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Determination of the Impact of Weft Density on Fabric Dynamic Thickness under Tensile Forces

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Abstract

This paper deals with the impact of fabric density on fabric thickness change when samples are subjected to uniaxial tensile forces in the weft direction. During stretching, fabric thickness changes depending on the value of the tensile force. In an effort to be as precise as possible in measuring fabric dynamic thickness changes and the area on which the tensile force acts, a new measuring apparatus was designed and constructed. This measuring apparatus allows the simultaneous measurement of fabric dynamic thickness, related tensile axial forces and extension. Measurements of the fabric dynamic thickness, breaking force and breaking extension during the stretching process were carried out on five samples of cotton woven fabric with a constant warp density and different weft densities in the same structural plain weave. Based on the experimentally obtained values, the paper presents diagrams of the relationship between dynamic changes in fabric thickness in relation to the tensile force and extension. The research presented in this paper shows that an increase in the tensile force increases fabric thickness for all weft densities. Also, the out-of-plane woven fabric ratio was calculated as a relation between the relative thickness strain and relative axial strain. The characteristic curve shows this ratio.

Key words: *woven fabrics, dynamic thickness, warp density, weft density, tensile force, extension, out-of-plane woven fabric ratio.*

Introduction

Fabric is a planar structure with pre-designed structural elements. One of the structural elements of fabric is its thickness as well as its internal geometric structure. Under the influence of various parameters, these fabric elements are subject to changes. Fabric thickness plays an important role in the manual processing, comfort, thermal insulation, design and end-use of textiles.

Fabric thickness change depends on various factors affecting fabric formation in the weaving process. Likewise, thickness depends on the individual preparatory stages of the weaving process. Changes in many factors in the weaving process as well as in weaving preparation affect fabric thickness change [1]. Fabric thickness change, depending on the effect of various parameters, is the issue, which is very important for theoretical and practical solutions of fabric constructions with designed properties. In order to clarify the effects of some specific parameters on fabric thickness, such as yarn count change, change in the warp and weft density, as well as change in the warp and weft thread tension in the weaving process, it is necessary to carry out experimental tests of fabric thickness change.

Many different methods are available for measuring fabric static thickness. This has been assessed by measuring the distance between two parallel plates separated by a fabric sample with a specified pressure applied on the plates. Various apparatuses for measuring static thickness have been developed. G.B. Haven, H.F. Schiefer, F.T. Peirce and J.R. Womersley were among the first to tackle the problem of static determination of thickness. Haven used a new fabric thickness measurer [2], and Shiefer – a compressometer for thickness and resilience measurements [3]. In his paper Pierce brought forth basic observations and gave many mathematical calculations and graphs for practical use, but assuming that the warp and weft threads in the fabric had a circular cross-section, i.e. the compression of yarn by compressive forces during the formation of the crossing point was not taken into consideration [4]. In his observations and specifying problems, Pierce assumed the fabric thickness was equal to the sum of the warp and weft thicknesses in the case of an ideally circular thread cross-section which would be just one of the countless theoretically and practically possible cases. According to this paper, fabric thickness remains unchanged even if the weft density changes, which, of course, does not correspond to the real state of the fabric structure. For these reasons the study deviates from the real values dominating in the fabric. J.R. Womersley took into account that due to changes in thread tension, certain deformations within the fabric itself could result [5]. Later on, many researchers used various types of thickness measuring devices [6-9].

Many other technologies and methods, such as magnetic inductance principles [10], image analysis [11] and parallel plate capacitor methods [12] were also used for evaluating fabric thickness. The methods mentioned above are not suitable for in-situ measurement of fabric dynamic thickness, which made it inconvenient to study fabric thickness evolution under different mechanical conditions.

In the process of manufacturing and use, fabrics are often subjected to the action of am axial tensile load. Tensile stress in fabric causes a change in fabric thickness and extension (longitudinal strain) in the direction of force effects. Fontaine, Durand and Freyburger developed a very lightweight inductive sensor to measure thickness evolution during such a tensile test [13]. In order to analyze the deformation of fabric thickness, Xiao, Long and Zeng developed an analytical model for a fabric out-of-plane deformation through the energy minimization method [14].

In this paper, fabric dynamic thickness and the relationships between thickness strain, axial strain and the axial force were tested and investigated using a specially constructed device for measuring fabric dynamic thickness. The out-of-plane woven fabric ratio was extracted from the relative thickness strain-relative axial strain curves in order to analyse fabric thickness deformation. The characteristic curve shows this relation.

The aim of this work was to determine the impact of weft density on the dynamic change in fabric thickness, using a newly constructed device, when the fabric was in an axial state of stress in the weft direction.

Woven fabric thickness

Textile fabrics cannot be easily described using the usual mathematical models. In contrast to materials of stable structure (e.g. metals), it is not easy to accurately measure textile dimensions. Due to the resiliency and easy variability of fabric shapes, deviation from the basic geometric shape is ever present. Since fabric has a planar structure, it is characterised by specific properties resulting from its characteristic structure. The problem is that due to the complex fabric structure, it is often necessary to idealise the general characteristics of the material studied.

