Modelling the impact of tensile and shear forces during the loop-forming process in knitting

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ABSTRACT – REZUMAT

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Knitting is a dynamic process during which the yarn simultaneously receives several mechanical forces such as tensile, shear and bending, especially when the new loop is drawn out of the old one by the needle hook. Many researchers analysed the factors mainly focusing on the tension variation during loop formation but seldom studied the impact of shearing force during new loop formation in detail. This paper presents an innovative method that introduces the shearing force as an important factor in the theoretical calculation model of forces in an integrated manner to understand the effect of tensile and shearing forces during a new loop-forming stage. It proves that the impact of shearing force acting along the yarn's cross-section is much more severe, which needs to be considered in the knitting machine design, knitting yarn selection and knitted products' quality control.

Keywords: *loop formation, tensile force, shearing force, modelling*

Modelarea impactului forțelor de tracțiune și de forfecare în timpul procesului de formare a ochiurilor de tricot

Tricotarea este un proces dinamic în timpul căruia firul este solicitat simultan de către mai multe forțe mecanice, cum ar fi forța de tracțiune, forța de forfecare și forța de îndoire, mai ales când noul ochi este creat prin cel vechi de cârligul acului. Mulți cercetători au analizat acești factori, concentrându-se în principal pe variația tensiunii în timpul formării ochiului în timpul procesului de tricotare, dar rareori au studiat în detaliu impactul forței de forfecare în timpul formării noului ochi. Această lucrare prezintă o metodă inovatoare care introduce forța de forfecare, ca un factor important în modelul de calcul teoretic al forțelor, într-o manieră integrată pentru a înțelege efectul forțelor de tracțiune și de forfecare în timpul unei noi etape de formare a ochiului. A fost demonstrat faptul că impactul forței de forfecare care acționează de-a lungul secțiunii transversale a firului este mult mai sever, ceea ce trebuie luat în considerare în proiectarea mașinii de tricotat, selecția firelor de tricotat și controlul calității produselor tricotate.

Cuvinte-cheie: *formarea ochiului de tricot, forța de tracțiune, forța de forfecare, modelare*

INTRODUCTION

Most researchers evaluated the effect of tension fluctuation in different zones of the knitting machines by using different theoretical or mathematical models. Those are useful for analysing the factors causing dynamic tension variation in various stages of the yarn movement over the contact point, yarn interaction with different elements of the knitting machine and finally, during the loop-forming process. The maximum value of tension is recorded. The exact degree of tension fluctuation during the loop-forming stage is still not precise. The magnitude of stress on the yarn rises in the knitting zone, and the degree of stress can be up to ten times higher than the stress at the entrance of the knitting system. The resultant bending deformation depends on the resistance of the yarn to the adhesive force, which acts on the moving part of the yarn in knitting. The resistance of the yarn to the loads relies on its viscoelastic properties. For example, since elastane yarns exhibit a lower elastic modulus, they offer lower resistance to the loads in knitting [1].

Textile yarns encounter different forces, including compression, bending and stretching forces. The mechanical properties of textile materials depend on factors such as strength, elasticity, extensibility, resilience, toughness, and stiffness. The mechanical properties are calculated from the load-deformation curves as the tensile, bending, shearing, and frictional forces under specific atmospheric conditions deform the fibres. The most commonly evaluated mechanical properties are the tensile properties because of the geometric shape and dimensions of fibres [2].

It is also worth considering that the yarn is bent during the knitting process into loops forming large curvatures, especially near the sinker and needle loops.

Plastic deformation can also occur due to the slippage of fibres or permanent extension of the fibres in the curved yarns [3]. According to the study's results, high-modulus yarns can withstand the bending stress of the knitting components. Thus, if simultaneous forces, i.e., tensile and bending forces, are applied to the yarn, some of the filaments are likely to fracture under the loading, which is less than the tensile strength of the yarn. This eventually decreases the strength of the knitted fabric. Hence, knitting tension must be lower than the tensile strength of the filament to avoid filament rupture [4]. Likewise, carbon fibre possesses ultimate tensile strength along its lengthwise direction, but the forces applied, such as; tension, compressive and shearing forces along the traverse direction, result in remarkable failure [5]. Manufacturing cotton knitted textiles with plated elastomeric yarns was done using a mathematical model to simulate dynamic stresses on yarns and knitting-in lengths. On a computer-aided measuring warp-knitting machine, the findings of the dynamic loads of yarns and lengths of knitting-in determined based on a computer simulation were validated experimentally. The computer simulation shows that feeding elastomeric yarn at a constant initial force results in different values of the pitch coefficient of knitting in the elastomeric yarn for a basic yarn. The pitch coefficient of knitting in the elastomeric yarn for a basic yarn refers to the angle of lifting the needles in the knitting zone. Knitting-in elastomeric yarns at 0.1 cN initial tension, a value of linear density expressed in dtex, will result in different lengths of knitting-in elastomeric yarn depending on the value of the angle of lifting the needles, and therefore various structural parameters of knitted fabrics and their characteristics [6].

