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Methods of Evaluating Knitted Fabrics with Elastomeric Threads in the Design Process of Compression Products

DOI: 10.5604/01.3001.0011.7303

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Abstract
One of the most important stages in the design process of compression products is describing the relationship between the force and elongation of the knitted fabric, using appropriate and scientifically justified force values in the fabric undergoing a stretching and relaxation test, in the form of a hysteresis loop. Research on this issue was carried out on two variants of knitted fabrics with elastomeric threads – a warp and a weft – knitted one. Based on the functions of the relation between the force and relative elongation determined and on Laplace's law, compression bands with intended values of unit pressure were designed and manufactured and then subjected to experimental verification. In addition, a procedure was presented for dividing compression fabrics into specific compression classes.

Key words: *compression products, knitted fabrics, elastomeric threads, unit pressure, Laplace's law, compression class, useful elongation.*

Introduction

Designing compression products supporting the process of external treatment should be based on Laplace's law (1), which describes the relation between unit pressure exerted on a cylindrical body model with circumference G_1 and the circumferential force F in a fabric strip of width s (***Figure 1***). Currently in many cases the technique of constructing compression products is based on identical percentage reduction of the basic structural dimensions, regardless of the patient's real body circumferences. The reduction value is often 10% for the first set, and 15% or 20% for all subsequent compression garments [1-5]. This leads to serious incompatibility with the indirect experimental method of unit pressure evaluation according to the stripline testing described in CEN/TR 15831:2009 (E), which uses Laplace's law for calculating the compression value [6].

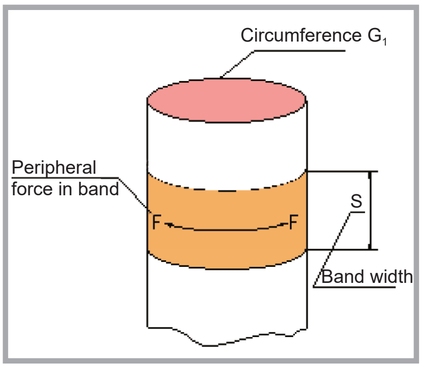

***Figure 1.** Cylindrical model of a body part covered with a compression band.*

$$P = \frac{2\pi F}{G_1 s} \qquad (1)$$

where:
F, cN – circumferential force in a fabric strip of width s,
G_1, cm – body part circumference,
s, cm – width of the fabric stri,
P, hPa – unit pressure.

According to Laplace's law, the length of circumference G_1 and the circumferential force *F* have a significant effect on the value of unit pressure.

Improving the accuracy of determining circumferences G_1 can be achieved by eliminating manual dimensioning of the human body and replacing it with the 3D scanning technique [7-13].

In practice, the same type of compression knitted fabric can be applied to products suitable for different lengths of circumferences G_1. Depending on the value of body circumference G_1 and the intended value of unit pressure, irrespective of the type of fabric, the value of force *F* equals that calculated from Laplace's law.

$$F = \frac{P \cdot G_1 \cdot s}{2\pi} \qquad (2)$$

As the same knitted fabric is often used for different lengths of circumferences G_1, an important stage in the design process of compression products becomes taking into account the complex relations between force *F* and relative elongation ε in dependence on the stretching range. In most works [13-15] on the modeling of compression products, a constant value of longitudinal rigidity of the fabric is adopted, irrespective of the relative elongation. In model studies, such an approach can be justified. An example of such research is work [14], in which, apart from the analytical model using Laplace's law, the results of modeling unit pressure with the finite element method for a cylinder and cone are also presented. Comparing unit pressure values calculated according to the analytical model and with the finite element method revealed differences in the range of 1-7%. On the other hand, works [13, 15] analysed the influence of the seam, the intended dimensional tolerances of body parts and the manufacturing tolerance of the compression product on the value of unit pressure in dependence on the longitudinal rigidity of the compression fabric. Different aspects concerning the design and modeling of compression products are presented in a review article [16].

