THEORETICAL ANALYSIS OF COMPRESSION OF RIB KNITTED FABRIC

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ABSTRACT: *Lateral compression of polymer fibrous materials is of great interest for various applications such as textile products, and fiber-reinforced composites. The ability of the fabric to deform under the force applied normally to its plane is determined by fiber properties, the compressibility and surface properties of the constituent yarn, and the fabric's structural characteristics. Many scientists have been working on modeling fibrous assembly's compression and recovery behavior. Van Wyk's compression theory was the first theoretical model explaining the compressional behavior of fiber mass. This theory is the simplest but most realistic model of compression. The process of plying or folding yarns balances the torque of the novel linear fibrous assembly and improves evenness, strength, and surface characteristics. Some properties of folded yarns have been extensively investigated but, there are no investigations of the effect of the ply twisting of yarns on the compression ability of rib knitted fabrics. This investigation continues the research attempting to provide insight into the potential of yarn folding in terms of compressional behavior. A mechanical model based on van Wyk's compression theory was applied to describe the multicyclic compression behavior of rib knits, both in the compression and relaxation phases. A high correlation between experimentally and theoretically obtained compression curves was established.*

Keywords: *yarn, ply twist, rib knitted fabric, compression, van Wyk's compression law.*

TEORIJSKA ANALIZA KOMPRESIJE REBRASTIH PLETENINA

APSTRAKT: *Lateralna kompresija polimernih vlaknastih sistema je vrlo interesantna sa aspekta različitih primena kao što su tekstilni proizvodi i kompoziti ojačani vlaknima. Sposobnost tekstilnog materijala da se deformiše pod dejstvom sile normalne na njegovu ravan određena je svojstvima vlakana, kompresibilnošću i svojstvima površine pređe i strukturnim karakteristikama samog materijala. Mnogi istraživači su radili na modelovanju kompresionog ponašanja vlaknastih snopova. Prvi teorijski model, koji je predložio van Wyk, je i najrealističniji model kompresije. Končanjem pređe se uravnotežava torzioni momenat čime se poboljšava jačina, ravnomernost i površinska* *svojstva novonastale strukture. Određena svojstva končanih pređa su dobro ispitana, međutim, nema istraživanja efekta končanja na kompresiono ponašanje rebrastih pletenina. Ovo istraživanje predstavlja nastavak istraživanja sa namerom da se ispita efekat končanja pređe na kompresiono ponašanje pletenina. Mehanički model zasnovan na van Wyk-ovoj teoriji kompresibilnosti je primenjen sa ciljem da se opiše ponašanje rebrastih pletenina pri višecikličnoj kompresiji i relaksaciji. Ustanovljena je visoka korelacija između eksperimentalno i teorijski dobijenih kompresionih kriva rebrastih pletenina.*

Ključne reči: *pređa, končanje, rebrasta pletenina, kompresija, van Wyk-ov zakon kompresije.*

1. INTRODUCTION

The mechanical properties, such as the compression of textile materials, are crucial for the tactile comfort of clothing since it is closely related to the smoothness and softness of the material. The compressibility of a fabric is defined as its ability to deform under the influence of applied force normal to its plane. Most clothing materials can change their thickness under very low pressures. The compression behaviour of textile materials is influenced by fiber properties, the compressibility and surface properties of the constituent yarn, and the fabric's structural characteristics. There have been many investigations of the compression properties of textile materials in dependence on fiber, yarn, and fabric characteristics. However, there are only a few investigations of the effect of the ply twisting of yarns on the compression behavior of textile materials [1, 2]. The plying or folding of yarns enhances properties such as uniformity, strength, resilience, and surface qualities. Stankovic et al. [3] indicated that using folded yarn in knitted fabric enables better thermal insulation. In the research conducted by Stankovic and Bizjak [2], single jersey knitted fabric made from two-folded hemp yarn exhibited higher compressibility than knit made from single hemp yarn. In more recent research, Stankovic et al. showed that an increase in the folding twist intensity of cotton yarn reduced compressibility but increased the resilience of rib knitted fabrics [1]. This study continues the research by theoretical analysis of the compression behavior of the rib knitted fabrics attempting to provide deeper insight into the effect of yarn folding on this mechanical property.
Many scientists have been working on modeling fibrous assembly's compression and recovery behavior. Van Wyk's compression theory was the first theoretical model explaining the compressional behavior of fiber mass [4]. Although this model was developed for wool with randomly oriented fibers, many scientists demonstrated that the model is also valid for fabrics with oriented fibers. However, Van Wyk's model does not account for compression hysteresis. Yet, starting from van Wyk theory and de Jong model, the compression hysteresis of rib knitted fabrics containing folded yarns were developed.

