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Numerical analysis of the slub yarn breaking strength using finite element method

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The numerical analysis of the slub yarn breaking strength has been made by using the finite element method (FEM). The slub yarn has been considered as skeletal structures since the yarn longitudinal length is much larger than its horizontal cross-section. Then, the accuracy of the proposed FEM model in calculating the slub yarn breaking strength has been validated by comparing the calculated results with the experimental data. This model can be used to calculate the slub yarn breaking strength normally and provides a theoretical support for product design.

Keywords: Analytical model, Breaking strength, Finite element method, Slub yarn

Slub yam is a kind of fancy yarn, in which axial directions distribute regularly or irregularly slub and basic yarn, and this special appearance makes the slub fabric very popular in the market. The appearance is one of the main factors of the yarn fracture[1,2]. How to improve the slub yarn mechanical properties, especially the slub yarn breaking strength, has been one of the attracted research topics recently[3,5].

Yarn breaking strength is one of the important indexes of yarn quality, which is determined on the comprehensive factors such as fibre properties, yarn structures, and spinning methods. Therefore, the research on the yarn breaking strength is very complicated[6], especially for the slub yarn. FEM is developed on the basis of physical analysis of structural mechanics and has been effectively used in many fields[7], such as computational mathematics[8,9], and computational mechanics[10]. It can be used in a wide variety of physical issues such as linear elastic mechanics, non-linear stress-strain relations, and fluid dynamics. FEM has been used especially in textile research in recent years due to its powerful computing function[11,12].

Therefore, attempts have been made to study slub yarn textile load by using finite element method. Firstly, the slub yarn is considered as skeletal structures since the yarn longitudinal length is much larger than its horizontal cross-section. Then, the accuracy of the proposed FEM model in calculating the slub yarn breaking strength has been validated by comparing the calculated results with the experimental data.

Methodology

Force analysis of slub yarn

Suppose the force of one element node $i(x_i,y_i)$ of the slub or the basic yarn is f_i, and the force components in the x-axis and y-axis are fi_x and f_{iy} respectively, anther element node $j(x_j,y_j)$ is f_j,, and the corresponding force components are f_{jx} and f_{jy}. Under the corresponding force, the displacements of the element nodes i and j in the x-axis and y-axis are u_i,v_i and u_j,v_j. The force analysis is shown in Fig.1. According to the equilibrium condition of forces, as shown below:

$$f_i = -f_j \qquad \ldots(1)$$

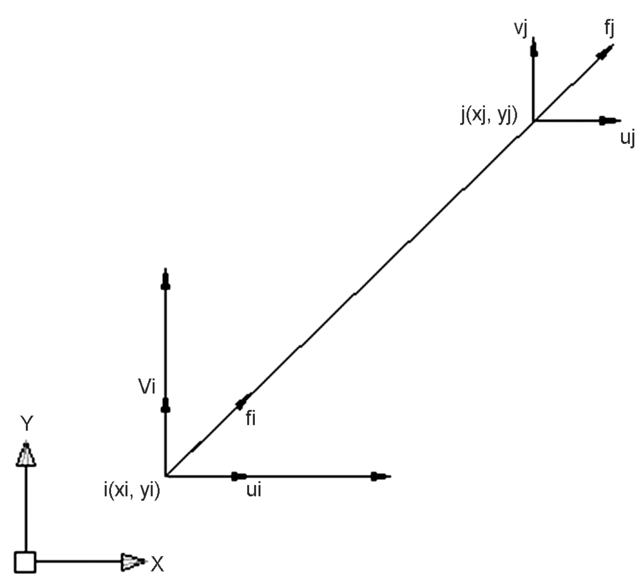

Fig. 1— Diagram of the slub yarn force

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Suppose the initial length of the slub or the basic yarn is l_0, and length change is Δl under the corresponding force, then according to the Hooke law:

$$f_i = k\times(-\Delta l) = \frac{EA}{l_0}\times(-\Delta l) = -EA\varepsilon \qquad \ldots(2)$$

$$f_j = -f_i = EA\varepsilon \qquad \ldots(3)$$

where E is the elastic modulus; and A, the section area. The strain ε is

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{\sqrt{(x_j+u_j-x_i-u_i)^2+(y_j+v_j-y_i-v_i)^2}-l_0}{l_0} = \frac{(x_j-x_i)(u_j-u_i)+(y_j-y_i)(v_j-v_i)}{(l_0)^2} \qquad \ldots(4)$$

Taking into account Eq. (4) in Eqs (2) - (3), we find that

$$\left.\begin{aligned} f_i &= (-EA)\times\frac{(x_j-x_i)(u_j-u_i)+(y_j-y_i)(v_j-v_i)}{(l_0)^2} \\ f_j &= (EA)\times\frac{(x_j-x_i)(u_j-u_i)+(y_j-y_i)(v_j-v_i)}{(l_0)^2} \end{aligned}\right\} \qquad \ldots(5)$$

