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Analysis of knitted fabrics deformations non-uniformity

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ABSTRACT

The article presents the tensile forces caused knitted fabrics' deformations non-uniformity analysis. At first, the tensile behaviour was analysed by applying new method based on specific Y-shaped and stretching specimen. This shape of specimen allows to fulfil wearing conditions of apparel made of knitted fabrics. After this, the article analyses research conditions and knitted fabrics' deformability physical characteristics and determines longitudinal, transverse and angular deformations. The deformations properties were evaluated using graphic and numerical methods. Investigations have shown that elastane fibres significantly influenced fabric deformability, dimensional changes and deformations' non-uniformity. Experiments have also shown that Y-shaped specimen tensile test is a simple, universal and reliable method suitable to obtain quantitative information about textile materials deformability.

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KEYWORDS
Knitted fabrics; textile deformations; deformations non-uniformity; finite element method (FEM); extension

1. Introduction

In recent years, the textile industry has been directed towards special types of garments, which should be comfortable for consumers, thus their technical, economical characteristics and quality became very important. Textile materials with new characteristics and specific, complex apparel products with various types of combinations are being developed (Audzevičiūtė-Liutkienė, Masteikaitė, Jucienė, Sacevičienė, & Dobilaitė, 2017; Ugbolue et al., 2010; Wambua, Ivens, & Verpoest, 2003; Yexiong, Jialu, & Liangsen, 2014). Textile material's mobility depends on its structure and elements position, as well as on its structural elements' deformation properties. The textile materials are required not only to hold their dimensional shape but also to deform at some degree. They are characterized as anisotropic and heterogeneous; therefore, the acting forces have a different effect on the type and degree of their deformation (Bekampienė, Diliūnas, Domskienė, & Strazdienė, 2008; Carvelli, Pazmino, Lomov, & Verpoest, 2012; Chen, Boisse, Park, Saouab, & Breard, 2011; Chen, Ding, & Yi, 2007; Chen & Ye, 2013; Dabiryan, Jeddi, & Rastgoo, 2012; Galliot & Luchsinger, 2010a; Ng, Ng, & Yu, 2005). That is why it is very important to predict fabric properties for the determination of garment's reaction that depend on various factors: different parts of orientation in the garment, different and various fabrics anisotropy, different parts of garment mobility in various directions, presence, and direction of seams and etc. (Bekampienė et al., 2008; Chen et al., 2007; Chen & Ye, 2013; Dabiryan et al., 2012; Dan et al., 2013; Ng, Ng, & Yu, 2005).

It is important to predict and evaluate fabrics properties during manufacture processes (modelling constructions, cutting, joining different parts of the garment and etc.) to guarantee high quality in exploitation (wearing, laundering and etc.). Evaluation of the textile materials deformation and their location lets increase efficiency of the product manufacture process, choose the optimal modelling construction of the garment and guarantee a high quality in exploitation. According to many researchers, the characteristics of shear and extension characterize behaviour of textile materials during their manufacture and exploitation (Galliot & Luchsinger, 2010b; Galliot & Luchsinger, 2010a; Hedfi, Belhadjsalah, & Ghith, 2011; Hivet & Boisse, 2005; Hong, Dongsheng, Oufu, & Ruru, 2011; Hu & Lo, 2002; Hu & Zhang, 1997, Hu, Lo, & Lo, 2000; Jevšnik, Kalaoğlu, Terliksiz, & Purgaj, 2014; Ji, Li, & Qiu, 2006; Klevaitytė & Masteikaitė, 2008).

It should be mentioned that it is difficult to find inexpensive, simple and efficient methods to determine textile materials mechanical behaviour and evaluate the whole system for research purposes. There is a lack of universal methods to evaluate the unique deformational behaviour for various textile materials that are used to produce wearable garments. It is important to decrease the amount of tested specimens, experimental materials, investigation costs and time expenditure.

Three-dimensional modelling and simulations of the deformations properties of textile materials and garments

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Table 1. Structure parameters of the knitted fabrics under investigation.