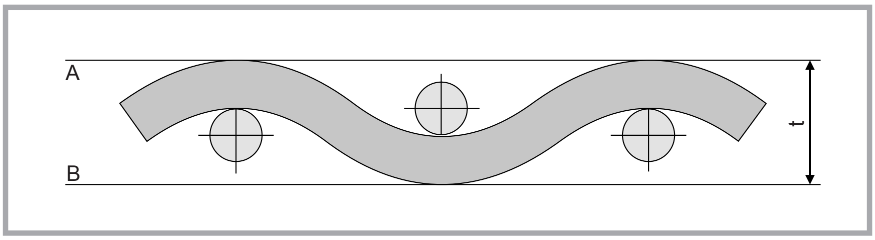

Figure 1. *Cross-section of plain-weave fabric: A) front side, B) back side, t) fabric thickness.*

Woven fabric thickness (t) is the third dimension, which is considerably smaller than the fabric width and length, but at the same time it is very important because it affects the usage and properties of the fabric. Finished fabric thickness depends on the diameters of warp (d_1) and weft (d_2) yarns, as well as on the warp (g_o) and weft (g_p) density, weave type (structure), raw material composition, thread tension during weaving, and the type of finishing treatment [15, 16]. Gray fabric thickness (t_{st}) may be lower or higher than the finished fabric thickness depending on the finishing treatments applied. If the fabric is either milled or raised in the finishing treatment, its thickness is considerably increased. However, the thickness is reduced, if the fabric is calendered or pressed.

By fabric thickness, the greatest distance between the surface of the front side (A) and the mutually parallel surface of the back side (B) of the fabric (***Figure 1***) is meant. Fabric thickness is measured in mm.

If yarn thickness changes and the other parameters remain the same, fabric thickness is directly dependent on the thickness of warp and weft threads. However, if the type of fabric weave is changed, fabric thickness can be affected to a great extent. Plain weave fabrics have minimum thickness, while twill weave and satin weave fabrics as well as fabrics in other weave types with smaller weave repeats have greater thickness. Maximum thickness is achieved if complex weave types are applied.

Fabric thickness depends on the level of warp and weft yarn twist. According to the theory of geometric thread disposition by Novikov [17], the arrangement of threads with a circular cross-section in a single-layer fabric of plain weave can be identified by one of nine structure "phases", (***Figure 2***). The term "phase" is indicative of a particular form of thread disposition i.e. between the two extremes of equal crimping or the absence of crimping in either the warp or weft. The distance between warp yarns is p_1, and that between weft yarns is p_2.

The first phase refers to the extreme case where the warp is very taut during weaving and the warp threads remain straight in one plane, while the weft is simultaneously around the warp. Fabric thickness is:

$$t = d_1 + 2 \cdot d_2 \text{ (mm)} \qquad (1)$$

In the ninth phase the situation is reverse: the weft remains straight, and warp yarns are bent around the weft to the greatest possible extent. Fabric thickness is:

$$t = 2 \cdot d_1 + d_2 \text{ (mm)} \qquad (2)$$

Between *the first and ninth phases* (excluding the fifth phase), the warp and weft both bend to varying degrees. With a greater warp density the weft is forced to run about them to a greater extent, causing greater fabric thickness. The thickness of both yarn systems, the interaction of their densities and the tension of warp and weft threads in the weaving process determine the amount of fabric thickness. Fabric thickness in these phases is:

$$t > d_1 + d_2 \text{ (mm)} \qquad (3)$$

The fifth phase corresponds to the case where the crimps of both thread systems lie in the same plane. In this case fabric thickness is equal to the sum of the warp and weft thread diameters. In this phase the crimp height of the warp h_1 is equal to the crimp height of the weft h_2. In this phase fabric thickness is:

$$t = d_1 + d_2 \text{ (mm)} \qquad (4)$$

Novikov suggested determining the difference between each phase by a rate of half of the thread radius (0.5 r).

An important assumption is made. In the transition to the following phase, a decrease in the crimp height of the warp