For the purpose of constructing products with an intended value of unit pressure, it is necessary to describe the relationship between force and elongation using real and scientifically justified values of forces in knitted fabric subjected to deformation hysteresis within different relative elongations. The results of tests conducted on knitted fabrics with elastomeric thread subjected to deformation

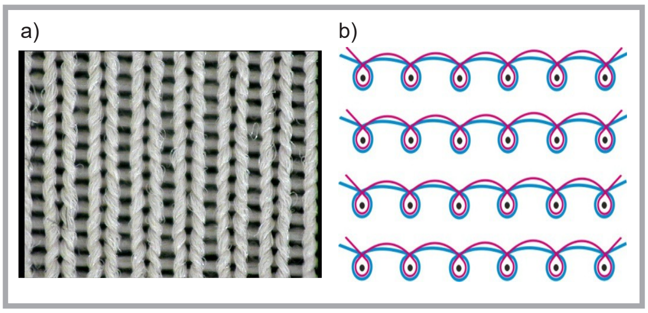

***Figure 2.** a) View of the face of a weft-knitted fabric plated with elastomeric yarns, b) Schematic record of the stitch of a weft-knitted fabric plated with elastomeric yarns. Fabric properties: wale density Pk =190/10 cm, course density Pr = 340/10 cm, surface density M = 260 g/m^2.*

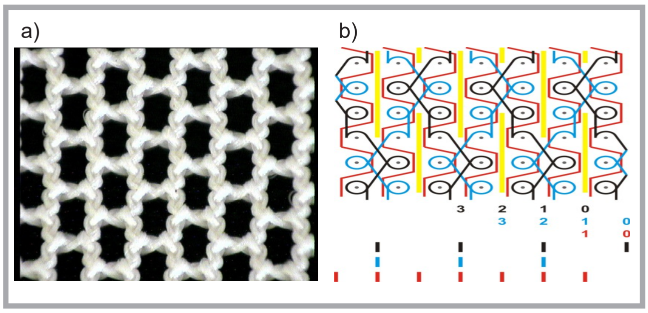

***Figure 3.** a) View of the face of a warp-knitted fabric with elastomeric yarns as the weft, b) Schematic record of the stitch of a warp-knitted fabric with elastomeric yarns as the weft. Fabric properties: wale density Pk = 120/10 cm, course density Pr = 740/10 cm, surface density M = 234 g/m^2.*

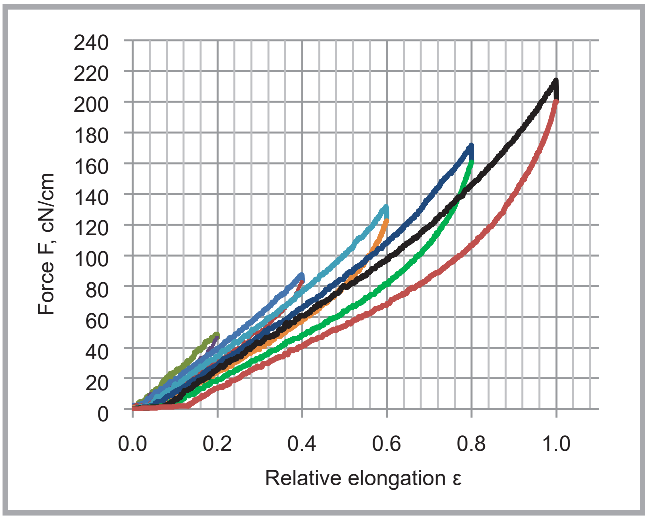

***Figure 4.** Hysteresis loops for the subsequent stretching ranges of a weft-knitted fabric plated with elastomeric yarn (variant 1).*

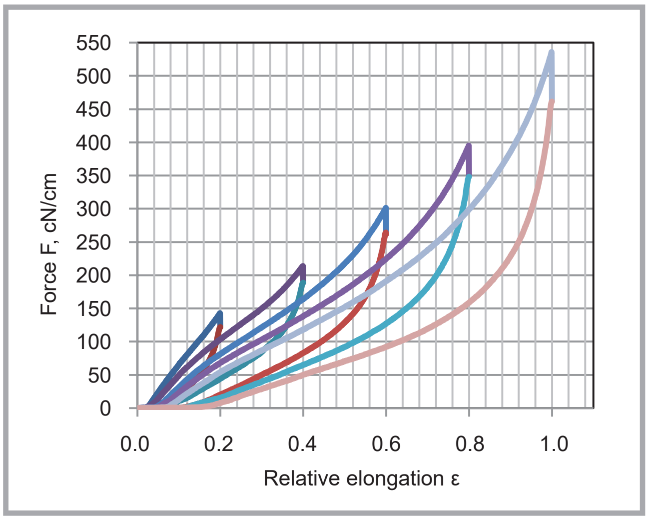

***Figure 5.** Hysteresis loops for subsequent stretching ranges of a warp-knitted fabric with elastomeric yarn as the weft (variant 2).*

hysteresis indicate significant differences in forces for the same elongation in cases where the fabrics are stretched to different values of relative elongation [17-18].

