned angles, which can be calculated as below:

$$l_{2b} = l_{2p} \times \cos(\theta_1) \tag{9}$$

$$\varphi_1 = \tan^{-1}\left(\frac{d}{l_{3b}}\right) \tag{10}$$

$$l_{3b} = l_{3p} \times \cos(\theta_2) \tag{11}$$

$$\varphi_2 = \tan^{-1}\left(\frac{d}{l_{3b}}\right) \tag{12}$$

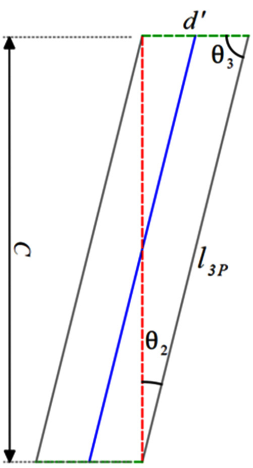

Fig. 6. Stitch shank.

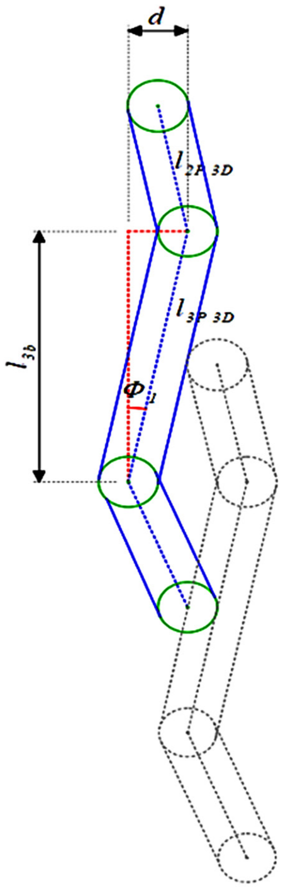

Fig. 7. Straight line model for the lateral view of the plain unit cell.

Thereafter, Eqs. (2), (5), and (8) are modified for the 3D state as follows:

$$l_{2p\ 3D} = \frac{l_{2p}}{\cos\varphi_1} \tag{13}$$

$$l_{3p\ 3D} = \frac{l_{3p}}{\cos\varphi_2} \tag{14}$$

$$L_{T\ 3D} = 6l_{2p\ 3D} + 2l_{3p\ 3D} = \frac{3(W - d') + 2\sqrt{C^2 + d'^2}}{\cos\varphi_1} \tag{15}$$

B. Rib 1×1 Loop Model

B.1. 2D State of the Model

The face loops in plain and rib structures are similar, i.e. consistent with the Smirfitt's assumption [16]. Therefore, in this part we can use the obtained equations in the first part, which is related to the plain knitted structure. The difference is that there is a linking portion between the face and back loops as given in the equation below (Fig. 8).

$$l_{4fR} = \frac{d'/2}{\cos\alpha} \tag{16}$$

As we know, the unit cell of rib 1×1 consists of the front and back loops, which are equal in value. Finally, the length of the loop in 2D state is equal to:

$$L_{TfR} = l_{1fR} + 2l_{2fR} + 2l_{3fR} + 2l_{4fR} \quad (17)$$

$$L_{TbR} = l_{1bR} + 2l_{2bR} + 2l_{3bR} + 2l_{4bR} \quad (18)$$

$$L_{TR} = L_{TfR} + L_{TbR} = \frac{3W + 2d' + 4\cos\alpha\sqrt{d'^2 + C^2}}{\cos\alpha} \quad (19)$$

B.2. 3D State of the Model

Due to the 3D nature of knitted fabrics, we should calculate the length of all sections in 3D state. A straight line model has been proposed for the side view of unit cell, which shows the loops in 3 dimensions (Fig. 9).

As it can be seen in 3D model, some sections such as l_{2fR}, l_{2bR}, l_{3fR}, l_{3bR}, l_{4fR}, and l_{4bR} make angles φ_{1fR}, φ_{1bR}, φ_{2fR}, φ_{2bR}, φ_{3fR}, and φ_{3bR} with the longitudinal direction, respectively. Therefore, their lengths should be calculated in 3D state. For this purpose, we have to obtain aforementioned angles, which can be calculated as below:

$$\varphi_{1fR} = \varphi_{1bR} = \tan^{-1}\left(\frac{d}{(W-d')/2}\right) \quad (20)$$

$$\varphi_{2fR} = \varphi_{2bR} = \tan^{-1}\left(\frac{d}{l_{3fR}}\right) \quad (21)$$

$$\varphi_{3fR} = \varphi_{3bR} = \tan^{-1}\left(\frac{d}{d'/2\cos\alpha}\right) \quad (22)$$