The dynamic forces in yarns in the knitting zone for linear cams and cams of a composite linear-circular function contour with a circumference were analysed using a computer simulation and an experimental test [7]. Cams with an infinite height of needles growing in the knitting zone under constant tension (negative) feeding were the subjects of this study. The yarn-robbing back effect remained until the loop construction cycle was completed. Loop creation conditions were established at the stages of discontinuous robbing back in the knitting zone using a deterministic digital model of the knitting process. A linear cam with a descending angle of 50° and a rising angle of 30° was utilized as an example. The depletion of the yarn reserve on the needle that was previously raised and positioned beyond the maximum descending depth point determines the presence of the discontinuous phenomenon of yarn robbing back into the knitting zone. This effect arises when the needle rising point's horizontal coordinate value is smaller than the needle spacing. Depending on the parameter value and descending depth, maximum pressures in yarns in the knitting zone may be up to 2.2 times stronger than under continuous robbing back conditions [8].

Sometimes, the tensile strength of the textile materials is enough to be knitted while there is yarn breakage along its traverse direction. This implies that the yarn exhibits poor shear strength along its traverse direction. Previous studies investigated the effect of tension variation in the knitting zone. Still, they did not consider a difference in the impact of tensile and shear forces acting during the new loop formation. It is not true that the tensile forces are higher than the shear forces for the materials to be used for knitting. This paper contributes to a better understanding of the importance of this model, which will help in the selection of yarns for the knitting process, especially in the case of technical yarns and high-performance yarns.

MODELLING THE IMPACT OF TENSILE AND SHEAR FORCE

Model introduction and basic assumptions

The theoretical study indicates that several forces act simultaneously on the yarn during the new loop formation. The magnitude of the forces varies from point to point. The tensile and shear forces act simultaneously on the yarn while the new loop is drawn out. The effect of the shear force is amplified when there is an angular deflection in the yarn, which contributes to the yarn bending up to a certain limit. The needle hook takes the yarn down with the two ends supported by the sinkers. The wrapping angle and gauge play an essential role in such a condition for change in the degree of shearing and tensile forces. Previous researchers have put forward many models indicating significant differences in tensile force during the new loops.

An approximated technique has been introduced to study the tension fluctuation during the knitting loop formation. The results indicate that the tension rises as the needle reaches the maximum knitting position. Furthermore, the tension on the yarn increases as the yarn runs over verges [9–11]. A discrete probabilistic model for evaluating the dynamic forces in the knitting has been presented, showing that the maximum force is applied to the yarn in the knitting zone. Moreover, the cam design is essential in increasing the knitting force's magnitude. In contrast, the knocking-off depth of the needles is also associated with the coefficient of variation of forces in the yarn in the knitting zone [12]. The novelty of this paper is the study of the influence of simultaneous tensile and shear forces acting along the yarn's cross-section. The shear force's magnitude depends on the machine's gauge and yarn's wrapping angle.

The following notations are valid for the entire model as given in figures 1–4: S_1, S_2 – sinkers; M^{th} – needles; θ_M – total wrapping angle; T_M – output tension on the needle 'M'; T_{M-1} – input tension on the needle 'M'; $T_{M''}$ – $\mathrm{TM}^{\mathrm{th}}$ force divided into vertical direction; $T_{M'}$ – $\mathrm{TM}^{\mathrm{th}}$ force divided into horizontal direction; $T_{M'-1}$ – T_{M-1} force divided into horizontal direction; $T_{M''-1}$ – T_{M-1} force divided into vertical direction; C – bending length.

Some of the assumptions behind this model are:

- The angular deflection of the yarn caused by the needle is the wrapping angle.
- The friction between yarn and knitting elements is neglected.
- The yarn is even in diameter.