Fabric code	Fibre composition, %	Knitting type	Mass per unit area w, g/m^2	Density, cm^{-1}	
				Lengthwise direction (abbr. le)	Crosswise direction (abbr. cr)
M1	70 modal, 30 milk protein	Double weft-knitted	166	15	15
M2-EL	66 modal, 30 milk protein, 4 elastane (course yarns)	weft-knitted	162	21	31
M3	100 bamboo	weft-knitted	168	17	22
M4-EL	95 bamboo, 5 elastane (wale and course yarns)	weft-knitted	176	19	27
M5-EL	97 bamboo, 3 elastane (course yarns)	weft-knitted	172	18	23
M6	100 cotton	weft-knitted	120	17	23
M7	100 polypropylene	weft-knitted	180	13	18

have received much attention in recent years in scientific literature (Dan et al., 2013; Hong, Dongsheng, Oufu, & Ruru, 2011; Lim & Istook, 2011; Lin et al., 2011; Liu, Kwok, Li, & Lao, 2010; Masteikaitė & Sacevičienė, 2010; Jevšnik, Kalaoğlu, Terliksiz & Purgaj, 2014). In the textile and apparel industry, 3D modelling is used not only to simulate the virtual garment's view, but also to evaluate the fabrics mechanical behaviour without the necessity to create a real product. Finite element method (FEM) is one of the most universal and widely used methods in engineering. In the textile industry, FEM is used to optimize textile materials, garment manufacturing processes, to evaluate and investigate the stress/strain distribution in fabrics (Allaoui et al., 2011; Hivet & Boisse, 2005; Ng, Ng, & Yu, 2005; Barauskas & Abraitienė, 2011; Omeroglu, Karaca, & Becerir, 2010; Pan, Zeronian, & Breard, 1993; Sacevičienė, Klevaitytė, Masteikaitė, & Audzevičiūtė, 2010; Senthilkumar, Kumar, & Anbuman, 2012).

The aim of this research was to analyse and evaluate the behaviour of knitted materials using a new Y-shaped specimen method according to the complex behaviour of textile materials during exploitation. Y-shaped method is simple and efficient method to analyse mechanical behaviour of textile materials and evaluate the whole system; it can be considered as universal method to evaluate unique deformational behaviour of various textile materials which are used to produce wearable garments.

2. Materials and methods

Seven knitted fabrics with different structure characteristics were purchased commercially as detailed in Table 1. In order to investigate the behaviour of the knitted fabrics during stretching, the samples included fabrics with elastane yarn (samples M2-EL, M4-EL, M5-EL) and fabrics made from non-stretch yarns (samples M1, M3, M6 and M7).

2.1. Experimental model

The Y-shaped specimens with the measurements $b = 100$ mm, b_1 = 50 mm, $l = 100$ mm (working zone) were prepared. At the beginning of the experiment, the angle between lengthwise and crosswise threads was α_0 = 90°. The horizontal lines parallel to the specimen horizontal selvages with interval of 10 mm ±1 mm were drawn and marked from 1st to 9th. Also, on the sides of the specimen two vertical lines V and one vertical line V_0 in the middle of specimen were drawn. The lines were performed using permanent fabric marking pen (line thickness did not exceed 0.1 mm) (Figure 1(a)).

The deformation of fabric during uniaxial stretching is non-uniform. Lateral contraction of the specimen does not become constant at a certain distance away from the clamps but increases gradually towards the centre of the specimen, forming a 'neck' in this type of experiment. With a purpose to perform analysis and determine the type of fabric deformation and also to evaluate fabrics deformation's non-uniformity after stretching, additionally three parameters h_{i}, tr_{i}, α_{i} were analysed in order to determine the longitudinal, transverse and angular deformations at the characteristic points of specimen – 1st, 5th and 9th (Figure 1(b)).

After stretching alterations of horizontal lines were determined by using parameter h_{i} and calculated as follows:

$$h_i = \frac{h}{l}100\%, \tag{1.1}$$

where h – distance from horizontal line to the new position of the point after extension, mm, $i = 1$st, 5th and 9th points; l – specimen length before tension, (100 mm).

The decrease of distance between vertical lines V was determined by parameter tr_{i} and was calculated in comparison with the initial width b_1 of the specimen:

$$tr_i = \frac{tr_1 - b_1}{b_1}100\%; \tag{1.2}$$

where b_1 – initial distance between vertical lines V before tension, (50 mm); tr_1 – distance between vertical lines V after extension, mm, $i = 1$st, 5th and 9th points.

The shear angle α_{i} was measured between the vertical and horizontal lines under tension. The parameter α_{i} was calculated using the following formula:

$$\propto_i = \frac{\propto_1 - \propto_0}{\propto_0}100\%, \tag{1.3}$$

where α_0 – initial angle between horizontal and vertical lines before tension (90°); α_1 – angle between horizontal and vertical lines after extension,°, $i = 1$st, 5th and 9th points.