In order to design individual circumferences of a compression product in a free state G_0 with an intended value of unit pressure P, it is necessary to know the mechanical characteristics of the knitted fabric in the form of the experimental relationship between the force and relative elongation F = f(ε).

The purpose of the considerations presented is to answer the following questions:

- which force values from the tension characteristics and relaxation- deformation of the knitted fabric should be taken into account to describe the relationship between force and relative elongation,
- what range of tensile forces should be adopted for testing the knitted fabric.

Material, test object and methods

Complex relations between parameters *F* and ε will be determined for an example of two variants of knitted fabrics, whose structures and basic properties are presented in ***Figures 2*** and ***3***.

Tests of knitted fabric were performed for relative elongations ε in the range of 0÷1,0 for separate stretching ranges increased by a relative elongation of 0.1. For each elongation value, tests were carried out on 5 rectangular samples cut along the wale-wise direction, with a free length of 100 mm and width of 75 mm, subjected to stretching and relaxation at a speed of 200 mm/min in accordance with PN-ENV 12718:2002 [19] on a Hounsfield tensile testing machine, using needles to stabilise the width of the fabric. For each stretching range, 6 hysteresis loops were performed. ***Figures 3*** and ***4*** show changes in the mean values of force as a function of relative elongation for the above- mentioned variants of knitted fabrics for selected successive ranges enlarged by a relative elongation of 0.2 for the 6th hysteresis loop in both the tension and relaxation phase. Adopting the force values from the 6th hysteresis loop results from the effect of mechanical conditioning on force changes. The greatest changes in force values are observed between the first and second hysteresis loop. For the subsequent hysteresis loops, the differences between force values are smaller, and practically disappear after the 5th & 6th loops.

The stretching and relaxation curves shown in ***Figures 4*** and ***5*** differ in the force values within the common range of relative elongation for different stretching ranges. The higher the relative elongation to which the fabrics are stretched, the lower the force values at the same relative elongation for both the tension and relaxation phases. Introducing the functions of force and elongation to the design process of compression products

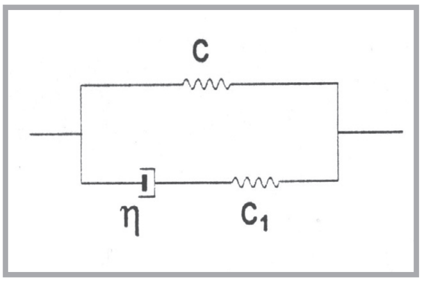

Figure 6. Three-element Zener model.

only for the maximum elongation range (e.g. ε = 1) leads to a significant overestimation of unit pressure for relatively small values of body circumferences. For example, for a warp knitted fabric (***Figure 3***) and circumference G_1 = 18 cm, the circumferential force for s = 1 cm at the intended pressure value P = 20 hPa equals $F = \frac{P \cdot G_1 \cdot s}{2\pi} = 57$ cN, which is obtained with elongation ε = 0,2.

On the other hand, for the deformation range ε = 0,2 of the knitted fabric stretched only up to this elongation value, the force at standstill equals F = 121 cN. According to Laplace's law, this results in the unit pressure P = 42.2 hPa, as long as the form of the function adopted in the design process is defined for the stretching range ε = 1.

To eliminate one of the causes of errors in the design process of compression products, in the mechanical characteristics one should take into account the complex relations between relative elongation and force in dependence on the stretching range. Therefore for the general mechanical characteristics of the knitted fabric, the force values obtained from individual stretching ranges were taken into account, and the greater the number of these stretching ranges, the more precise the mechanical characteristics of the knitted fabric.

Model interpretations of experimental results

To answer the question as to which force values from the tension characteristics and relaxation – deformation of the knitted fabric should be taken into account to properly describe the relationship between force and relative elongation, an analysis was made of the results of the process of stretching and relaxation of the fabric in relation to its rheological properties and conditions of use of the products supporting external treatment. Textiles, including knitted fabrics, are characterised by good viscoelastic properties, and the relationship between relative elongation ε, the value of the tensile force F and time t of the force action can be qualitatively described by the rheological three-element Zener model ***(Figure 6***) and resulting equation [20].

$$F + \frac{\eta}{C_1}\frac{\mathrm{dF}}{\mathrm{dt}} = C\varepsilon + (C + C_1)\frac{\eta}{c_1}\, d\varepsilon\frac{\mathrm{dt}}{} \qquad (3)$$

where:
C, C_1 – elasticity constants,
η – absolute viscosity.