Thereafter, the 2D equations are modified to the 3D state as bellow:

$$l_{2fR\,3D} = \frac{l_{2fR}}{\cos\varphi_{1fR}} = l_{2bR\,3D} \quad (23)$$

$$l_{3fR\,3D} = \frac{l_{3fR}}{\cos\varphi_{2fR}} = l_{3bR\,3D} \quad (24)$$

$$l_{4fR\,3D} = \frac{l_{4fR}}{\cos\varphi_{3fR}} = l_{4bR\,3D} \quad (25)$$

The angle of linking portions between the face and back loops is represented by gamma (Fig. 10) as follows:

$$\gamma = \cos^{-1}\left(\frac{d'}{2l_{4fR}}\right) \quad (26)$$

$$\theta = \pi - \left(\frac{\pi}{2} - \gamma\right) \quad (27)$$

Finally, the length of loop in 3D state is equal to:

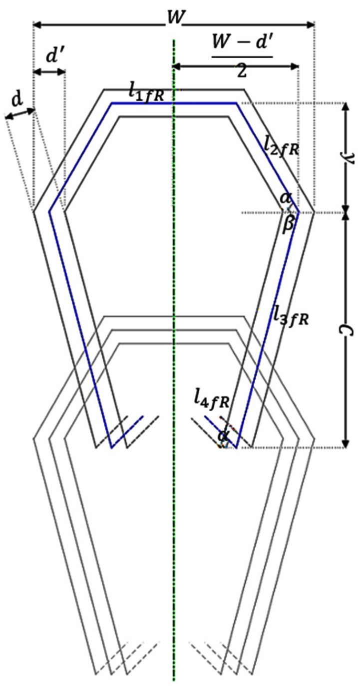

Fig. 8. Unit cell of rib 1×1 structure.

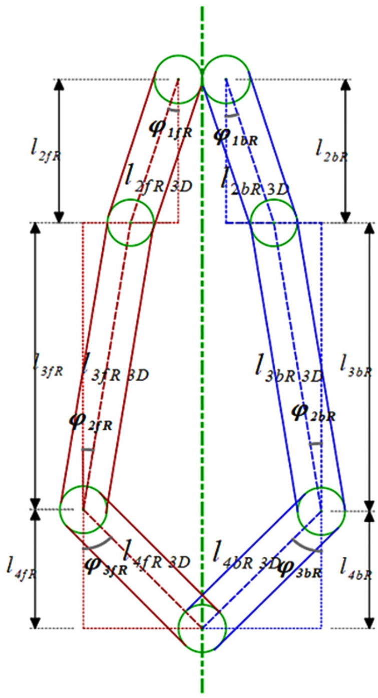

Fig. 9. Straight line model for the side view of the unit cell of rib 1×1.

$$L_{TfR3D} = l_{1fR3D} + 2l_{2fR3D} + 2l_{3fR3D} + 2l_{4fR3D} \quad (28)$$

$$L_{TbR3D} = l_{1bR3D} + 2l_{2bR3D} + 2l_{3bR3D} + 2l_{4bR3D} \quad (29)$$

$$L_{TR3D} = L_{TfR3D} + L_{Tb3D} = \left[\frac{(W-d')(\cos\varphi_1 + 2)}{\cos\varphi_1} + \frac{4\sqrt{d'^2 + C^2}}{\cos\varphi_2} + \frac{2d'}{\cos\alpha\cos\varphi_3}\right] \quad (30)$$

C. Interlock Loop Model

C.1. 2D State of the Model

The face loop in the plain and interlock structures is similar. In addition, the interlock loop model is very similar to the rib 1×1 loop, except that in the three-dimensional model, the linking portions between the face and back has a longer length and a different angle than the rib model. Thus the equations of the interlock loop in the two-dimensional state are quite similar to the Eqs. (2) to (7).

C.2. 3D State of the Model

Due to the 3D nature of knitted fabrics, we should calculate the length of all sections in the 3D state. The side view of this model is similar to that of rib 1×1 (Fig. 11). So we can use Eqs. (20) to (25) for this model.