Wrapping angle

The yarn during knitting remains in contact with the different contact points and knitting elements until the final loop formation as shown in figure 1. The yarn is wrapped around different deflecting points along with the knitting elements of the machine. The Wrapping angle between the needle and yarn is indicated in figure 2. The wrapping angle varies instantaneously from point to point since knitting is a dynamic process where the tension fluctuates at each point. Therefore, a significant change exists between input and output tension. The input tension is denoted by ‘TM–1’ and ‘TM’ is the output tension on the needle ‘M’. The ‘a’ is the number of needles which come from the gauge of the machine. It is assumed that θ_M is the total wrapping angle formed by the Mth needle in the stage of maximum bent position. The ‘C’ indicates the total bending length of the yarn as a result of yarn deflection caused by the needle as represented in figure 3.

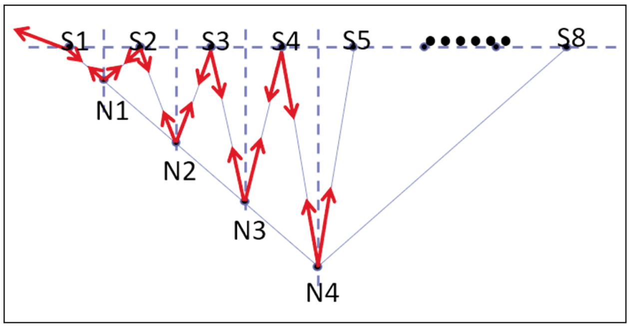

Fig. 1. Needles movement during loop formation

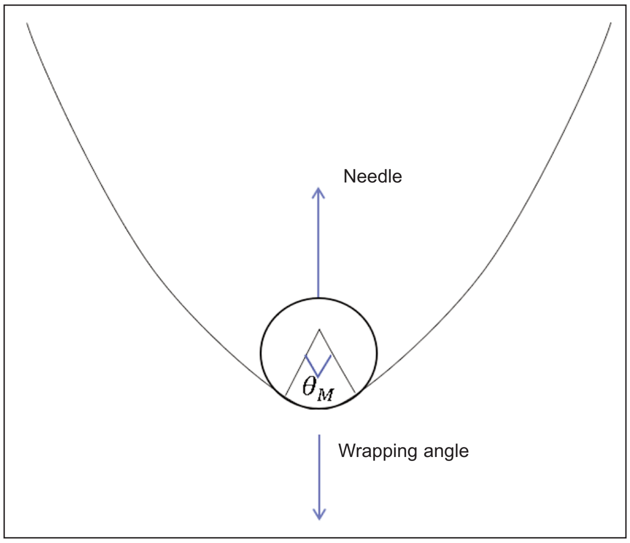

Fig. 2. Wrapping angle between needle and yarn

The wrapping angle can be calculated with the following equation 2 as derived from figure 2.

$$\tan\frac{\theta_M}{2} = \frac{\frac{a}{2} - R}{c} \qquad (1)$$

$$\frac{\theta_M}{2} = \arctan\frac{\frac{a}{2} - R}{c} \qquad (2)$$

Here, $\frac{\theta_M}{2}$ is the half-wrapping angle, R is the radius of the needle, and C is the bending length of the yarn.

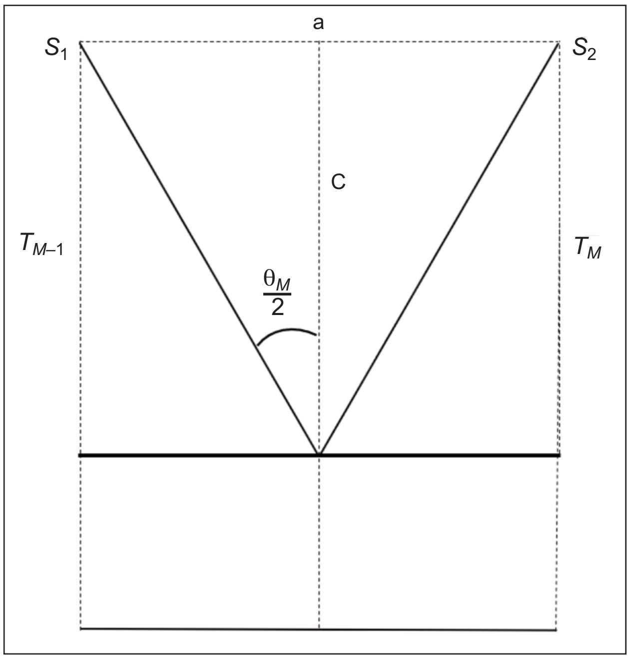

Fig. 3. Total wrapping angle when the needle carrying the yarn bends at maximum position