Adopting stretching conditions $\frac{d\varepsilon}{dt}$ = const and F_0 = 0, we obtain ***Equation (4)*** describing the stretching process

$$F_D = C \cdot \varepsilon + \eta \cdot \frac{d\varepsilon}{\mathrm{dt}}\left(1 - e^{\frac{-\mathrm{t}C_1}{\eta}}\right) \qquad (4)$$

The values of force F_D calculated during the process of dynamic stretching according to ***Equation (4)*** for the variant of warp-knitted fabric with elastomeric threads and measurement conditions for relative elongation ε = 1 obtained after 30 s ($\frac{d\varepsilon}{dt}$ = 0,03333) and with the following values of rheological parameters C = 460 cN/cm, C_1 = 400 cN/cm & η = 2114 cN·s/cm equals F_D=530,2 cN/cm (***Figure 7***). This value corresponds to the results obtained in the experimental test (***Figure 8***). Constants C and C_1 can be determined on the basis of experimental studies and from two equations: $(C + C_1) \cdot \varepsilon = F_{max}$ – referring to rapid dynamic stretching, and $C \cdot \varepsilon = F_{min}$ – referring to a long relaxation period.

According to the Zener model, at the moment the extreme value of relative elongation is obtained – i.e. when the stretching process stops – the value of $\frac{d\varepsilon}{dt}$ = 0 –, which causes an incremental decrease in the force value as a result of transition to the relaxation phase.

For the following relaxation conditions: ε = const and $\frac{d\varepsilon}{dt}$ = 0, we obtain ***Equation (5)***, describing the relaxation process according to the Zener model. For the rheological parameters and measurement conditions at standstill adopted, we obtain force F_R = 461,4 cN.

$$F_R = C \cdot \varepsilon + C_1 \cdot \varepsilon\left(e^{\frac{-\mathrm{t}C_1}{\eta}}\right) \qquad (5)$$

The difference in forces $\Delta F = F_D - F_R$ = 68,8 cN corresponds to the incremental change in force values at standstill. Then, depending on the standstill duration, force values further decrease as relaxation occurs. Theoretically with the passage of time t → ∞, expression ($-\mathrm{t}C_1/\eta$) – describing the relaxation process, tends to zero, since the deformation of spring C_1 is received by the attenuator.

It should be noted that during the relaxation phase at standstill, the force value increases, as the term $\eta \cdot \frac{d\varepsilon}{dt}$ from the negative value takes a value of 0, and the relationship between rheological parameters and the measurement conditions can be again described by the equation for the relaxation phase, which is proven by both model simulations (***Figure 7***) and the experimental test (***Figure 8***). The existing differences between the model and experimental values are due to the nonlinearity of the system and anisotropy of the viscoelastic properties of the knitted fabrics. Taking into account the considerations and conditions of use of compression products presented, which are applied in therapies of a relatively long duration [5] and are most often used at rest, for the description of the function of force and relative elongation we adopted the force values from the relaxation phase i.e. at standstill, when the stretching process is stopped in the sixth hysteresis loop for particular stretching ranges. Final mechanical characteristics of the knitted fabric in the form of the function of force and relative elongation are shown in ***Figures 9*** and ***10***.

The physical-mathematical description of the relationship between force and relative elongation shown in ***Figures 9*** and ***10*** takes into account the differences in the relations between the values F and ε in dependence on the stretching range and rheological properties of the compression fabrics tested.

