Krzysztof Kowalski[1],
Magdalena Kłonowska[1,*],
Anita Ilska[1, 2]

Selecting Appropriate Longitudinal Rigidity of Knitted Fabric in Compression Products of Standardised Size

DOI: 10.5604/01.3001.0013.9017

[1] **Lodz University of Technology, Department of Knitting Technology and Textile Machines,**
Lodz, Poland,
* e-mail: magdalena.klonowska@p.lodz.pl

[2] **Łukasiewicz Research Network – Textile Research Institute,**
Lodz, Poland

Abstract
Based on the models developed, the changes in unit pressure exerted by ready-made compression products were evaluated in dependence on the longitudinal rigidity, compression class, dimensional tolerance and product size. Tests made it possible to determine the maximum permissible values of longitudinal rigidity for individual compression classes and product sizes, which, if not exceeded, ensure that the pressure exerted falls within the given compression class. Experimental verification carried out on an example of a commercial compression product from the first and second compression classes showed that the main reason for the differences between the declared and experimentally determined values of unit pressure was the overestimated longitudinal rigidity of the knitted fabric and dimensional tolerance of the size ranges and errors in the design procedure, resulting from not sticking to the principle of designing the product for the middle circumference value and the middle pressure from the compression class.

Key words: *compression products, unit pressure, Laplace's law, compression classes, longitudinal rigidity, knitted fabric, product size.*

Introduction

In the design of compression products supporting the process of external treatment, one of the most important parameters is the value of unit pressure which the product exerts on the user's body. The value range of this parameter is determined from the medical point of view, depending on the type of therapy, and should be strictly observed [1-6]. Most of the ready-made compression products supporting the process of external treatment available on the market appear in various sizes and manufacturing tolerances. Manufacturing tolerance determines the difference between the middle value of the body circumference and the extreme values of the size range width. The product fulfills quality requirements for the given compression class regarding the value range of unit pressure when it provides an appropriate compression value for the entire size range width. The pressure value is assessed using Laplace's law, most often by an indirect method based on measuring the force in the knitted fabric from which the product is made, which is stretched out to the length of the body circumference. A detailed procedure for assessing the pressure value is contained in the standards [7-9], which refer to the evaluation of stockings and compression sleeves used in the treatment of varicose veins and lymphedema. In [10], based on the models developed, an analysis was made of the impact of the assumed manufacturing tolerances of the compression product on the value of unit pressure in dependence on the longitudinal rigidity of the compression fabric for relatively small body circumferences. The research results presented made it possible to formulate some guidelines for the design of compression products for small body circumferences. In the design procedure of compression products, regardless of the manufacturing technique, the important factors affecting the intended value of unit pressure include the dimensioning accuracy of body circumferences G_1 and their distance from the base [11]. Relatively high accuracy in determining the value of circumferences G_1 can be obtained by using 3D scanners [12-19], which eliminate some of the reasons for the scatter of measurement results which are due to the manual methods of taking the measurements. The review article [20] presents different aspects of the design and modelling of compression products.

The aim of this work is to document, on the basis of the algorithms developed and experimental studies, the influence of the longitudinal rigidity of knitted fabric in ready-made compression products for tabulated body circumferences on the value of unit pressure, and to indicate the maximum permissible values of longitudinal rigidity of the fabric depending on the dimensional tolerance and product size.

Methodology

The following assumptions were made for the research presented in this work:

1. The relationship between the unit pressure P, the circumferential force F in knitted fabric of width s and the body circumference G_i is described by Laplace's equation
2. The dependence between the force F and relative elongation ε of the knitted fabric is described by the linear relationship $F = a \cdot \varepsilon$
3. The difference between the middle value of the i-th body circumference G_{isr} and its extreme values G_{imax} and G_{imin} is determined by the dimensional tolerance of the given size $\Delta G_i = G_{isr} - G_{imin}$, $\Delta G_i = G_{imin} - G_{isr}$.