Shear and tensile forces

The change in input tension relies on the area of contact and the stresses over the contact surface. The increment in the input tension causes the stress build-up between the yarn and knitting elements, which leads to yarn flattening. As the yarn enters the knitting zone, the tension increases between the yarn and the knitting components while the yarn will be in a flattened state between the needle hooks. The impact of shear force along the yarn cross-section increases and can be severe to cause permanent deformation in the yarn [13]. The input and output tension is divided into horizontal and vertical components using trigonometric functions to calculate the impact of tensile and shear forces. The following equations represent the input tension. The horizontal component of input tension is indicated by equation 3:

$$T_{M-1} = T_{M''-1} \cdot \cos\frac{\theta_M}{2} \qquad (3)$$

The vertical component of input tension is given by equation 4:

$$T_{M'-1} = T_{M''-1} \cdot \sin\frac{\theta_M}{2} \qquad (4)$$

The horizontal component of output tension is shown in equation 5, while equation 6 indicates the vertical component of output tension.

$$T_M = T_{M''} \cdot \cos\frac{\theta_M}{2} \tag{5}$$

$$T_{M'} = T_{M''} \cdot \sin\frac{\theta_M}{2} \tag{6}$$

The tension fluctuation during the yarn movement throughout the yarn path is due to the yarn's contact with several contact points. The magnitude depends on the coefficient of friction (μ) and the wrapping angle (θ) of the yarn with the contact points. The final tension (T_0) of the yarn is obtained by multiplying the initial tension (T_i) of the yarn with a factor derived from the yarn wrapping angle (θ) and coefficient of friction (μ) between yarn and rod/pulley as follows:

$$T_0 = T_i e^{\mu\theta} \tag{7}$$

Replacing T_0 by T_M, T_i by T_{M-1} and θ by θ_M, equation (7) becomes:

$$T_M = T_{M-1} e^{\mu\theta_M} \tag{8}$$

$$T_M = T_1 e^{\mu\Sigma\theta_M} \tag{9}$$

Here, $\Sigma\theta_M$ is the sum of the total wrapping angles of the Mth needles. By putting this value of TM from equation 9 into equation 8, we get:

$$T_{M-1} = \frac{T_1 e^{\mu\Sigma\theta_M}}{e^{\mu\theta_M}} \tag{10}$$

Shear force

S_1 and S_2 are sinkers. As yarn stays over the sinkers and needle stretches the yarn downwards for loop formation as shown in figure 3. The shear force F_S acting from S_1 to S_2 for a loop drawing can be given as:

$$F_S = T_M \cos\frac{\theta_M}{2} + T_{M-1} \cos\frac{\theta_M}{2} \tag{11}$$

$$F_S = \cos\frac{\theta_M}{2}\,(T_M + T_{M-1}) \tag{12}$$

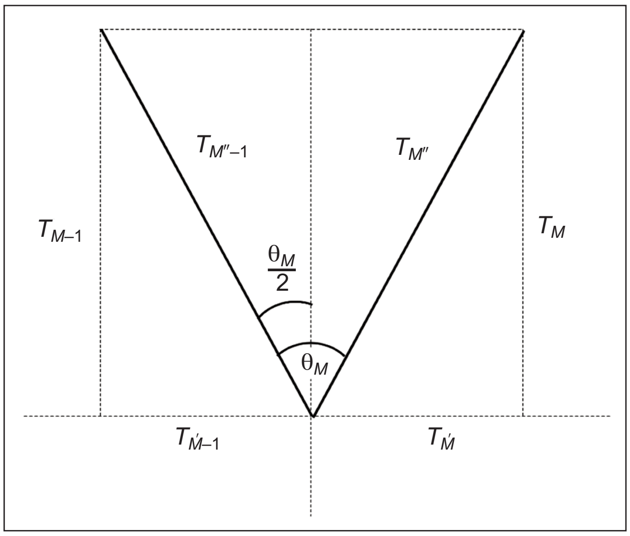

Fig. 4. Resolving input and output tension into vertical and horizontal components

By substituting the values of TM and TM-1 from equations 9 and 10 into equation 12, it follows:

$$F_S = \cos\frac{\theta_M}{2}\,(T_1 e^{\mu\Sigma\theta_M} + T_1 e^{\mu\Sigma\theta_M} \cdot e^{-\mu\theta_M}) \tag{13}$$

$$F_S = \cos\frac{\theta_M}{2}\, T_1 (e^{\mu\Sigma\theta_M} + e^{M(\Sigma\theta_M - \theta_M)}) \tag{14}$$