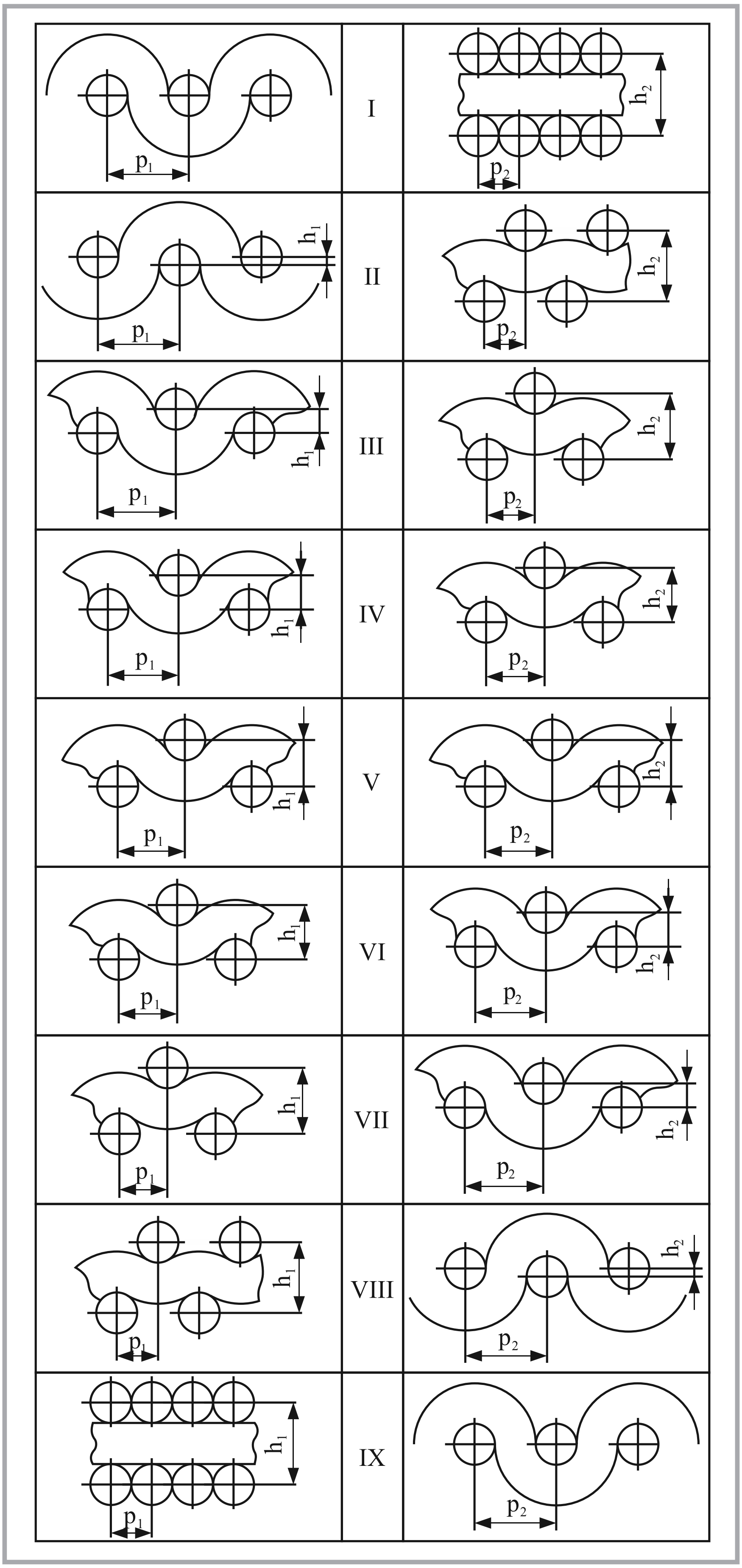

Figure 2. Phases of geometrical disposition of threads in single-layer plain weave woven structures by Novikov.

thread h_1 is equal to an increase in the crimp height of the weft thread h_2. For example, with equal diameters $d_1 = d_2$ of warp and weft threads, the crimp height of the warp thread h_1 increases by 0.5 r, and that of the weft thread h_2 decreases by the same value. Thus, it is observed that:

$$t = d_1 + d_2 = h_1 + h_2 = 4 \cdot r \text{ (mm)} \quad (5)$$

As a basic characteristic of woven fabric structure, Novikov suggested that the crimp height ratio of the warp and weft threads (h_1/ h_2) can be expressed by the coefficient K_h^N.

Table 1 presents, according to Novikov, fabric thicknesses and coefficient values K_h^N of the crimp height in all nine phases. It is necessary to note that for the first phase $K_h^I = 0/8 = 0$, and for the ninth phase $K_h^{IX} = 8/0 = \infty$. In the first phase, the warp threads can theoretically occupy a position one above the other and similarly in the ninth phase with the weft threads. It is noted, however, that this is a theoretical guess, and that it is practically impossible to get these positions. Another essential disadvantage is the integer designation of the phases.

Fabric thickness in other structural solutions depends on the relationship between the densities of warp and weft threads, their thicknesses and raw material composition, as well as on the tension during weaving.

Out-of-plane woven fabric ratio

If a fabric is stretched in one direction, it tends to contract in the direction perpendicular to the that of stretch. Yarns in the direction of the tensile force are flattened out (extended), and in the orthogonal or non-loading direction the yarns have a longer geometrical path to 'curve around' [18]. Because there is no limiting force, the waviness (amplitude) of yarn in the vertical direction of the force increases. The consequence of this is dimension reduction of the fabric width [19-21]. During the extension of the fabric, the thickness of the fabric is also changed.

Woven fabrics are elastic orthotropic materials with a very small deformation defined as orthotropic plates with two mutually perpendicular planes of elastic symmetry. The x-axis runs in the weft direction, the y-axis – in the warp direction, and the z-axis is perpendicular to the plane of woven fabric. Under the action of external loading, in-plane stresses occur: σ_x is the normal stress in the weft direction, σ_y – the normal stress in the warp direction, and τ_{xy} is the shear stress in the xy plane. Out-of-plane stresses σ_z, τ_{xz}, ${}_{zy}$ are assumed to be small and can be neglected.

During the testing of fabric stretch, the initial length of the sample tested l_0 is increased by Δl, and the final sample length of the fabric is l. The initial width of the fabric sample b_0 is decreased by Δb,and the final sample width is b. The initial thickness of the fabric sample t_0 is changed by Δt, and the final sample thickness is t. Changing the thickness represents the out-of-plane deformation which is caused by the action of the axial load. Change in thickness and fabric length takes place in two mutually perpendicular planes.