As it can be seen in Fig. 11, the angle of linking portions between the face and back loops is represented by gamma:

$$\gamma = \cos^{-1}\left(\frac{W-d'}{2l_{4fl}}\right) \quad (31)$$

$$\theta = \pi - \left(\frac{\pi}{2} - \gamma\right) \quad (32)$$

Finally, the length of loop in 3D state is equal to:

$$L_{Tfl3D} = l_{1f3D} + 2l_{2fl3D} + 2l_{3fl3D} + 2l_{4fl3D} \quad (33)$$

$$L_{TbI3D} = l_{1bI3D} + 2l_{2bI3D} + 2l_{3bI3D} + 2l_{4bI3D} \quad (34)$$

$$L_{TI3D} = l_{TfI3D} + L_{TbI3D} \quad (35)$$

III. VERIFICATION OF THE MODEL

We used the structural data of a wide range of samples

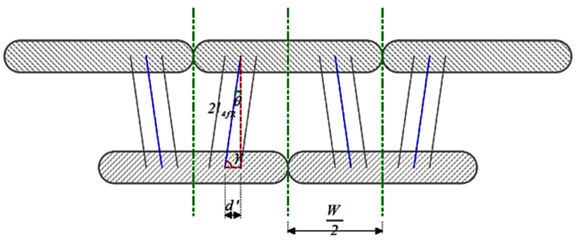

Fig. 10. Top view of the rib 1×1 loops.

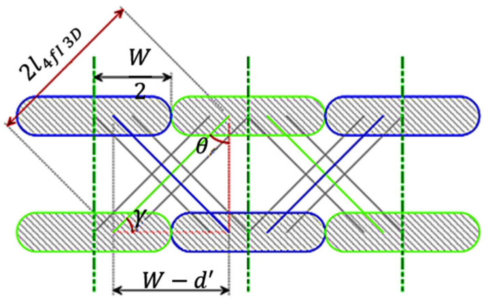

Fig. 11. Top view of the interlock loops.

(Table I) [17] to evaluate our plain model and compared it with the Chamberlain [6] and Pierce [7] models in Table II.

Based on the results from Table II, the average error of the proposed models is 7.71, 4.27, and 4.94% for Chamberlain, Pierce and straight line models, respectively. According to these results, the straight-line geometric model has a 2.77% more accurate prediction than the Chamberlain model, and also with a very small difference of 0.67%, it has a weaker prediction than the Pierce model. This shows that the accuracy of the straight line geometric model is good. To evaluate the accuracy of the generated models, Plain weft knitted, rib 1×1, and interlock fabrics were produced in three different densities using C-glass (99 tex) yarn on a 7-gage electronic flat knitting machine Stoll CMS330TC model. The structural details of the fabrics are given in Table III.

These fabrics were fixed during production on the machine by a stabilized liquid and then taken out of the machine.

In this research, a loop length is obtained by splitting a course of fabric and measuring the length in a smooth and undulating state and dividing the length obtained by the number of loops in that course. This operation is repeated three times for each sample type, and finally, the resulting loop length is related to an average loop of each texture structure.

The theoretical and experimental results of dimensional properties are given in Table IV.

Based on the results from Table IV, the average error rates on each of the plain, rib 1×1 and interlock fabrics are 11.35, 4.13, and 5.12 percent, respectively.

In order to better evaluate the proposed models, in addition to the data obtained in this research, data from other articles with different yarn diameters and materials such as cotton, glass, acrylic and wool have been used. The results were analyzed for an average loop length (Table V) [8,17-22].

The error rates from Table V for the plain, rib 1×1, and interlock fabrics are 2.49, 4.19, and 6.4 percent,

TABLE I
MAIN PARAMETERS AND MEASURED LOOP LENGTHS OF THE SAMPLES [17]

Sample	Yarn count Ne	Course density courses/inch	Wale density wales/inch	Yarn thickness (mm)	Loop length (mm)
1	1/30	26.6	32.6	0.190	3.912
2		31.2	34.4		3.416
3		35.5	34.2		3.122
4		37.9	33.8		3.040
5		40.9	33.9		2.926
6		44.8	36.7		2.746
7		26.9	31.5		3.866
8		32.6	33.0		3.432
9		37.2	34.1		3.109
10		41.6	36.7		2.972
11		42.9	37.0		2.870
12		48.2	37.1		2.715
13	1/12	18.6	21.5	0.330	5.664
14		20.6	22.5		5.187
15		23.9	23.3		4.836
16		28.4	23.4		4.315
17	1/20	17.7	24.7	0.235	5.364
18		20.6	24.3		4.968
19		23.6	26.4		4.470
20		27.9	28.1		4.001

TABLE II
COMPARISON BETWEEN DIFFERENT GEOMETRIC MODELS [17]