Suppose the angle between slub yarn length direction and x-axis is β, then the forces f_i and f_j can be rewritten as

$$\left.\begin{aligned} f_{ix} &= f_i\cos\beta = \frac{-EA}{l_0}\times((u_j-u_i)\cos^2\beta+(v_j-v_i)\cos\beta\sin\beta) \\ f_{iy} &= f_i\sin\beta = \frac{-EA}{l_0}\times((u_j-u_i)\cos\beta\sin\beta+(v_j-v_i)\sin^2\beta) \end{aligned}\right\} \qquad \ldots(6)$$

$$\left.\begin{aligned} f_{jx} &= f_j\cos\beta = \frac{EA}{l_0}\times((u_j-u_i)\cos^2\beta+(v_j-v_i)\cos\beta\sin\beta) \\ f_{jy} &= f_j\sin\beta = \frac{EA}{l_0}\times((u_j-u_i)\cos\beta\sin\beta+(v_j-v_i)\sin^2\beta) \end{aligned}\right\} \qquad \ldots(7)$$

The Eqs (6) and (7) can be rewritten as the following matrix equation:

$$f = Ku \qquad \ldots(8)$$

where vector $f = \left(f_{ix}, f_{iy}, f_{jx}, f_{jy}\right)^T$; $u = \left(u_i, v_i, u_j, v_j\right)^T$; and K is the stiffness matrix as given below:

$$K = \frac{EA}{l_0}\begin{pmatrix} \cos^2\beta & \sin\beta\cos\beta & -\cos^2\beta & -\sin\beta\cos\beta \\ \cos\beta\sin\beta & \sin^2\beta & -\cos\beta\sin\beta & -\sin^2\beta \\ -\cos^2\beta & -\sin\beta\cos\beta & \cos^2\beta & \sin\beta\cos\beta \\ -\cos\beta\sin\beta & -\sin^2\beta & \cos\beta\sin\beta & \sin^2\beta \end{pmatrix} \qquad \ldots(9)$$

The Eq. (8) is the mechanics equation of the slub or the basic yarn, and l_0 can be the length of the slub or the basic yarn. Finite element analysis of the slub yarn breaking strength is described hereunder according to the Eq. (8).

Finite element analysis of slub yarn breaking strength

In this section, the finite element analysis of the slub yarn breaking strength is presented according to Eq. (8). ANSYS is one of the most professional softwares and can efficiently solve the static types of the structure, dynamics, vibration, linear and nonlinear problems. Therefore, ANSYS10.0 has been used for this study.

Finite element model of slub yarn

The actual structure of the slub yarn is very complex, and it is impossible to analyze the yarn force in accordance with the actual yarn structure completely. Therefore, in this study, the slub yarn has been considered as skeletal structures since the yarn longitudinal length is much larger than its horizontal cross-section (>> 10:1). According to the output of the program, we know that the total number of the finite element mesh of the slub yarn is 62002, and the total number of the finite element node is 118287.

The transition section of the slub yarn is the stress concentrated part. Therefore, eight nodes in this part are chosen for loads application, namely node1(-0.12, -0.25, 0.67), node2(-0.12, -0.40, 0.67), node3(0.12, -0.25, -0.67), node4(0.12, -0.28, -0.67), node5(-0.52, 0, 0), node6(-0.52, 0, -0.28), node7 (-0.52, 0.8, 0.28), and node8(0.52, 0.8, -0.28). The stress change of the chosen nodes is shown in Fig.2.

Table 1— Twisting angle and twist conversion

Slub length mm	Slub twisting angle β_1, deg			Basic yarn twisting angle β_2 , deg			Slub twist /10cm			Basic yarn twist /10cm		
	48.6tex	14.6tex	9.7tex	48.6tex	14.6tex	9.7tex	48.6tex	14.6tex	9.7tex	48.6tex	14.6tex	9.7tex
1.5	19.21	20.84	20.76	19.48	23.19	23.17	39.37	50.63	49.23	50.45	71.65	69.03
2.0	19.47	17.58	19.50	19.56	22.02	21.34	39.95	53.12	41.46	51.60	59.63	63.83
2.5	19.87	21.2	20.74	20.21	23.20	22.31	40.84	50.67	45.55	52.83	73.00	58.91
3.0	20.18	16.53	22.53	21.09	21.11	21.11	41.53	52.66	50.49	53.06	55.86	56.49
4.0	20.21	21.02	21.02	21.23	22.21	22.21	41.60	53.85	45.13	53.15	73.32	60.12
5.0	21.07	22.12	20.12	22.22	23.18	21.28	43.54	52.58	51.20	53.58	76.50	56.75
6.0	21.74	20.33	20.23	22.51	22.54	21.34	45.06	48.13	51.46	53.90	69.73	56.83
7.0	22.03	19.65	19.76	23.04	21.37	21.17	45.73	48.65	50.74	64.16	67.20	54.90
8.0	22.56	21.71	21.81	23.27	23.62	23.42	46.95	52.30	50.31	54.60	74.93	63.43