It is known that knitted fabrics undergo small loads and large strains. In comparison with woven fabrics, knitted

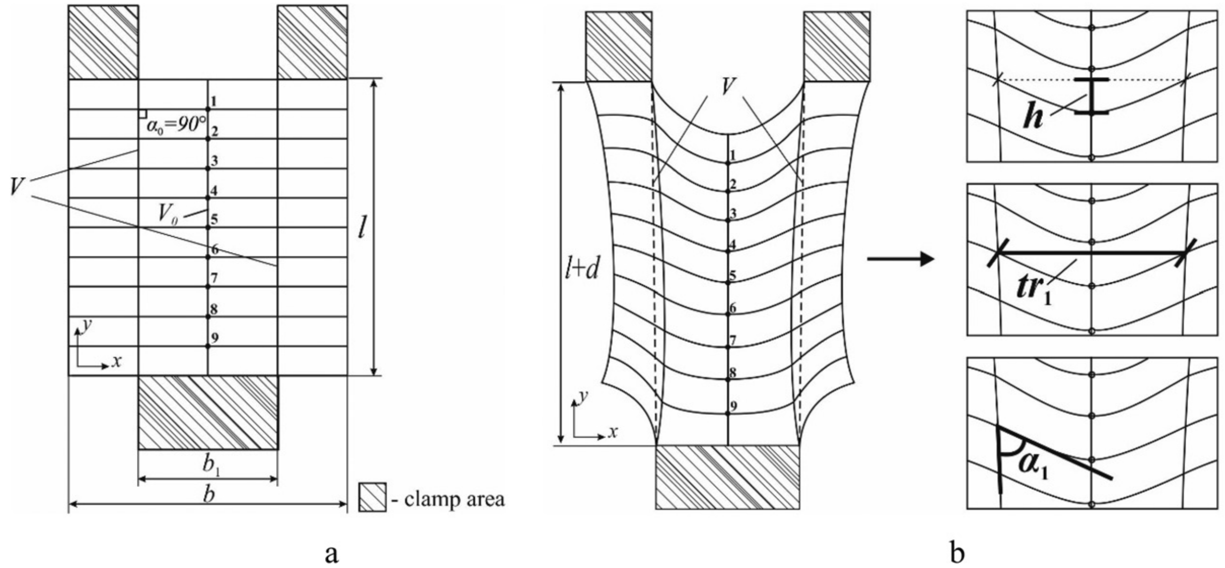

Figure 1. Initial shape of the Y-shaped specimen and its basic measurements (a) and metrical scheme of geometrical parameters during tension process (b).

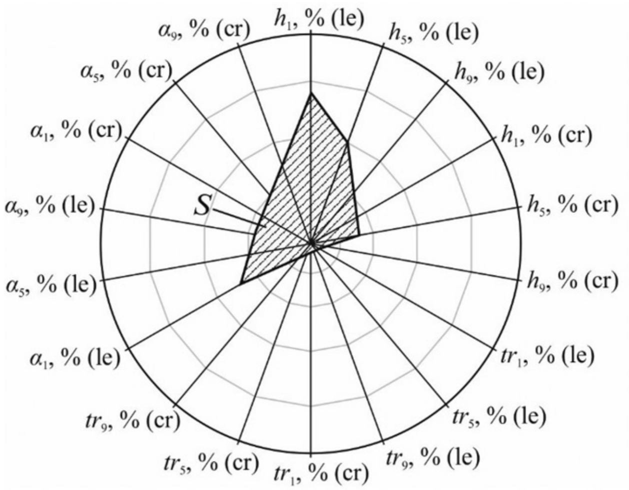

Figure 2. Polar diagram of complex parameter S; le – lengthwise direction; cr – crosswise direction.

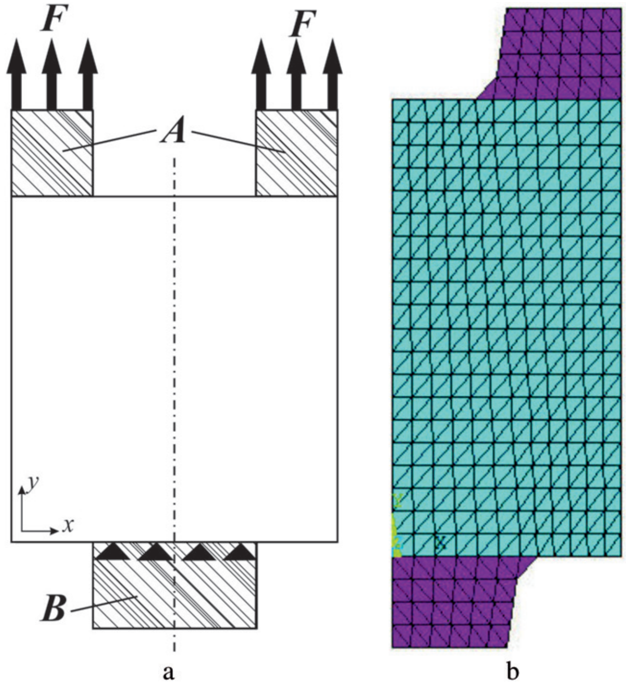

Figure 3. Principal scheme of Y-shaped specimen (a) and specimen divided into finite elements (b).