Absolute longitudinal strain (absolute axial or extension strain):

$$\Delta l = l - l_0 \tag{6}$$

Absolute transverse strain (absolute contraction strain):

$$\Delta b = b - b_0. \tag{7}$$

Absolute thickness strain:

$$\Delta t = t - t_0. \tag{8}$$

The relative longitudinal strain (relative axial or extension strain) is defined as:

$$\varepsilon = \frac{\Delta l}{l_0}\cdot 100\% = \left(\frac{l}{l_0}-1\right)\cdot 100\%. \tag{9}$$

The transverse strain (relative contraction strain) is defined as:

$$\varepsilon_s = \frac{\Delta b}{b_0}\cdot 100\% = \left(\frac{b}{b_0}-1\right)\cdot 100\%. \tag{10}$$

The relative thickness strain ε_t is defined as:

$$\varepsilon_t = \frac{\Delta t}{t_0}\cdot 100\% = \left(\frac{t}{t_0}-1\right)\cdot 100\%. \tag{11}$$

In order to study the out-of-plane woven fabric ratio, it is necessary to analyse the relationship between the relative thickness strain and relative axial strain directly by experimental measurements. The ratio of thickness strain to axial strain is defined as the out-of-plane woven fabric ratio λ. Based on ***Equation (12)***, the out-of-plane woven fabric ratio of the sample can be expressed as:

$$\lambda = -\frac{\varepsilon_t}{\varepsilon} = -\frac{l_0}{t_0}\cdot\frac{t-t_0}{l-l_0} \tag{12}$$

Table 1. *Phases of geometric disposition of yarns within the fabric structure according to Novikov.*

Yarn disposition phase	Crimp height of warp yarns h_1	Crimp height of weft yarns h_2	$K_h^N = h_1/h_2$	Fabric thickness t /yarn radius r
I	0 · r	4 · r	0	6
II	0.5 · r	3.5 · r	0.143	5.5
III	1 · r	3 · r	0.333	5
IV	1.5 · r	2.5 · r	0.6	4.5
V	2 · r	2 · r	1.666	4
VI	2.5 · r	1.5 · r	1	4.5
VII	3 · r	1 · r	3	5
VIII	3.5 · r	0.5 · r	7	5.5
IX	4 · r	0 · r	∞	6

Table 2. *Description of woven fabric.*

Fabric code	Yarn count, tex		Yarn density, cm^{-1}		Mass, g/m^2	Thickness t_0, mm
	warp	weft	warp	weft		
U18	30	30	23	18	135.12	0.364
U20	30	30	23	20	141.24	0.365
U22	30	30	23	22	149.41	0.366
U24	30	30	23	24	157.61	0.366
U26	30	30	23	26	165.34	0.367

Due to fabric anisotropy, the out-of-plane woven fabric ratio λ changes in the process of fabric sample extension.

Experimental part

The experimental part deals with measurements of fabric thickness when a tensile force acts on fabric samples until rupture. For this purpose a new device for dynamic measurements of fabric thickness changes when a tensile force acts on the fabric sample was designed and constructed. Values of tensile forces, associated extensions (stretching) and associated fabric thicknesses were found during testing. By means of the test results obtained, diagrams of fabric sample thickness change in relation to the extension and tensile force were determined. The influence of warp and weft density on the fabric thickness was observed. The out-of-plane woven fabric ratio when a tensile force acts in the weft direction was also calculated.

Test samples

To carry out this study, five cotton woven fabrics of different weft density (18, 20, 22, 24 & 26 cm^{-1}) and of the same warp density (23 cm^{-1}) were obtained. In this work, orthogonal plain weave fabric was considered. Cotton yarn for the warp and weft had the same yarn count (Tt = 30 tex). ***Table 2*** shows structural properties of the woven fabrics tested. Fabric samples of the structural properties mentioned were woven on a Picanol OMNIplus 800 air-jet weaving machine.

Standard ISO 5084:1996 describes a method for determination of the initial thickness t_0 of fabric and the thickness of yarn. Based on the measurements, the mean value of yarn thickness was obtained, amounting to 0.182 mm.

Before testing, all samples were conditioned under standard atmospheric conditions (relative humidity 65 ± 2%, temperature 20 ± 2 °C).

For the purposes of this testing, standard samples with dimensions 300 x 50 mm were cut and clamped in the clamps of the tensile tester at a distance of l_0 = 200 mm and subjected to a uniaxial tensile load till rupture. The pulling speed of the clamps was 100 mm/min.

The samples were cut in the weft direction and five tests carried out on the tensile tester for the cutting directions of the specimen mentioned. For the cutting direction, average values of the axial force, as well as the associated extension and thickness, obtained from five measurements are shown in diagrams and are used to calculate the out-of-plain woven fabric ratio. Tensile properties of all samples were tested according to ISO 13934-1: 2008 using the strip method on the fabric tensile tester.