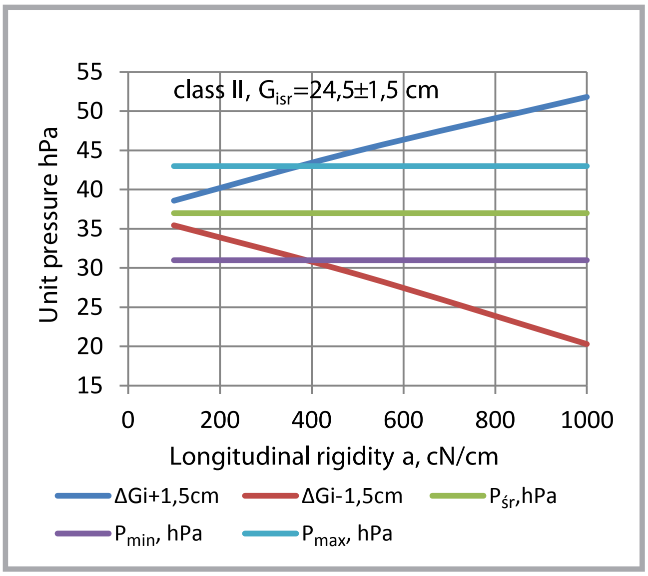

Figure 1. *Changes in unit pressure P for the middle value of G_{isr} and extreme values of circumferences $G_{isr} \mp \Delta G_i$ in dependence on the longitudinal rigidity of the knitted fabric.*

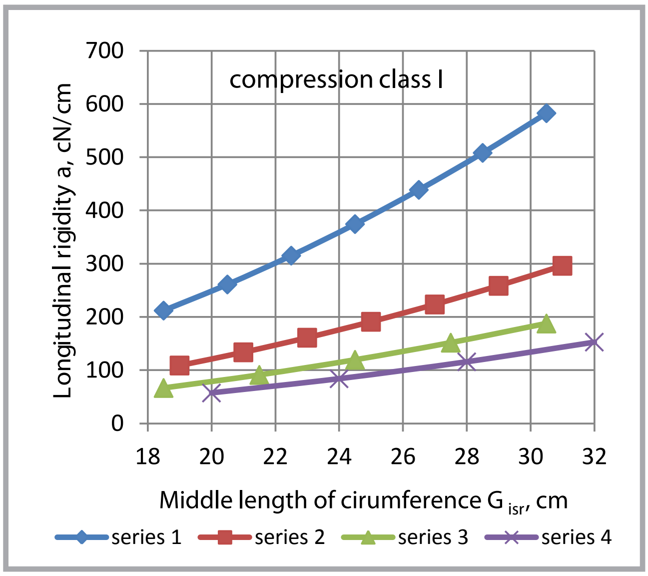

Figure 2. *Maximum permissible longitudinal rigidity of a knitted fabric in dependence on the middle value of circumference lengths and dimensional tolerance for individual size groups. Series 1 – ΔG_i = ± 0.5 cm, series 2 – ΔG_i = ± 1.0 cm, series 3 – ΔG_i = ± 1.5 cm, series 4 – ΔG_i = ± 2.0 cm.*

The aim of the considerations is to calculate the maximum longitudinal rigidity *a* cN/cm of a compression fabric for which the value of unit pressure *P* exceeds neither the lower nor the upper pressure value for the given compression class when changing the length of the circumference G_{isr} by ± ΔG_i. The considerations are based on the assumption that compression hosiery products for individual sizes are designed and manufactured for the middle values of circumferences G_{isr} from the given size range and for the middle value of unit pressure P_{sr} for the given compression class. Circumference lengths G_{0i} in a relaxed state for the middle value of body circumferences G_{isr} and for the middle value of unit pressure $P_{sr} = 0.5(P_{max} + P_{min})$ for the given compression class ***Equation (1)***.

$$G_{0i} = \frac{2\pi a \cdot G_{isr}}{P_{sr} \cdot G_{isr} \cdot s + 2\pi a} \qquad (1)$$