fabrics have much more extensibility. Taking into account, the real conditions of garment manufacturing and the wear process, the extension ε_Y = 40% was reached, and maximum load did not exceed 5 N/cm. Therefore, the sample fabrics during the experiment were deformed within the limits of elasticity and as a result the elements of the fabrics structure were left undamaged. Complex parameter S was obtained from polar diagram drawn applying three parameters (h_i, tr_i, α_i) of fabric deformation. *AutoDesk AutoCAD 2014* software was used to calculate the area S (Figure 2). Complex parameter S allows describing fabric deformability and wear properties by one numeral value.

Each specimen's data were analysed in lengthwise and crosswise direction using the average results of six specimens. The total relative error of the measurement did not exceed 5.0%. The specimen's extension was carried out using a *Tinius Olsen HT10* tension machine. A cross-head speed was kept at $v = 10 \pm 1$ mm/min. A lower speed was selected in order to observe and record changes in the geometric dimensions of the materials. All fabrics were conditioned in standard atmosphere conditions of 65% RH and 20 °C according to the requirements of the international standard LST EN ISO 139: 2005/A1: 2011. The obtained data of deformation characteristics were processed statistically and coefficient of variation did not exceed 10.0%.

2.2. Numerical model

In this part, the tested knitted fabrics deformations were investigated and evaluated using numerical model. *ANSYS* software package was used to simulate knitted fabric behaviour during uniaxial tension. To shorten the calculation time, only one symmetrical side of the specimen was used

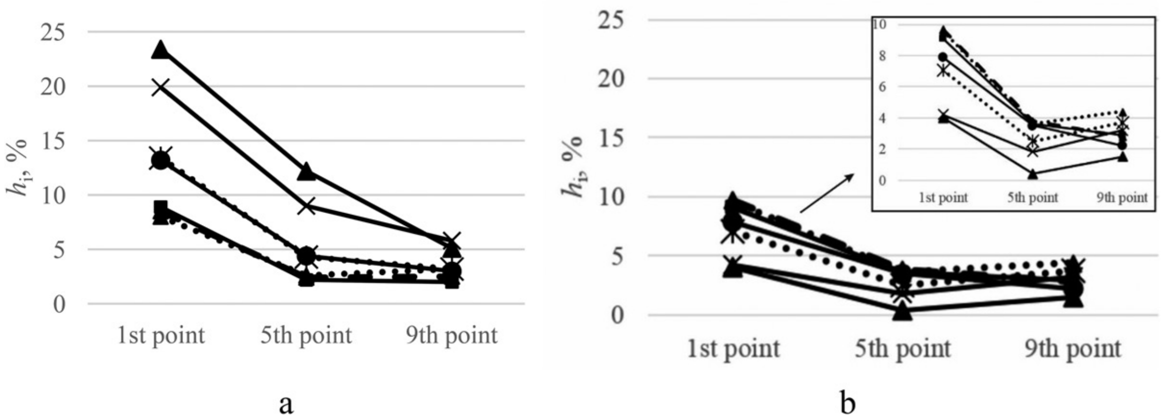

Figure 4. Characteristic h_i in three points of specimen in lengthwise direction (a) and crosswise direction (b).