Apparatus for measuring fabric thickness change

For the purposes of this study, an apparatus for monitoring and measuring thickness changes of fabric under a lon-

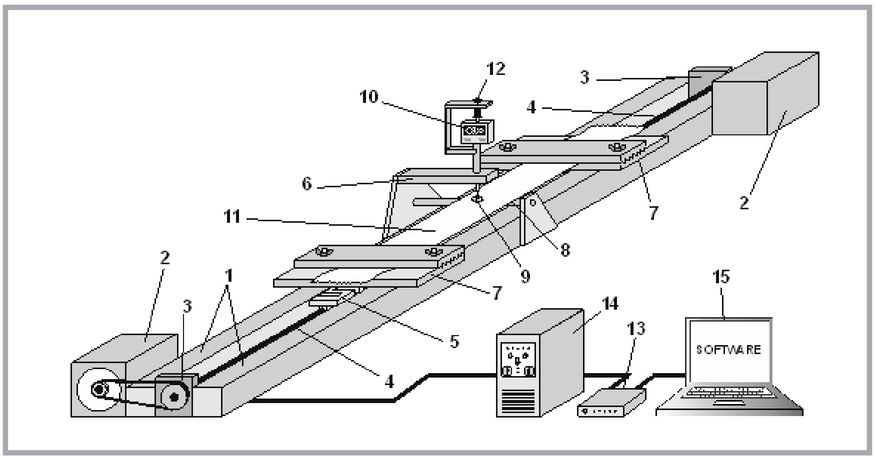

Figure 3. Schematic representation of the device for measuring fabric thickness during elongation. ***Note:*** *1 – bearing structure of the device for measuring fabric thickness during elongation, 2 – motor, 3 – transmission system, 4 – screw rod, 5 – force transducer cell, 6 – bearing structure of the thickness gauge, 7 – fabric clamps, 8 – reference axle of the thickness gauge, 9 – feeler of the thickness gauge, 10 – digital thickness gauge, 11 – fabric test specimen, 12 – displacement force setting of the thickness gauge, 13 – PC interface with A/D converter, 14 – Power & Control Unit with manual settings, 15 – PC (laptop).*

gitudinal tensile force acting on a fabric test specimen was designed and constructed. Using this apparatus a fabric test specimen is stretched and loaded at a constant pulling speed until the moment of specimen rupture. ***Figure 3*** shows a schematic representation of the apparatus, and ***Figure 4*** – a photographic representation of the apparatus for measuring fabric thickness. The device constructed is fully automated and computer-controlled, and works at a constant pulling speed. The maximum measuring resolution of pulling (stretching) is 3.5 µm. The test specimen of fabric (11) is fastened between the movable fabric clamps. The clamps are moved by the electric drive (2) using the transmission system (3) at a constant speed, and they move by means of the screw rod (4) fastened to the bearing structure (1). The force transducer cell (5) is connected to the clamp on one side, and on the other the motor (2) moves the clamp by means of the transmission system (3). A force transducer cell for a range up to 200 N is used. The electric motor work (2) is computer-controlled using the power and control unit with manual settings (14). In the middle of the test specimen, a digital thickness gauge (10) with a displacer (9) resting on the fabric specimen is placed. The displacer diameter is 25.4 mm and the displacer area – 5.06 cm^2. The accuracy of the thickness measurement is 0.001 mm. The full measurement range of the thickness gauge ranges from 0 to 25.4 mm. The displacer rests on the fabric, under which the reference axle of the thickness gauge (8) is affixed to the support of the thickness measurement system (6). The measuring pressure of the displacer is 1 kPa. The digital thickness gauge applied is also equipped with a displacement force setting (12). The whole system is connected to a computer (15) through the computer interface with A/D converter (13), and controlled by the serial port.

Overview of the results and discussion

During the testing process, the tensile force, extension and sample dynamic thickness are detected and recorded. Typical curves of these values are shown in ***Figures 5-8*** when the force acts in the weft direction.

Microsoft Excel software was used for statistical analysis of data at $p < 0.05$ for five measurements. Diagrams (F-ε) of average values of test results of the action of the tensile force F and the corresponding relative extension strain ε until rupture of the fabric test specimens when a force acts in the weft direction are shown in ***Figure 5***.

Figure 5 shows that in the case where a force acts in the weft direction with increasing weft density, the values of tensile forces and associated elongations at break of the fabric test specimen increase.

At the beginning of the stretching step (before the tensile force acts), the initial thickness of the fabric t_0 is measured. It is obvious that fabric thickness is highly dependent on the value of stretching i.e. the tensile force. The action of the tensile force on fabric samples that were cut in the weft direction causes an internal interaction between the weft and warp yarns during extension. Therefore, there

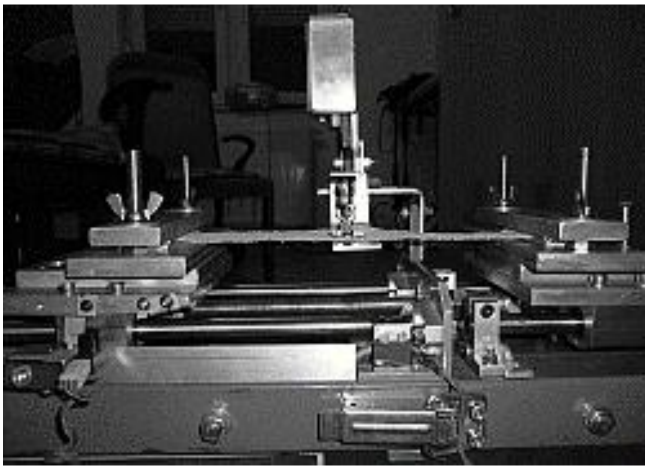

Figure 4. *Photo of the device for measuring fabric thickness during elongation.*