The maximum longitudinal rigidity *a* cN/cm of a compression fabric for which the unit pressure *P* exceeds neither the lower nor the upper pressure value when changing the length of the circumference G_{isr} by $\pm \Delta G_i$ by can be calculated from ***Equations (4)*** and ***(5)***. ***Equation (4)*** was obtained by comparing the sides of ***Equation (1)*** with ***Equation (2)*** and ***Equation (5)*** by comparing ***Equation (1)*** with ***Equation (3)***.

$$G_{0i} = \frac{2\pi a \cdot G_{sr}}{P_{min} \cdot (G_{isr} + \Delta G_i)s + 2\pi a} \qquad (2)$$

$$G_{0i} = \frac{2\pi a \cdot G_{isr}}{P_{max} \cdot (G_{isr} - \Delta G_i)s + 2\pi a} \qquad (3)$$

$$a \leq \frac{G_{sr} \cdot s(G_{isr} - \Delta G_i) \cdot (P_{sr} - P_{min})}{2\pi \cdot \Delta G_i} \qquad (4)$$

$$a \leq \frac{G_{sr} \cdot s(G_{isr} + \Delta G_i) \cdot (P_{max} - P_{sr})}{2\pi \cdot \Delta G_i} \qquad (5)$$

The maximum permissible longitudinal rigidity of the knitted fabric was calculated for the minimum leg circumference, i.e. the narrowest point above the ankle. The choice of this place is justified by the fact that the shortest circumferences are the most sensitive to the longitudinal rigidity of the knitted fabric, as well as to the dimensional tolerance, size and manufacturing tolerance of the product [10]. In addition, the value of unit pressure at the narrowest point above the ankle is clearly and normatively defined [7-9]. Analysis of the size charts for compression hosiery products shows that manufacturers tend to apply different size ranges (***Table 1***). However, tolerance $\Delta G_i = \pm 0.5$ cm makes the production of ready-made compression products similar to that of "custom-made" articles, especially for larger body circumferences.

Exemplary changes in unit pressure for compression class II, for extreme values of the size range $G_{isr} \pm \Delta G_i$ in dependence on the longitudinal rigidity are shown in ***Figure 1***. With the increasing longitudinal rigidity of the knitted fabric, the change in body circumference in relation to its middle value G_{isr} by $\Delta G_i = +1.5$ cm causes a linear increase in pressure for a positive value of ΔG_i or a pressure decrease for its negative value. The points of intersection of straight lines for $\Delta G_i = 1.5$ cm and $\Delta G_i = -1.5$ cm with pressure values for the upper and lower limits of the class – P_{min} and P_{max} – determine the maximum permissible values of longitudinal rigidity of the knitted fabric, which, if not exceeded, guarantee pressure within the given compression class.

Analysis of ***Figures 2-4*** shows that when the size of the product increases, the maximum permissible values of longitudinal rigidity of the knitted fabric also rise, according to the square function (4 & 5).

Table 1. *Leg circumferences at the narrowest point above the ankle for different sizes.*

Range tolerance, cm	Size range width, cm	*Circumferences at the narrowest point above the ankle, cm*
$\Delta G_i = \pm 0.5$	18-19, 19-20 31-32	
$\Delta G_i = \pm 1.0$	18-20, 20-22 30-32	
$\Delta G_i = \pm 1.5$	18-21, 21-24 30-33	
$\Delta G_i = \pm 2.0$	18-22, 22-26 30-34	

Figure 3. *Maximum permissible longitudinal rigidity of a knitted fabric in dependence on the middle value of circumference lengths and dimensional tolerances for individual size groups. Series 1 – $\Delta G_i = \pm 0.5$ cm, series 2 – $\Delta G_i = \pm 1.0$ cm, series 3 – $\Delta G_i = \pm 1.5$ cm, series 4 – $\Delta G_i = \pm 2.0$ cm.*

Figure 4. *Maximum permissible longitudinal rigidity of a knitted fabric in dependence on the middle value of circumference lengths and dimensional tolerances for individual size groups. Series 1 – $\Delta G_i = \pm 0.5$ cm, series 2 – $\Delta G_i = \pm 1.0$ cm, series 3 – $\Delta G_i = \pm 1.5$ cm, series 4 – $\Delta G_i = \pm 2.0$ cm.*

Applying higher longitudinal rigidities of the compression fabrics than the ones determined by the analytical method, according to ***Equations (4)*** and ***(5)***, leads to an over – or underestimation of the value of unit pressure, beyond the range of a given compression class. The greater the dimensional tolerance $\pm \Delta G_i$ (series 3, 4), the lower the values of longitudinal rigidity of the knitted fabric that should be applied, as they show less sensitivity to changes in the unit pressure caused by the differences between the average value of circumferences G_{isr} and their extreme values $G_{isr} \mp \Delta G_i$.