Experimental verification of unit pressure

Based on the functions defining the relation between force and relative elongation obtained for the fabrics analysed and on Laplace's law, the lengths of the compression bands in a relaxed state G_0 were calculated, with the intended values of unit pressure P in the range of 10÷30 hPa, for a cylindrical body model with circumference G_1 = 34.7 cm. ***Table 1*** shows the band circumferences in a relaxed state G_0 for the two fabrics analysed. The bands were made on an autolap machine using the flat seam technique, with the seam width Ls = 0.4 cm. Unit pressure was measured using a PICOPRESS device, made by MICROLAB ELEKTRONICA

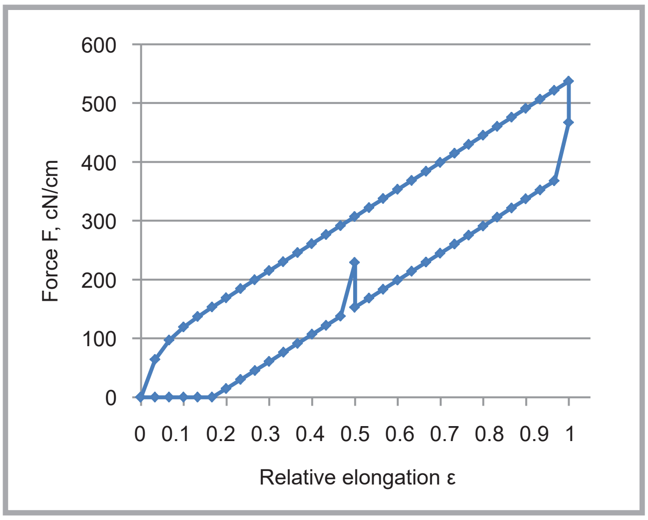

Figure 7. *Hysteresis diagram according to standard three-element Zener Model.*

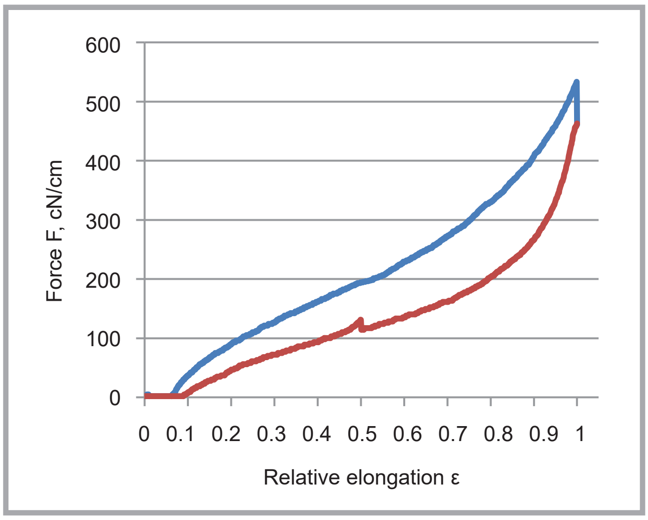

Figure 8. *Experimental diagram of hysteresis for a warp-knitted fabric with elastomeric threads as the weft*

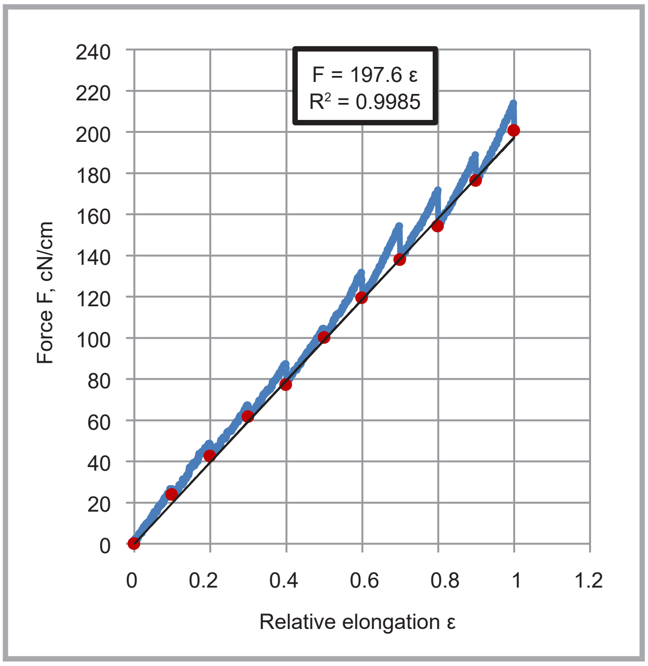

Figure 9. *Force values as a function of relative elongation in the 6th hysteresis loop for different fabric stretching ranges (variant 1).*