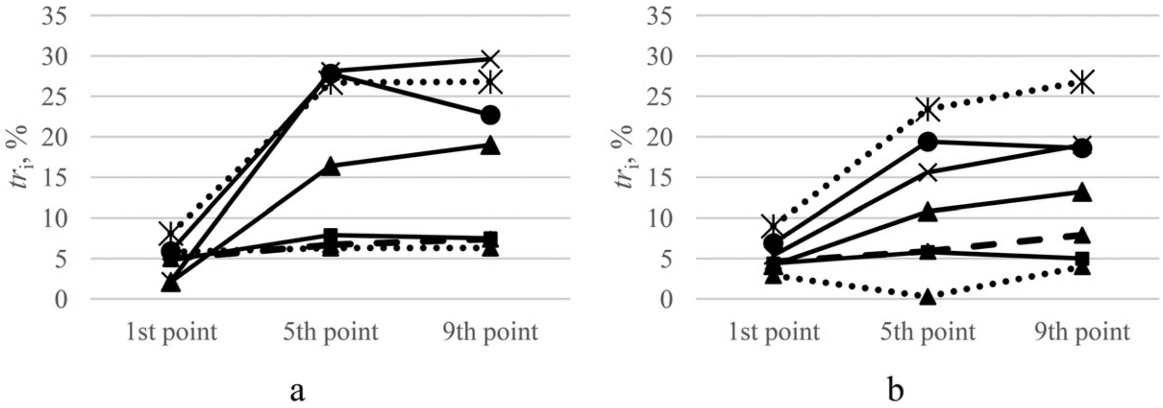

Figure 5. Characteristic tr_i in three points of specimen in lengthwise direction (a) and crosswise direction (b).

(Figure 3(a)). In this study, the yarns are considered as orthotropic solid bodies. In order to ensure adequacy of the model to the real stress-strain state, typical in case of the whole Y-shaped specimen, the structure was fixed by indicating symmetry conditions to the corresponding surfaces. Structural displacements were restricted by fixing part *B* rigidly and parts *A* were allowed only vertical motion. For the simulation purposes, the knitted fabric M7 (100% polypropylene) in lengthwise direction was used in this study with the following mechanical properties: E_x = 0.9 MPa and E_y = 2.0 MPa (Young‘s modulus), $G_{x,y}$ = 0.018 MPa (shear modulus), μ_1 = 0.43 and μ_2 = 0.19 (the Poisson ratio). These mechanical properties were indicated by manufacturers. Since all the components of the real investigated object were basically of flat type, its geometrical model is made from surfaces, while in numerical model these surfaces are split using *Plane 42* type finite elements (Figure 3(b)) (Chen, Boisse, Park, Saouab, & Breard, 2011; Sidabraitė & Masteikaitė, 2003; Wambua, Ivens, & Verpoest, 2003).

The grid was regular, its elements had two degrees of freedom in every nodal point and allowed calculating all the parameters, necessary to evaluate the state of elastically deformable flat thin-walls structures (Hedfi, Belhadjsalah, & Ghith, 2011; Lomov et al., 2007; Yexiong, Jialu, & Liangsen, 2014). Designing the numerical model, it was considered that knitted fabric was deformed up to 40 mm by 5 mm steps.

3. Results and discussion

3.1. Uniaxial test on Y-shaped specimen

When the gauge length stretched from l to $l + d$ (distance between clamps), Y-shaped specimen was affected by opposite direction forces. The geometry of fabric loops changed when Y-shaped specimen subjected to the tensile forces and elastic deformation of knitted fabrics occurred in two stages. In the first stage, only the head of loop is deformed and all of the interconnecting links contacted each other. In the second stage, the length of elements was changed. A result of this phenomenon is complex deformations. The most significant longitudinal, transverse and angular deformations were determined in the centre of the specimen (rectangular area between vertical lines *V)* (Figure 1(b)). The parameters h_i, tr_i and α_i, which represents the deformation properties and deformation non-uniformity after stretching, are presented in Figures 4, 5 and 6, respectively. Parameters h_1, h_5 and h_9 define longitudinal deformations and alterations of longitudinal dimensions and range from 2.0 to 23.4% in lengthwise direction and from 0.4 to 9.7% in crosswise direction. The greatest changes in the values of parameter h_i of both directions were observed at the 1^{st} point. Meanwhile the lowest changes in parameter h_i of knitted fabrics were also established in the 9^{th} point, here, the values of parameter h_9 did not exceeded 10%. In Figure 4, parameter h_i curves are located diversely. The curves of fabrics M1 and M7 demonstrate the most significant longitudinal alterations