Sample	Chamberlain [17]	Percentage error [17]	Peirce [17]	Percentage error [17]	Straight line model	Percentage error
1	3.240	17.16	3.818	2.41	3.638	7.00
2	3.071	10.11	3.495	2.31	3.243	5.06
3	3.089	1.05	3.302	5.79	3.066	1.79
4	3.125	2.80	3.220	5.92	3.006	1.11
5	3.116	6.50	3.120	6.62	2.906	0.68
6	2.878	4.83	2.955	7.61	2.634	4.07
7	3.354	13.25	3.823	1.10	3.699	4.32
8	3.201	6.71	3.457	0.73	3.269	4.75
9	3.098	0.36	3.239	4.18	3.010	3.18
10	2.878	3.14	3.042	2.36	2.715	8.64
11	2.855	0.53	2.999	4.50	2.664	7.17
12	2.847	4.87	2.867	5.59	2.537	6.55
13	4.913	13.26	5.873	3.68	5.236	7.55
14	4.695	9.48	5.555	7.10	4.825	6.97
15	4.534	6.25	5.176	7.02	4.385	9.32
16	4.514	4.61	4.834	12.03	4.058	5.95
17	4.277	20.27	5.294	1.31	5.191	3.22
18	4.347	12.50	4.907	1.23	4.847	2.43
19	4.001	10.49	4.511	0.90	4.292	3.98
20	3.759	6.03	4.121	3.00	3.798	5.07
ave		7.71		4.2		4.94

TABLE III
CHARACTERISTICS OF THE PRODUCED FABRICS

Fabric structure	Density	Fabric code	CPC	WPC	Experimental loop length (cm)
Plain	Loose	P_l	12	7.5	1.45
	Medium	P_m	18	10	1.05
	Tight	P_t	19	11.5	0.95
Rib 1×1	Loose	R_l	9	7	1.4
	Medium	R_m	9.75	9.5	1.17
	Tight	R_t	11.75	10.5	0.95
Interlock	Loose	I_l	15	10	1.0
	Medium	I_m	16	13	0.9
	Tight	I_t	18	14	0.80

TABLE IV
THEORETICAL AND EXPERIMENTAL RESULTS OF DIMENSIONAL PARAMETERS

Fabric code	Experimental loop length (cm)	Theoretical loop length (cm)	Percentage error	Average error
P_l	1.45	1.292	10.91	
P_m	1.05	0.943	10.19	11.35
P_t	0.95	0.826	12.95	
R_l	1.4	1.317	5.91	
R_m	1.17	1.104	5.60	4.13
R_t	0.95	0.991	0.89	
I_l	1.0	1.36	4.80	
I_m	0.9	1.06	6.18	5.12
I_t	0.80	0.908	4.39	

TABLE V
COMPARISON OF THEORETICAL STRAIGHT LINE MODEL WITH THE EXPERIMENTAL RESULTS OF OTHER RESEARCHERS

Fabric structure	Code	WPC	CPC	D (mm)	Experimental loop length (mm)	Theoretical loop length (mm)	Percentage error	Average error
Plain	P1 [19]	14	21.35	0.118	3.036	3.207	5.65	
	P2 [17]	9.5	8.11	0.235	4.968	4.934	0.68	2.49
	P3 [17]	18.07	19.64	0.150	2.337	2.310	1.15	
Rib 1×1	R1 [19]	12.06	13.35	0.118	3.171	3.287	3.66	
	R2 [20]	4.75	2.67	0.182	11.3	11.106	1.71	4.19
	R3 [8]	7.97	17.75	0.1276	4.28	3.97	7.2	
Interlock	I1 [19]	12.98	11.6	0.118	3.649	3.780	3.61	
	I2 [21]	3.9	4.2	0.330	11.57	11.084	4.19	6.4
	I3 [22]	19.29	10.23	0.1105	3.0	3.342	11.4	

respectively. The results obtained from Tables IV and V indicate that the sum of the errors is less than 10%, which indicates the good accuracy of the straight-line geometric model for predicting loop length for the three basic weft knitted fabrics.

IV. CONCLUSION

In the analysis of the mechanical properties of fabrics, it is necessary to investigate their structure. Therefore, in the present research, we proposed straight line loop models in 2D and 3D states for the basic structures of weft knitted fabrics (plain, rib 1×1 and interlock) with necessary simplifications. For this purpose, we suppose that the Plain knitting has a loop for unit cell, and rib 1×1 and interlock knitting divide the unit cell into two main parts: front needle bed loop and back needle bed loop. To evaluate these loop models, the loop length of produced fabrics in this work was measured and compared with the theoretical results of the models. In addition, the data of loop length from the fabrics produced by other researches with different yarns diameters and different materials such as cotton, glass, acrylic, and wool have been also used. The results of these comparisons showed that the straight-line models can predict the loop length of these kind of fabrics properly.

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