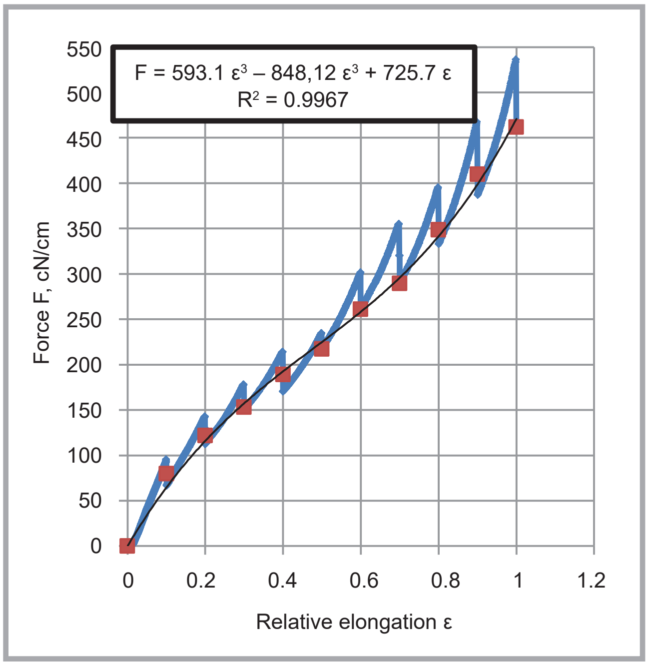

Figure 10. *Force values as a function of relative elongation in the 6th hysteresis loop for different fabric stretching ranges (variant 2).*

(S.a.a di Bergamo Giorgio & C., Italy), at a measurement resolution of 1 mmHg.

The existing differences between the intended unit pressure and values measured can be ascribed to the manufacturing tolerance of the band (hand cutting, joining with a seam), which is ± 0.2 cm, and the manual method of placing the bands on the cylinder (***Figure 11***). Manual placing does not guarantee equal values of circumferential forces, due to the uneven elongation of the knitted fabric and friction forces between the band and surface of the cylinder, which counteract equalisation of the circumferential forces.

Procedure for determining fabric suitability for a particular compression class

The maximum stretching range of a compression fabric is closely related to its suitability for a particular compression class and its useful elongation.

In the procedure for determining the suitability of a knitted fabric for a particular compression class, the following three steps can be distinguished:

In accordance with PN-P-04953:1972 (Methods of testing textile products,

Table 1. *Parameters and dimensions of the compression band. Parameters calculated: cylinder circumference G_l = 34,7 cm, seam width Ls = 0,4 cm.*

P, hPa	Variants of knitted fabrics	Go, cm
10	W1	32,1
15		30,7
20		29,3
25		27,8
30		26,4
10	W2	27,2
15		24,6
20		22,5
25		20.6
30		19,1

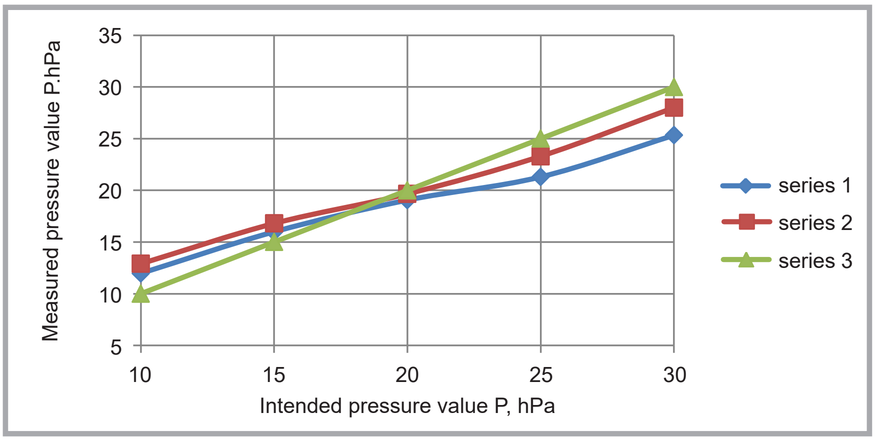

Figure 11. *Test results of unit pressure exerted by compression bands on a cylindrical model with circumference G_1 = 34,7 cm. Series 1 – pressure for variant W_1, series 2 – pressure for variant W_2, series 3 – intended pressure values.*