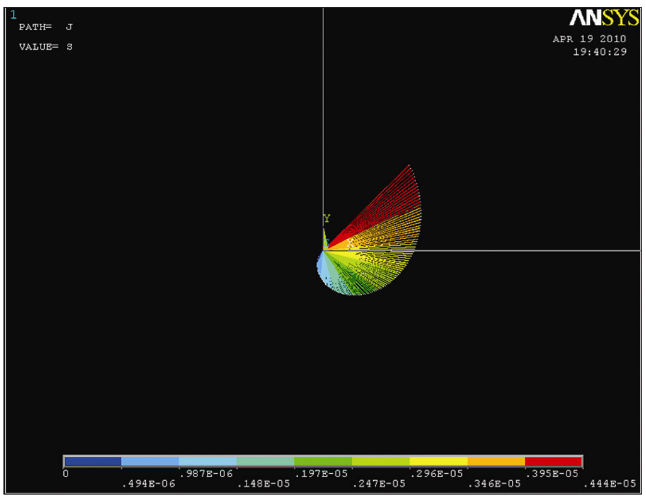

Fig.2 — Stress change of the chosen nodes

Results and Discussion

Slub Yarn Spinning Parameter Design

For validating the accuracy of the proposed FEM model in calculating the slub yarn breaking strength, three types of the cotton slub yarn with different basic yarn count, namely 48.6 tex, 14.6 tex, and 9.7 tex are spun in the EJM128K-SM ring spinning frame with ZJ-5 digital slub yarn devise. For convenient comparing, the same roving is used in the spinning, and the roving feeding is taken as 4.25 g/10m. The cotton fibre properties used in the experiments are fibre length 33.5mm, fibre strength 24.5 g/tex, and micronaire value 4.1. For each yarn count, nine kinds of slub yarn with slub length 1.5, 2, 2.5, 3, 4, 5, 6, 7, and 8 cm are spun respectively. The specific spinning process parameters are basic yarn length 5cm, slub ratio 200%, and design twist 50.2/10cm for 48.6tex, 55.31/10cm for 14.6tex and 53.12/10 cm for 9.7tex.

Measurement of Yarn Twist Angle

The twisting angle of the slub yarn can be measured using the DZ3 video microscope, the images of slub and basic yarns can be obtained this microscope. Then, using the Image-Pro Express, the images of each part of the slub yarn can be analyzed and the twisting angle of the slub and basic yarns can be measured respectively. According to the following equation [13], we can get the actual yarn twist:

$$T_{tex} = 892 \mathrm{tg} \beta \sqrt{\frac{\delta}{N_{tex}}} \quad \text{...(10)}$$

The twisting angle of the slub and basic yarns and their corresponding actual twists are shown in Table 1.

Taking into account the twisting angles as in Eq. (8), we can get the forces correspondingly. Then, the force data can be introduced into the finite element model as mentioned and the corresponding yarn breaking strength can be obtained.

Results Analysis

For validating the accuracy of the proposed FEM model in calculating the slub yarn breaking strength, the breaking strength of the three types of the spun slub yarns are also measured using the YG063 single yarn tester. The test conditions are set as follows: temperature 20°C, humidity 65(%RH), initial pretension 24.3cN, fragment interval 1 m, and tensile rate 50 cm/min. Then, the simulation data can be presented by using the FEM model. The yarn breaking strength actual value tested by YG063 and the simulation value given by the FEM model are presented in Table 2.

According to the data comparison between the actual values and the simulation values in Table 2, it can be seen that the proposed FEM model in this

Table 2— Breaking strength of slub yarn

Slub length mm	Actual value, cN			Simulation value, cN		
	48.6tex	14.6tex	9.7tex	48.6tex	14.6tex	9.7tex
1.5	1120.4	910.4	764.0	1162.7	932.5	802.1
2.0	970.1	870.1	751.0	1000.5	912.3	763.2
2.5	860.2	845.6	745.4	890.5	875.0	752.6
3.0	856.3	765.3	736.5	871.3	837.1	737.5
4.0	791.0	769.6	719.4	862.4	824.6	726.4
5.0	786.3	745.8	705.5	790.2	758.7	711.3
6.0	771.5	729.1	700.3	785.4	757.1	710.0
7.0	767.8	727.3	673.2	773.2	765.8	691.4
8.0	740.2	716.5	665.1	756.1	720.4	680.2

study in calculating the slub yarn breaking strength is accurate and the results are reliable.

The numerical analysis of the breaking strength of slub yarn has been given by using the FEM in this study, and the accuracy of the proposed FEM model in calculating the slub yarn breaking strength has been validated by comparing it with the experimental data. The slub yarn FEM model provides a theoretical support for product design. However, for simplifying analysis, the slub yarn is considered as skeletal structures since the yarn longitudinal length is much larger than its horizontal cross-section in this paper, and there are some other factors such as the friction between the fibres, which can affect the discussion. These need further study.

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