2. MECHANICAL MODEL FOR THE LATERAL COMPRESSION OF TEXTILE MATERIALS

Van Wyk's theory relates the pressure and volume of a randomly oriented fiber mass during compression. He derived the equation that correlates Young's modulus for the fiber, mass of the fibers, density of the fiber and intrinsic volume or the volume of the mass at zero pressure [4]. Later van Wyk corrected the equation by including the incompressible volume (Equation 1):

$$P = KE\frac{m^3}{\rho^3}\left(\frac{1}{(V-V')^3} - \frac{1}{(V_0-V')^3}\right) \tag{1}$$

gde je E – Young's modulus for the fiber, m – mass of the fibers, ρ - fiber density, V_0 – intrinsic volume (volume of the fiber mass at zero pressure), K – dimensionless constant determined by the structure of fiber assembly (included due to assumptions made).
Based on van Wyk's theory, de Jong et al. proposed a mechanical model for the lateral compression of woven fabrics describing the compression curves [5]. According to the model, the fabric is considered a three-layer structure one of which is a relatively incompressible inner layer occupied by two outer layers on either side as illustrated in Figure 1. The inner layer consists of assemblies of fibers forming yarn with a small amount of air space. Fibers projecting from the fabric's surface with a large content of air between them form the compressible outer layers.

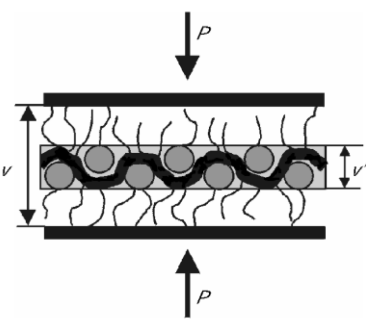

Figure 1: Three-layer structure of textile materials according to de Jong and al. mechanical model [5].

At lower compression force, the protruding fibers from the outer layers are compressed, which is considered elastic deformation. When the compression force overcomes inter-yarn and inter-fiber friction, fiber slippage takes place. The fabric thickness undergoes deformation nonlinearly in this stage. A further increase in compression force results in a slight reduction in fabric thickness, forming a densely packed fiber assembly. The initial elastic deformation of fibers themselves takes place in this stage. Optical measurements confirmed this three-layer model [5]. Starting from Equation 1, de Jong evaluated the three-parameter model with three unknown parameters: the volume at zero pressure, the incompressible volume, and the mechanical parameter determined by the mass of fibers in the compressible surface layers and their orientation. To simplify the model, de Jong assumed that the volume at zero pressure is relatively high, simplifying equation 1. This way, the two-parameter model with the incompressible volume V' (Equation 2), and mechanical parameter a' (Equation 3) is derived [5].

$$V' = V - \frac{2W}{P} \tag{2}$$

$$a' = \frac{8W^3}{P^2} \tag{3}$$

gde je W – compression energy, V – the volume of the fiber mass under pressure applied, P – applied pressure.

3. MATERIALS AND METHODS

Single hemp and cotton yarns with 50 tex were used for the production of three two-folded yarns: hemp yarn (FCs) with folding twist intensity of 300 m^{-1}, and two cotton yarns with the folding twist (secondary twist) of 300 m^{-1} and 600 m^{-1} (FCo1 and FCo2, respectively). These yarns were ply twisted in the S direction, opposite the spinning twist. These three two-folded yarns and two assembled hemp yarns (2Cs) were used to produce rib knitted fabrics. By combining one of the two cotton folded yarns (FCo1 and FCo2) with one of the two complex hemp yarns (FCs and 2Cs), four variants of 1x1 rib knitted fabrics were obtained:

- FCo1+ 2Cs: two-folded cotton yarn with lower folding twist level + two assembled hemp yarn;
- FCo1+ FCs: two-folded cotton yarn with lower folding twist level + two-folded hemp yarn;
- FCo2+ 2Cs: two-folded cotton yarn with higher folding twist level + two assembled hemp yarn;
- FCo2+ FCs: two-folded cotton yarn with higher folding twist level + two-folded hemp yarn.