Summary charts of the maximum permissible values of longitudinal rigidity a, cN/cm for individual compression classes I, II and III, the middle length of the circumference G_{isr} and dimensional tolerance $\mp \Delta G_i$ shown in ***Figure 5-7*** confirm the assumptions regarding compression classes and the hypothesis that the higher the compression class, the higher the maximum permissible values of longitudinal rigidity of the knitted fabric.

Results and discussion

Experimental verification of the compatibility of unit pressure exerted by ready-made compression products used in the treatment of varicose vein and lymphedema is based on the assumption that these products are designed and manufactured

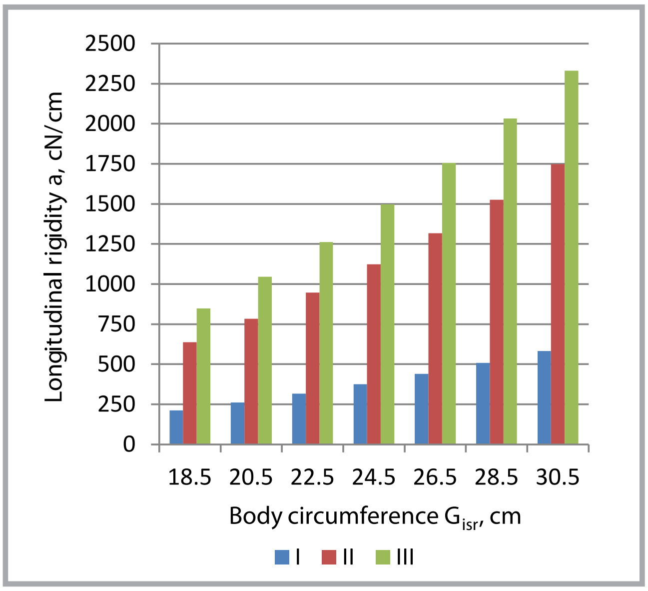

Figure 5. *Maximum permissible value of longitudinal rigidity of a knitted fabric a, cN/cm in dependence on the middle value of circumferences G_{isr}, the compression class and dimensional tolerance for individual size groups for series 1 – $\Delta G_i = \pm 0.5$ cm.*

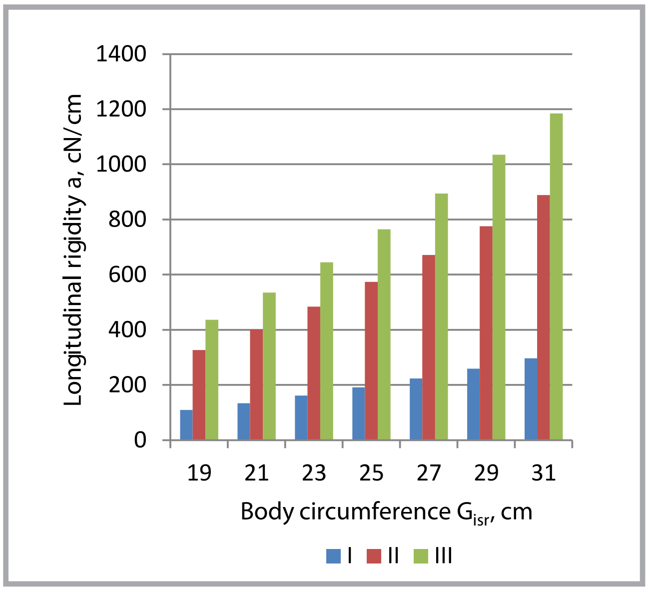

Figure 6. *Maximum permissible value of longitudinal rigidity of a knitted fabric a, cN/cm in dependence on the middle value of circumferences G_{isr}, the compression class and dimensional tolerance for individual size groups for $\Delta G_i = \pm 1.0$ cm.*