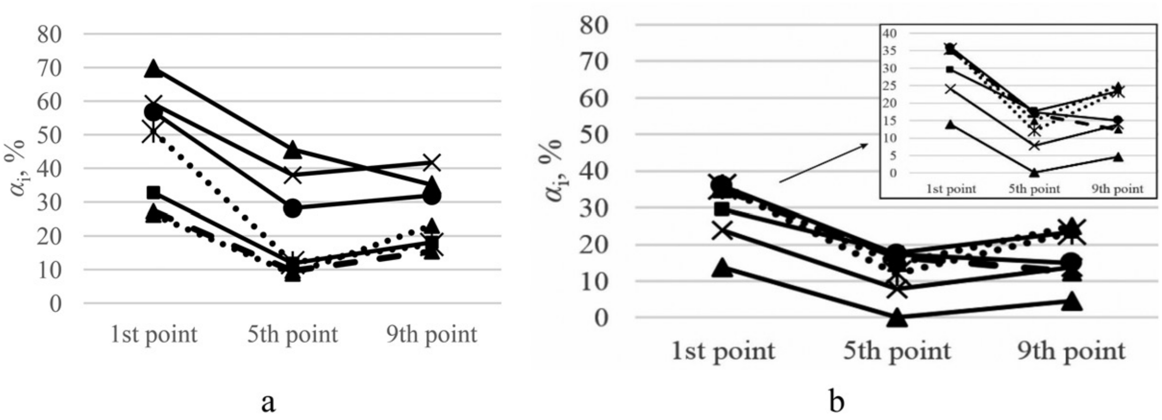

Figure 6. Characteristic α_i in three points of specimen in lengthwise direction (a) and crosswise direction (b).

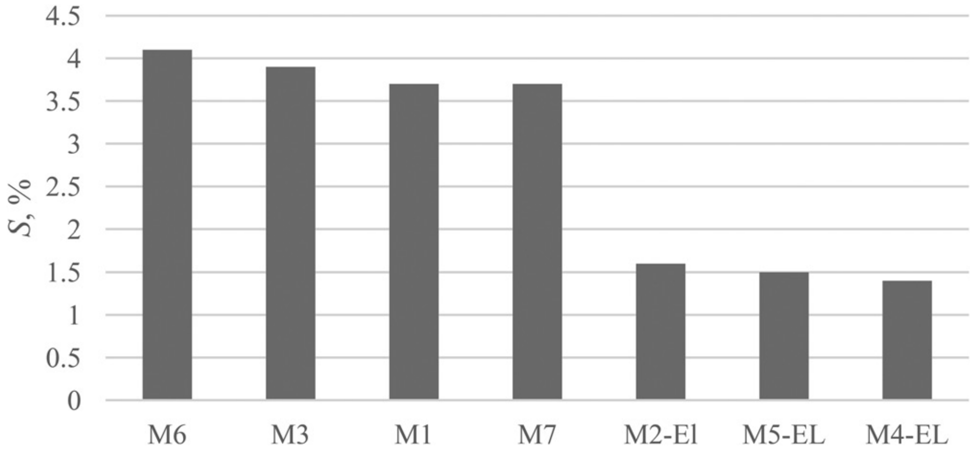

Figure 7. Arrangement of the complex parameter S_Y from the highest to the smallest values.

where parameter h_i reaches up to 20% in the 1st point in lengthwise direction. In knitted fabrics M3 and M6 lower longitudinal alterations were determined and in knitted fabrics M2-EL, M4-EL, M5-EL longitudinal deformations in lengthwise direction marginally (Figure 4(a)) were determined. By contrary, parameter h_i values in knitted fabrics M2-EL, M4-EL and M5-EL demonstrate the most significant longitudinal alterations in the crosswise direction (Figure 4(b)). The reason for such reversal phenomenon could be the fabrics knitted structure. The parameter h_i, when loops are subjected to a tension along wale direction under low displacement, depends mostly on fibres viscosity. However, when loops are subjected to a tension along course direction, parameter h_i depends more significantly on fabrics density. In comparison with non-uniformities in lengthwise direction, non-uniformities in crosswise direction are significantly lower. In crosswise direction changes in parameter h_i of all the tested knitted fabrics between 5th and 9th points are very similar (vary from 0.5 to 1.9%), here, the curves from 5th to 9th point remain almost on equilibrium. In lengthwise direction longitudinal deformations of non-elastane knitted fabrics are more significant compared to the knitted fabrics containing elastane yarns due to the higher stiffness under longitudinal tension.

Parameters tr_1, tr_5 and tr_9 were used to define transverse deformations and alterations of transverse dimensions and range from 2.1 to 29.6% in lengthwise direction and from 0.3 to 26.8% in crosswise direction. If the knitted fabric loops were subjected to the tension along wale direction the threads will be stretched in wale direction too. Then the loops become slender, and the fibres inside loops are compressed and there is a tensile stress field in wale direction in threads. If the knitted fabric loops are subjected a tension along course direction the threads are stretched in course direction and the loops become flat. Therefore, parameter tr_1 and deformations non-uniformities of knitted fabrics depend on fabric density, structure stability and yarns stretching. According to the results of parameter tr_i presented in Figure 5, the greatest values of both directions were determined in the 5th and 9th points as against in the 1st point, where values of characteristic tr_1 did not exceed 9%. As it is evident from Figure 5, the lowest transversal changes were determined in fabrics containing elastane yarns M2-EL, M4-EL and M5-EL. Parameter tr_i is the most significant for knitted fabrics M1, M3 and M6 at the 5th and 9th points. These fabrics are less mobile and tensile due to the yarns being more affected by friction, along with the compression forces and transverse dimensions of specimens decrease more rapidly.