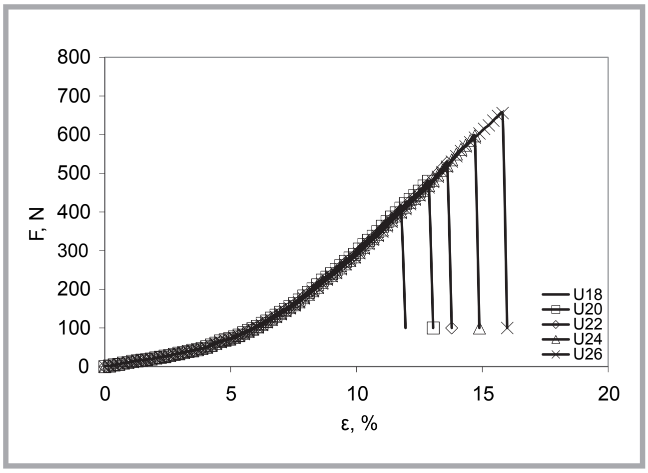

Figure 5. *Diagram of tensile force- relative extension (F-ε) when a force acts in the weft direction.*

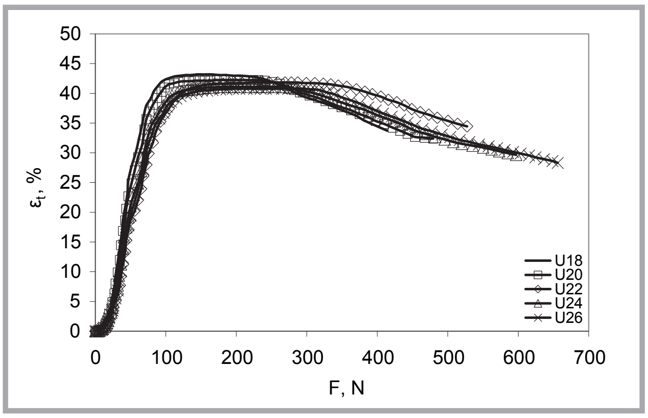

Figure 6. Diagram of tensile force – relative thickness strain (F-ε_t) when a force acts in the weft direction.

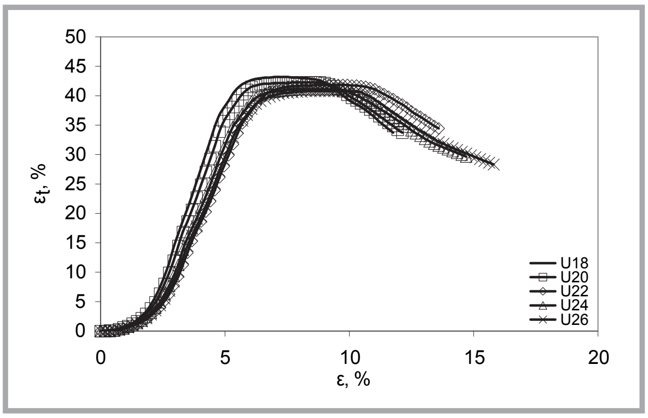

Figure 7. Diagram of relative thickness strain – relative extension (ε_t-ε) when a force acts in the weft direction.

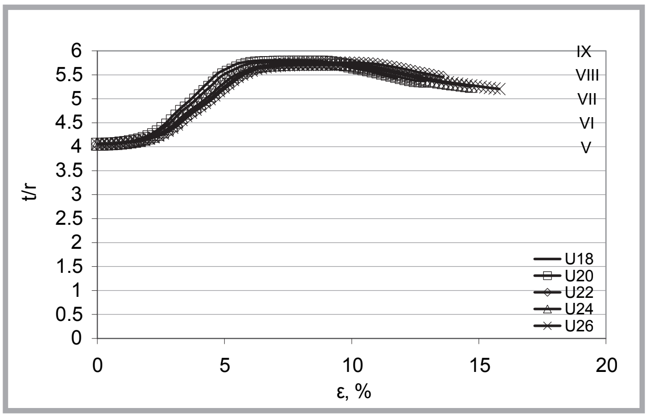

Figure 8. Relationship between fabric thickness (t), yarn radius (r), and relative extension when a force acts in the weft direction, according to Novikov.