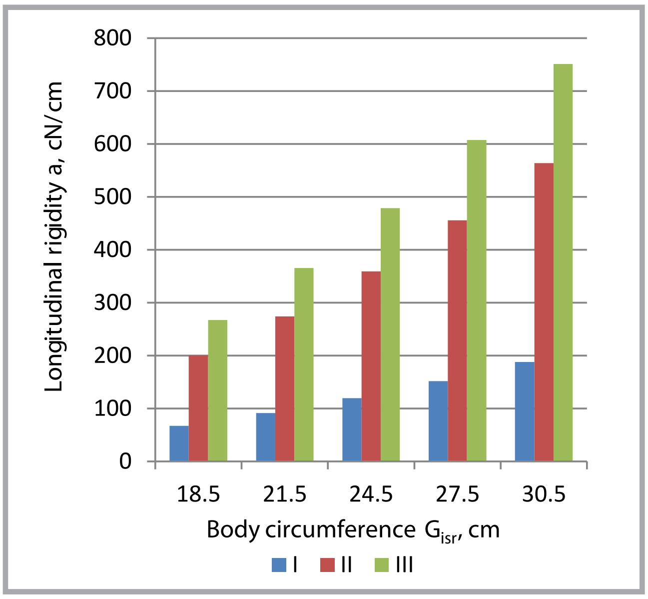

Figure 7. *Maximum permissible value of longitudinal rigidity of a knitted fabric a, cN/cm in dependence on the middle value of circumferences G_{isr}, the compression class and dimensional tolerance for individual size groups for $\Delta G_i = \pm 1.5$ cm.*

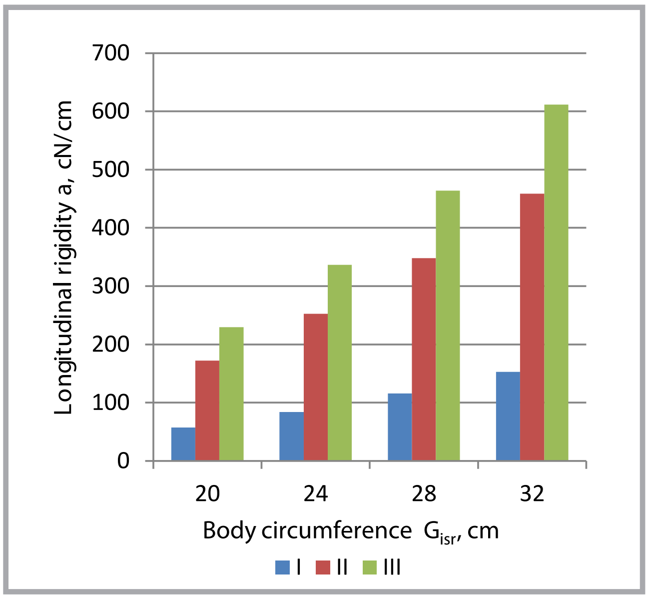

Figure 8. *Maximum permissible value of longitudinal rigidity of a knitted fabric a, cN/cm in dependence on the middle value of circumferences G_{isr}, the compression class and dimensional tolerance for individual size groups – manufacturer B, $\Delta G_i = \pm 2.0$ cm.*

for the middle circumference value from the size range and the middle value of pressure for the given compression class. Relative elongation values ε were calculated according to the ***Equations (6)*** and ***(7)*** on the basis of the free length measurement of circumferences G_{0i} of commercial compression products, such as stockings, the middle value of circumference G_{isr} and its extreme values, i.e. increased and reduced by tolerance ΔG_i for the declared size.

$$\varepsilon_{isr} = \frac{G_{isr}}{G_{io}} - 1 \qquad (6)$$

$$\varepsilon_{(G_{isr} \pm \Delta G_i)} = \frac{G_{isr} \pm \Delta G_i}{G_{io}} - 1 \qquad (7)$$

Then, for the determined values of relative elongations ε, the force *F* in the knitted fabric was measured. For this purpose, a few samples of knitted fabric were collected from stockings at the point above the ankle with the smallest circumference, and in accordance with standard [7], they were subjected to stretching and relaxation up to the determined values of relative elongation *ε*. For each value of relative elongation, tests were carried out on 4 samples with a free length of 100 mm and width of 75 mm, subjected to stretching and relaxation processes at a speed of 200 mm/min on a Hounsfield tensile testing machine, using needles to stabilise the width of the fabric.