Parameters α_1, α_5 and α_9 define angular deformations and alterations of angular dimensions and range from 8.8 to 69.8% in lengthwise direction and from 0.2 to 35.9% in crosswise direction (Figure 6).

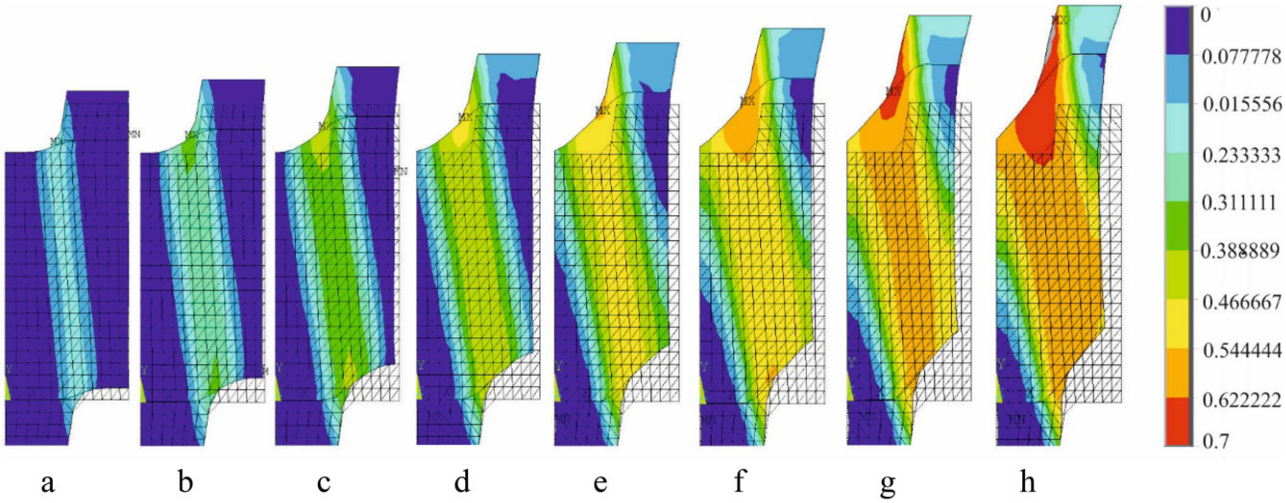

Figure 8. The views of deformations zones in knitted fabric M7 when specimen's full elongation is 5 mm (a), 10 mm (b), 15 mm (c), 20 mm (d), 25 mm (e), 30 mm (f), 35 mm (g), 40 mm (h).

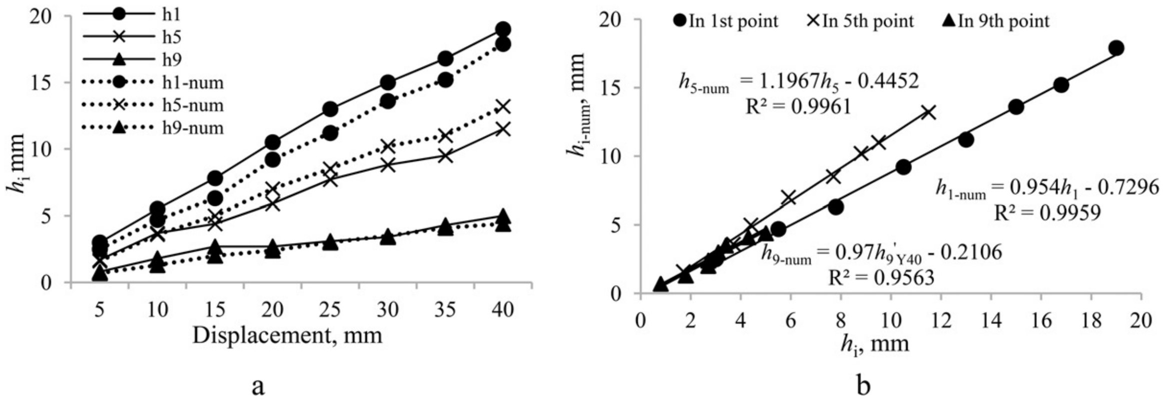

Figure 9. Comparison of results of experimental (*hi*) and numerical ($h_{\text{i-num}}$) methods (a) and dependency between experimental (*hi*) and numerical $h_{\text{i-num}}$ methods (b).