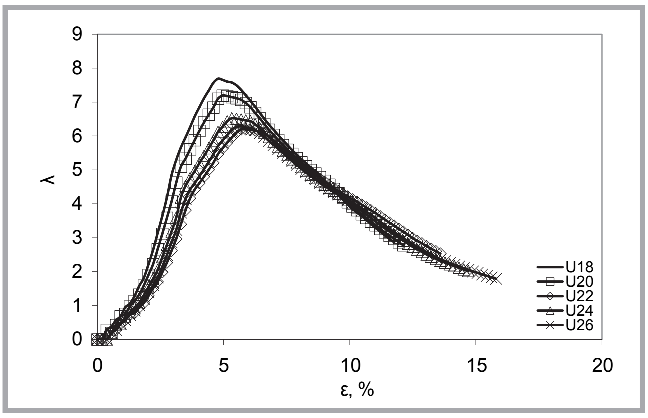

Figure 9. Out-of-plane woven fabric ratio λ when force acts on samples cut in the weft direction.

is a change in fabric dynamic thickness. Fabric thickness changes while the tensile force stretches the fabric.

In taking readings of the fabric sample thickness *t* after the action of the force, the relative change in thickness ε_t is calculated according to ***Equation (11)*** and the relative change in length *ε* according to ***Equation (9)***.

When the force acts in the weft direction, the relationship between the tensile force F and associated relative change in thickness ε_t of the fabric sample is as shown in ***Figure 6***. The thickness strain-axial strain curves (ε_t-ε) in ***Figure 7*** show typical non-linear relationships for five fabric samples when a tensile force acts in the weft direction.

The curve of relative change in fabric thickness in dependence on the tensile force and extension can be divided into four zones (***Figures 6*** and *7*). In the first zone the relative change in fabric thickness increases slightly. In the second zone the increase in the relative change in fabric thickness is steep; it increases almost linearly due to the tensile force and extension. In this zone the weaving-in is balanced, and fabric extension starts. In the third zone maximum relative change in fabric thickness is achieved, which is nearly constant with increasing force and extension. In the fourth zone an additional increase in force and extension causes a slight reduction in the relative change in fabric thickness.

At the beginning of stretching in the test specimen with a tensile force acting in the weft direction in the first zone, relative change in fabric thickness is very low and slightly increases due to frictional resistance to bending the threads (***Figure 6***). The first zone is longer in the dependency diagram (ε_t-ε) than in diagram (ε_t -*F*), (***Figure 6***).

In the second zone, with a force acting in the weft direction, weaving-in of the weft thread gradually decreases (***Figures 6*** and *7*). As a result of balancing the weaving-in of weft threads, an increase in pressure on the warp threads results. This pressure creates additional strain in warp threads and stimulates a simultaneous and continuous exchange of the weaving-in of warp and weft threads, resulting in an increase in weaving-in of warp threads. Evidence of this internal interaction is the narrowing of the fabric in the transverse direction, i.e. in the direction perpendicular to the direction of stretching, which causes a change in fabric thickness. Weft threads get closer to each other and straighten (becoming straight lines), while warp threads simultaneously increase their waviness. Due to this occurrence, the rectangular shape of the sample gets lost, i.e. the fabric sample is narrowed. This results in an increase in fabric thickness. The relative change in fabric thickness changes very much and increases, reaching its maximum.

In the third zone there is an increase in force and extension with a constant relative change in fabric thickness (***Figures 6*** and *7*). This may be explained by the fact that the weft threads were completely straightened and got closer to each other laterally, i.e. there is no available space for further lateral narrowing. Two reasons may lead to the cessation of the lateral narrowing of the fabric: first, due to the cessation of balancing the weaving-in in the direction of fabric extension, and second, due to fabric structure. If there is a possibility of further narrowing of the fabric, it cannot continue since there is no available space between adjacent yarns in the fabric, the consequence of which being that no additional narrowing of the fabric is possible. The fabric can still withstand extension, but the thickness cannot increase further. In the fourth zone the end threads of the fabric sample become loose, resulting in fabric slackening. Reaching the cessation of balancing the weaving-in of yarns, values of the relative change in fabric thickness decrease (fall). The extension force increases and the relative change in fabric thickness decreases until fabric rupture (***Figures 6*** and *7*).

When a force acts in the weft direction (***Figures 6*** and ***7***), the values of tensile forces are in the range from F = 0 N to F = 3 N in the first zone, and the values of relative extension range from ε = 0% to ε = 2%. In this area the relative fabric thickness slightly increases from zero to the value of ε_t = 2.5%. Then in the second phase the relative fabric thickness ε_t grows rapidly. Values of the tensile force increase from F = 30 N to F = 110 N, while those of the relative extension rise from ε = 2% to ε = 6%. For ε_t > 2.5% the relative fabric thickness ε_t increases, and when the force is about F = 110 N and the relative extension amounts to ε = 6%, it reaches the maximum value, amounting to ε_t = 40 – 43%. In the third zone the highest average value of relative fabric thickness is reached, with its average value amounting to ε_t = 41.5 % which is constant in the area where values of the tensile force rise from F = 110 N to F = 260 N, and those of the relative extension rise from ε = 6% to ε = 9.5%. In the case of a further increase in force and relative extension in the fourth zone, the relative fabric thickness decreases more rapidly from its average value of ε_t = 41.5% to fabric rupture.

Fabrics of different weft densities reach approximately the same maximum values of relative fabric thickness with almost equal forces and relative extensions. It follows that the weft density does not affect fabric thickness when it is subjected to the action of a tensile force in the weft direction.