Figure 9. *Exemplary values of force as a function of the relative elongation in the 6th hysteresis loop in the tension phase for the determined values of relative elongation for a compression stocking from compression class II for three sizes and middle values of circumferences G_{isr}.*

The value of force *F* was taken from the 6th hysteresis loop after the end of the tension phase [21]. In accordance with Laplace's law (8), the value of unit pressure *P* was calculated, which was then compared to pressure values declared for the particular compression class.

$$P = \frac{2\pi \cdot F}{(G_{isr} \mp \Delta G_i) \cdot s} \qquad (8)$$

Analysis of ***Figures 10*** and ***11*** shows that for the five sizes analysed, the unit pressure *P* determined experimentally exceeds the pressure declared for the given compression class, for both the middle value of circumference G_{isr} and its extreme values $G_{isr} \pm \Delta G_i$. The reasons for these differences in the case of compression class I is the overestimated longitudinal rigidity of the compression fabric in relation to the dimensional tolerance of the size range and errors in the design procedure resulting from not sticking to the principle of designing the product for the middle circumference length and middle pressure value from the given compression class. Only for one size from compression class I was the intended value of unit pressure ob-

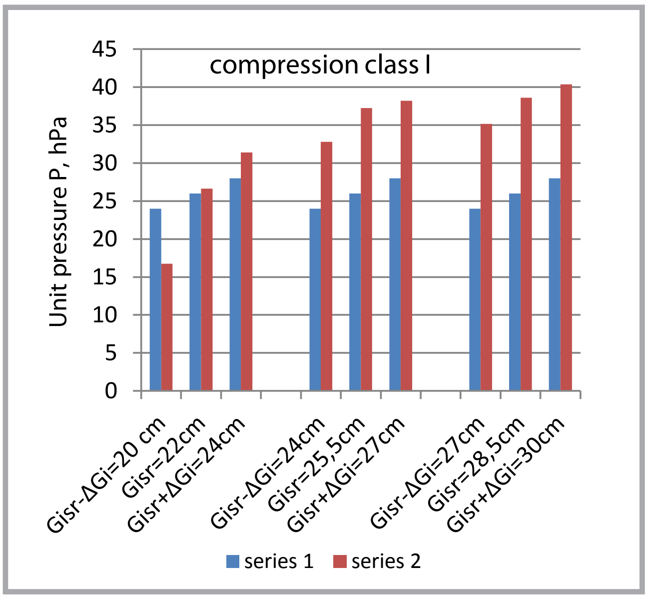

Figure 10. *Values of unit pressure P for three sizes of compression stockings. Series 1 – normative values for compression class I 24-28 hPa, series 2 – experimentally determined pressure values.*