The greatest changes in the values of parameter α_i were observed for polypropylene knitted fabric M7 and fabrics M1, M3 and M6 knitted from cellulose spun yarns in lengthwise direction. Changes in the parameter α_i of knitted fabrics M2-EL, M4-EL and M5-EL were low due to good extensibility and dimensional stability. Analysis of the obtained results has shown the same trend in the parameters h_i and α_i values, here, the greatest changes in the values were detected at the 1st point (Figures 4 and 6). Also the values of parameter α_i of knitted fabrics M7 and M1 reached the highest value in the lengthwise direction compared with the results in the crosswise direction as parameter h_i. During knitted fabric stretching with the extension distance $\varepsilon_Y = 40\%$ specimen elongation occurs due to the shearing and tightening of the fabric structure, and partly to loops extension. Therefore, fabrics made from non-stretch yarns undergo on friction and deformations.

According to the changes of three parameters h_i, tr_i and α_i have been estimated complex parameter *S*, which characterize general woven fabrics deformability. The aforesaid parameter has been arranged from the smallest to the highest values (Figure 7).

The results presented in Figure 7 demonstrate different deformation rate of tested knitted fabrics. It was determined that knitted fabrics M2-EL, M4-EL, M5-EL might be characterized as more flexible and stretchable ($S_Y < 2.0\%$). Meanwhile knitted fabrics M1, M3 and M6 demonstrate more significant deformability of structure elements. It means that less mobile structure fabrics, especially made from non-stretch yarns (samples M1, M3, M6 and M7) are more affected by friction and non-uniformities are more significant. The abovementioned factors affect significant differences of complex parameter *S* between knitted fabrics M1, M3, M6, M7 and M2-El, M4-El, M5-EL (from 2.31 up to 2.93 times).

3.2. Evaluation of deformation non-uniformity using numerical model

The predicted total displacement diagram as is shown in Figure 8. The aforesaid diagram illustrates knitted fabrics deformations zones and deformations non-uniformity after stretching were Y-shaped specimen is deformed till 40 mm by 5 mm steps.

It can be seen that the deformations zones were not significant and located from upper to bottom selvages diagonally deforming by 5–10 mm (Figure 8(a,b)). Deformations zones reached value of 0.4, when the specimen's full elongation was 15–20 mm (yellow field) (Figure 8(c,d)). Deformations zones extended and reached the middle of the specimen deforming by 25 mm (Figure 8(e)). In the specimen selvages, especially upper, deformations reached the critical limit and deformations zones extended almost in the whole specimen when specimen's full elongation was 30 mm (Figure 8(f)). In the upper and bottom selvages of the specimen, deformations reached about 0.6, deforming from 35 to 40 mm (Figure 8(g,h)). Also, the most significant deformations zones were located in the upper selvages, top of the middle part of specimen and at the sides of specimen. In case to verify acceptability of numerical ($h_{i\text{-num}}$) research methodology results, they were compared with experimental (h_{i}) results in the 1st, 5th and 9th points (Figure 9(a)). According to the values of parameters h_{i} and $h_{\mathrm{i\text{-}num}}$ presented in Figure 9(a), the difference between the above parameters did not exceed 9.8%.

In Figure 9(b), the linear dependency between experimental and numerical methods was determined ($R^2 = 0.9563 \div 0.9961$). This identifies the strong linear dependency between the experimental and numerical methods.

4. Conclusions

The obtained results illustrated that knitted fabrics' deformations non-uniformities of the knitted fabrics depend on the fibre content, especially in case of elastane fibres. The most significant deformations non-uniformities were established to fabrics made from non-stretch yarns (samples M1, M3, M6 and M7).

The applied test method based on uniaxial Y-shaped specimen was established to allow determining changes in the properties of knitted fabrics after stretching thereof.

Numerical experiment of Y-shaped specimen clearly demonstrated deformation zones in knitted fabrics specimens and confirmed fabrics deformation non-uniformity.

Research determined the significant correspondence between numerical and experimental methods. This means there was strong linear dependency between experimental and numerical methods. Therefore, it can be stated that the experimental Y-shaped specimen method results are suitable for both practical and scientific use.

Disclosure statement

No potential conflict of interest was reported by authors.

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