When a force acts in the weft direction (***Figure 8***), the relationship between the fabric and yarn radius (*t/r*) is 4.1 at the beginning of the measurement, which corresponds to the V phase according to Novikov. In the area of relative extension from ε = 1.8 % to ε = 5.7 % the ratio of *t/r* linearly rises with the relative extension, and *at* = 3.1% ratio *d/r* is 4.5, corresponding to phase VI. When ε = 4.23%, ratio *t/r* is 5, corresponding to phase VII. When ε = 5.45%, ratio *t/r* is 5.5 corresponding to phase VIII. In phase IX ratio *d/r* reaches the maximum value which is 5.8 when ε = 7.2%. When t/r reaches the maximum value (phase IX), a slight decline in the relationship between the fabric thickness and yarn radius ensues.

Determination of out-of-plane woven fabric ratio

According to ***Equation (12)*** and based on the experimental values of the relative thickness strain ε_t and relative axial strain ε according to ***Figure 7***, values of the out-of-plane woven fabric ratio λ are calculated for the case where a force acts on samples cut in the weft direction. ***Figure 8*** shows a curve of the values of the out-of-plane woven fabric ratio λ in relation to its axial strain for the case where a force acts on samples cut in the weft direction.

The shape of the out-of-plane woven fabric ratio curve is a result of internal interactions in woven fabrics. A change in the values of the relative thickness strain of woven fabrics, shown in ***Figure 7***, affects the shape of the out-of-plane woven fabric's ratio curve, displayed in ***Figure 9***. In the early stages of the curves (from axial strain 0 to 1%, ***Figure 7***), the variation in fabric thickness is very small, and the out-of-plane woven fabric ratio is approximately zero, shown in ***Figure 9***. This means the fabric has stable thickness in the low stress condition, which is explained by the fact that that the co-constraints of the interlaced warp and weft threads in the fabrics prevent the crimp stretching of the yarns in the loading direction. As the stretching progresses, the value of the relative thickness strain increases very quickly, shown in ***Figure 7***, and the out-of-plane woven fabric ratio shows linearity with the relative axial strain, observed in ***Figure 9***. In the area between ε = 1% and ε = 5.9% the out-of-plane woven fabric ratio λ increases very quickly. When a force acts on samples that are cut in the weft direction, at a relative extension of the woven fabric between ε = 4.8% and ε = 5.9% the out-of-plane woven fabric ratio λ assumes the maximum value, between λ = 6.19% and λ = 7.69%, shown in ***Figure 9***. After reaching the maximum value, the out-of-plane woven fabric ratio curve decreases, the likely cause of which is that yarns in the fabric begin to stretch and λ of the yarns along the tension direction decreases quickly. This is considered to be the main factor affecting thickness strain during stretching. Thereafter, the out-of-plane woven fabric ratio gradually becomes small in the latter part of the curves. This implies that the thickness change becomes small again when the axial strain becomes higher, and deformation is mainly caused by the squeezing and deformation of yarns.

In the weft direction the values of the out-of-plane woven fabric ratio decrease with increasing weft yarn density at the same relative extension, ***Figure 9***.

Conclusions

Investigations of fabric thickness changes under the influence of tensile axial forces acting in the weft direction were carried out on a fabric sample of known fineness, constant warp density and variable weft density. Measurements of fabric dynamic thickness were performed on a newly constructed measuring apparatus which simultaneously records all necessary values of a changing tensile force and associated extension. The thickness strain-axial strain relationship and corresponding out-of-plane woven fabric ratio of five fabrics were obtained using the newly constructed measuring device.

The intersection of warp and weft threads causes a certain deformation of the shape of the yarn cross-section and a certain fabric density is obtained under the influence of forces in the warp and weft. The fabric thickness parameter may be used to observe and measure this deformation. The intensity of thickness change depends on a number of structural elements of yarn and fabric as well as on the technological conditions of fabric formation. The internal fabric structure opposes the influence of external forces, which lasts until the dwelling of the fabric, where forces are balanced and the fabric takes on its final parameters. Test results have shown that an increase in axial tensile forces on the fabric causes an increase in fabric thickness for all fabric densities. When a force acts in the weft direction, the thickness increases, probably because of competition between the two following phenomena. First, the weft yarn decrimps, which makes the fabric thicker. As a result of balancing the weaving-in of weft threads, an increase in pressure on warp threads results. This pressure creates the additional strain of warp threads and stimulates a simultaneous and continuous exchange of the weaving-in of warp and weft threads, resulting in an increase in in-weaving in the warp threads. Second, the internal interaction of threads causes the narrowing of the fabric in the transverse direction, which causes a change in fabric thickness. Weft threads get closer to each other and straighten, and warp threads simultaneously increase their waviness. Due to this occurrence the rectangular shape of the sample gets lost, i.e. the fabric sample is narrowed. This results in an increase in fabric thickness.

The results show that the thickness strain-axial strain curves are non-linear and could be divided into three approximate linear regions, making it possible to define the out-of-plane woven fabric ratio. Deviations of fabric thickness results were small for different weft yarn densities of the woven fabric. When a force acted in the weft direction, the difference in maximum fabric thicknesses was 1.7% = 0.009 mm. It follows that a change in weft density does not affect fabric thickness change when the fabric is subjected to the action of a tensile force in the weft direction.

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