The rib knitted fabrics were compressed and relaxed for five cycles starting with a minimal load (0.29 N), through a progressively increased load from 1.67 N (4.12 N, 6.57 N, 11.48 N) to approximately tenfold load (16.38 N). When the maximum compressive force was applied, the test was reversed until the sample was relaxed completely. The compression behavior of these knitted fabrics was evaluated elsewhere [1]. In that paper, the energy properties of the knitted fabrics were calculated based on the compression-release curve for each compression cycle. In addition, the percentages of plastic (D_p) and viscoelastic (D_{ve}) deformation components were calculated. The data necessary for van Wyk's parameters calculation are given in Table 1.

		FCo1+2Cs	FCo1+FCs	FCo2+2Cs	FCo2+FCs
Energy dissipated, x 10^{-3}J	1. cycle	3.00	2.70	2.50	2.90
	5. cycle	0.88	0.88	0.75	0.92
Plastic deformation (%)		51.4	50.0	52.5	50.7
Viscoelastic deformation (%)		48.6	50.0	47.5	49.3

Table 1: Data for van Wyk's parameters calculation [1]

4. RESULTS AND DISCUSSION

To construct the theoretical compression curves, van Wyk's parameters - incompressible volume (V') and mechanical parameter (a') were calculated according to equations 2 and 3, respectively. The calculated values of these parameters of the two-parameter compression model are given in Table 2. Based on these parameters, the sample volume values were calculated for each level of compression load within all five compression cycles. This paper presents the data for the first and fifth cycles.

Table 2: Van Wyk's parameters for the two-parameter model of compression

Knitted fabric designation	Incompressible volume, V′ (mm^3)	Mechanical parameter, a' ($N \cdot mm^7$)	Correlation coeficient, r^2
1. cycle			
FCo1+2Cs	88.625	3296.413	0.74
FCo1+FCs	96.025	2403.085	0.71
FCo2+2Cs	103.155	1907.647	0.71
FCo2+FCs	100.862	2977.638	0.70
5. cycle			
FCo1+2Cs	102.884	83.200	0.67
FCo1+FCs	108.004	83.200	0.66
FCo2+2Cs	114.460	51.506	0.64
FCo2+FCs	113.772	95.070	0.65

The correlation coefficients ranging from 0.64 to 0.74, indicated a high coincidence of the calculated values of the sample volume with the experimentally measured data. This means that a two-parameter model can be successfully applied for the description of the compression curves of the rib knitted fabrics. On the other hand, it is generally considered that van Wyk's theory does not explain hysteresis caused by fiber slippage and friction effects. Despite this, Stankovic successfully implemented a two-parameter model to determine the compression hysteresis of plain [6] and rib [7] knitted fabrics. Starting from de Jong's consideration of fabric compression, in this study, the release or decompression curve of the compression cycle was determined by the same line of approach. Using the data from Table 1, van Wyk's parameters for a decompression curve were calculated (Table 3). The incompressible volume and mechanical parameter for the first and fifth cycles are presented in Table 3. An extremely high correlation coefficient (0.91 – 0.92) confirmed the possibility of using a two-parameter model for describing the decompression curve.

Table 3: Van Wyk’s parameters for the two-parameter model of decompression

Knitted fabric designation	Incompressible volume, V′ (mm^3)	Mechanical parameter, a' (N·mm^7)	Correlation coeficient, r^2
1. cycle			
FCo1+2Cs	100.032	445.903	0.92
FCo1+FCs	106.572	300.386	0.92
FCo2+2Cs	112.433	276.042	0.91
FCo2+FCs	112.032	388.057	0.92
5. cycle			
FCo1+2Cs	106.228	11.274	0.92
FCo1+FCs	111.442	10.400	0.92
FCo2+2Cs	117.244	7.453	0.91
FCo2+FCs	117.316	12.390	0.92