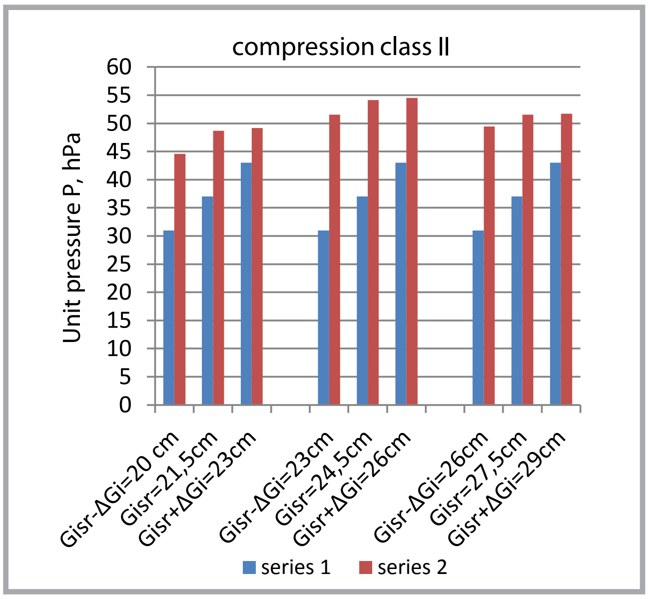

Figure 11. *Values of unit pressure P for three sizes of compression stockings. Series 1 – normative values for compression class II 31-43 hPa, series 2 – experimentally determined pressure values.*

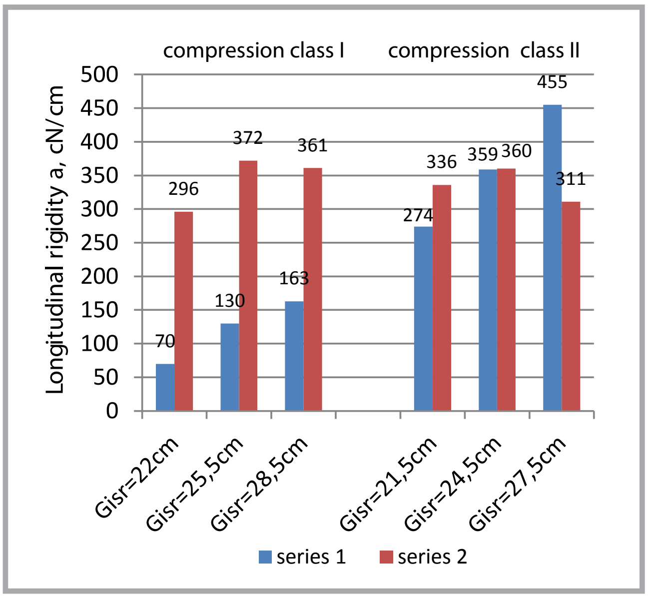

Figure 12. *Longitudinal rigidity of knitted fabric a = F/ε for the middle values of size ranges, series 1 – values calculated from Laplace's law according to* ***Equations (4)*** *and* ***(5)****, series 2 – experimental values.*

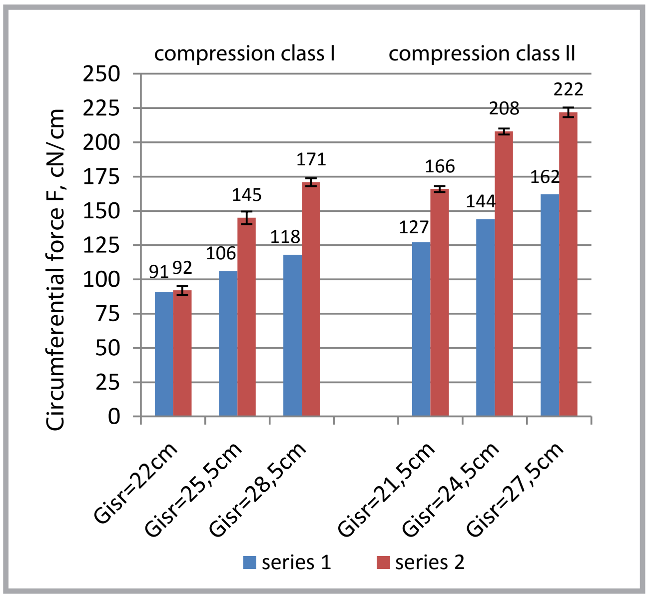

Figure 13. *Circumferential force in knitted fabric for middle values of size ranges, series 1 – values calculated from Laplace's law series 2 – experimental values.*

tained for the middle circumference G_{isr} = 22 cm. However, due to the relatively large size range width – G_{isr} ± 2 cm, a large drop in the pressure value was observed for the minimum circumference $G_{isr} - 2$ cm (***Figure 10***). This results from both the overestimated longitudinal rigidity of the knitted fabric and large dimensional tolerance of the size range. In order to fulfill the compression level requirements for the entire size range, the maximum longitudinal rigidity in this case should not exceed 70 cN/cm (***Figure 12***). For relatively small body circumferences, the values of unit pressure demonstrate high sensitivity to changes in the dimensional tolerance of the size range and longitudinal rigidity of the compression fabric [10]. Overestimated values of unit pressure for in the case of compression class II (***Figure 11***) are mainly due to the overestimated circumferential force *F* (***Figure 13***), which results from not sticking to the principle of designing the product for the middle circumference from the size range and for the middle pressure value from the given compression class.