Tensile force

The yarn movement is dynamic in the knitting process. The tension increases gradually as the yarn moves over different contact points and knitting elements. Therefore, output tension T_M is higher than the input tension T_{M-1} because the coefficient of friction and wrapping angles of yarn with the other knitting elements increase. Then it is given as:

$$T_M \cdot \sin\frac{\theta_M}{2} > T_{M-1} \cdot \sin\frac{\theta_M}{2} \tag{15}$$

If the frictional force is added, the movement of yarn is balanced in the knitting process. So, the following formula can be used. Evaluating equation 15 with the frictional and shear forces, it becomes:

$$T_M \cdot \sin\frac{\theta_M}{2} = T_{M-1} \cdot \sin\frac{\theta_M}{2} + \mu F_S \tag{16}$$

Due to the unknown values of the friction coefficient, the following formula can be used:

$$F_T = T_M \cdot \sin\frac{\theta_M}{2} = T_1 \cdot e^{\mu\Sigma\theta_M} \cdot \sin\frac{\theta_M}{2} \tag{17}$$

RESULTS AND DISCUSSION

The impact of shearing and tensile forces was calculated for 5 G, 7 G and 9 G knitting machines, as shown in figure 5. The results show that the tensile force decreases from 0.81 cN, 0.69 cN, and 0.58 cN with the increase of machine gauge of 5 G, 7 G and 9 G, respectively. Contrarily, the shear force increases from 5 cN, 5.6 cN, and 5.91 cN with the increase of machine gauge of 5 G, 7 G and 9 G, respectively. The results validated the theoretical analysis for the flat knitting machines with different gauges. The results agree with the theoretical analysis so that as the gauge of the machine increases, the number of needles increases by an inch. Thus, the wrapping angle of the yarn to sinker and knitting elements decreases. It is clear from the results that as the machine gauge increases, the influence of shearing force is more intense along the yarn cross-section. The wrapping angle decreases concerning the machine gauge increase. Since the wrapping angle becomes narrower, the needle hook acts like a cutting blade, which can cause yarn failure during knitting. Therefore, the shearing force's magnitude is higher than the tensile force's at the stage of new loop formation. Hence, the impact of shear force must be considered about tensile forces for higher gauge knitting machines. The higher degree of shear force can cause yarn failure no matter if the yarn exhibits higher tensile behaviour.

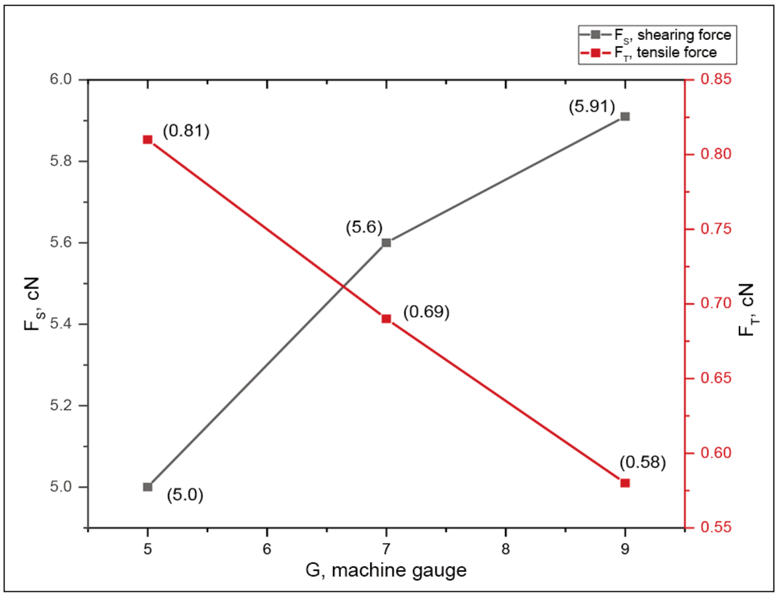

Fig. 5. Effect of gauge length on shear and tensile properties during knitting process

CONCLUSIONS

An approach to modelling the tensile and shearing force along the yarn cross-section provided the results, which are in good agreement with experimental tests. This indicates that the intensity of shear force is higher than that of tensile force. Moreover, the impact of shear force is more complex than the impact of tensile force acting on the yarn during the loop formation process. So, the perception of the only requirement for adequate tensile strength is invalid.

Sometimes, the materials do not exhibit enough tensile strength, but they own weak behaviour against the shear stress. The primary reason for their failure is the lack of shear strength rather than the lack of tensile strength. The machine's gauge plays a vital role in the variation of the magnitude of tensile and shear forces. Therefore, the shearing strength of the materials should be considered, along with the tensile strength.

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