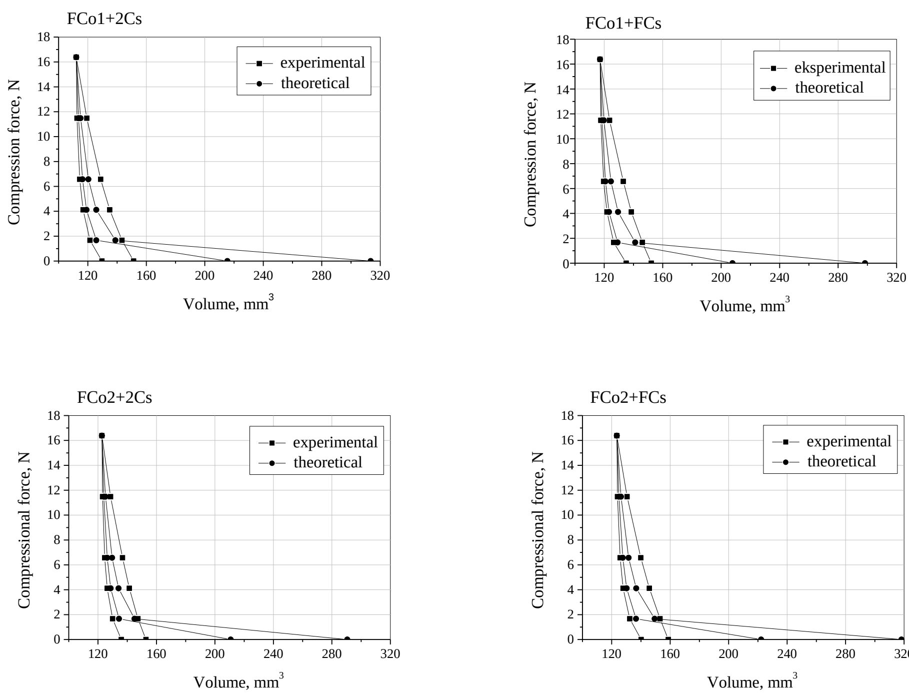

Figure 2: Compressional curves of the first cycle for multicycle compression of rib knits

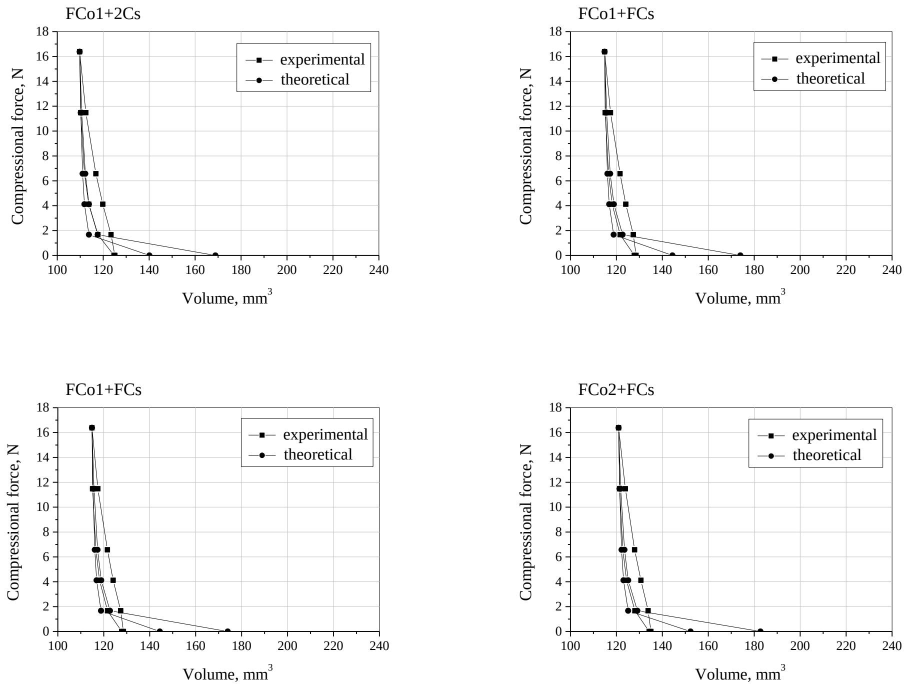

Figure 3: Compressional curves of the fifth cycle for multicycle compression of rib knits

The graphs in Figures 2 and 3 show the experimental and theoretical compression curves for the 1st and 5th cycles of multicycle compression of rib knitted fabrics. Almost identical theoretical and experimental relaxation curves can be observed, except in the case of complete relaxation of the sample. Larger deviations were observed between the sample's theoretical and experimentally determined initial thickness. This is believed to be due to the two-parameter compression model applied.

5. CONCLUSION

The two-parameter model derived from van Wyk's compression theory was applied successfully to approximate the compression curves of the rib knitted fabrics in the pressure range from 0.45 to 2560 cN/cm^2. Moreover, the decompression curves were also successfully described with the same model based on the nonelastic deformation components. For this two-parameter model, which has a linear character, to be applied to the compression behavior of knitted fabrics, it is necessary to use it on the outer compressible layers of knitted fabrics, which are considered to deform linearly under compression force.

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