Theoretical considerations, the results of which are presented in ***Figures 1-8***, confirm that the selection of the longitudinal rigidity of the knitted fabric is an important element in the modelling and design procedure of knitted compression products with the intended value of unit pressure for the given compression class, size and size range.

Figure 14 shows the maximum differences between the experimental values of unit pressure for individual middle and extreme circumference values of a given size. The analyses performed proved that the maximum pressure difference ΔP within the size ranges equaled 2.7 hPa, while the average value for the 18 circumferences analysed was 1.7 hPa. It should be noted that the differences in values ΔP did not differ significantly in relation to the range width and unit pressure of compression classes I and II.

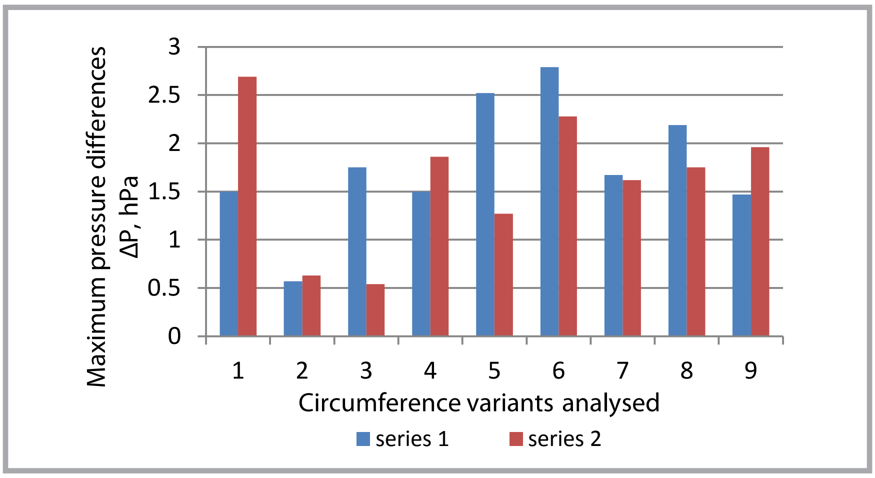

Figure 14. *Maximum differences in unit pressure values* $\Delta P = P_{max} - P_{min}$ *for individual stocking sizes, determined experimentally, Series 1 – for variants from compression class I, series 2 – for variants from compression class II.*

Conclusions

1. Selecting proper longitudinal rigidity of knitted fabric is an important element in the modelling and design procedure of knitted compression products with the intended value of unit pressure for the given compression class, size and size range.
2. The larger the dimensional tolerance $\pm\Delta G_i$, the lower the values of longitudinal rigidity of the knitted fabric that should be applied, as they show smaller sensitivity to changes in unit pressure due to differences between the average value of circumferences G_{isr} and their extreme values $G_{isr} \mp \Delta G_i$.
3. The experimental results of unit pressure obtained for compression products from the 1st and 2nd compression classes differed from the declared pressure values for both the extreme and middle values from the size range.
4. The main reason for the differences between the declared values of unit pressure and those determined experimentally is the overestimated longitudinal rigidity of the knitted fabric as well as too large size ranges in relation to the longitudinal rigidity.
5. Ready-made compression products can fulfill quality requirements regarding the pressure value if they are designed according to Laplace's law for the middle circumference from the size range and for the middle value of pressure from the given compression class, including the procedure for selecting the longitudinal rigidity of knitted fabric for the given compression class, as well as the size and dimensional tolerance of the size range.

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Received 22.07.2018 Reviewed 19.09.2019