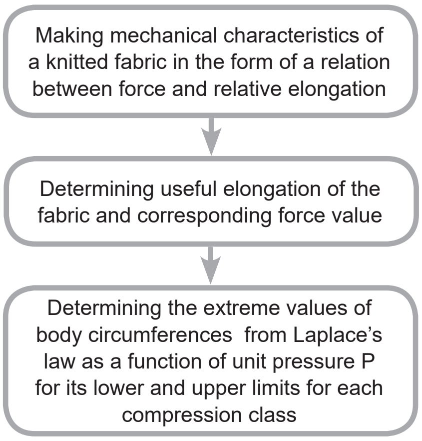

Figure 12. *Stages of the procedure for determining fabric suitability for a particular compression class.*

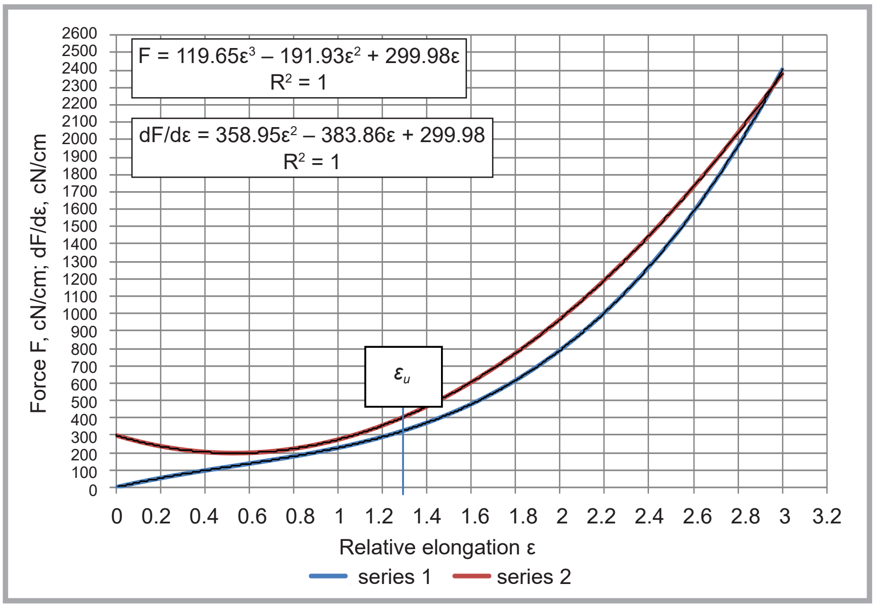

Figure 13. *Stretching of a weft-knitted fabric plated with elastomeric yarn – series 1, and its first derivative – series 2.*

Elastic products, Determining elasticity indices) – the term "useful elongation" stands for relative elongation at stretching corresponding to the initial part of the stretching graph, characterised by a faster increase in elongation in relation to the force increase.

After useful elongation is exceeded, the value of longitudinal rigidity increases, due to deformation of the stitch, which is made of a non-elastomeric yarn.

However, this method of determining useful elongation is burdened with error, resulting from the subjective choice of the segment with the greatest curvature. Therefore in our tests useful elongation was determined on the basis of the first derivative of the function of the force and relative elongation dF/dε, which describes the values of longitudinal

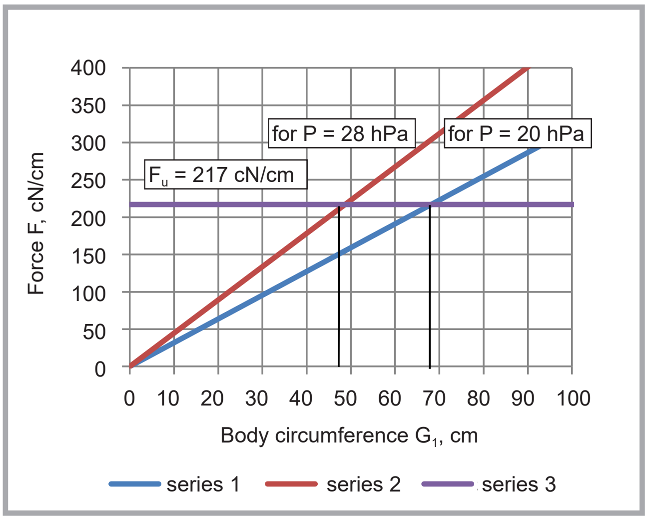

Figure 14. *Graphic illustration of determining maximum body circumferences for the lower and upper limits of 1st compression class. Series 1 – for the lower limit of 1st compression class, series 2 – for the upper limit of 1st compression class, series 3 – force value for ε_{max} = 0,85 ε_u.*

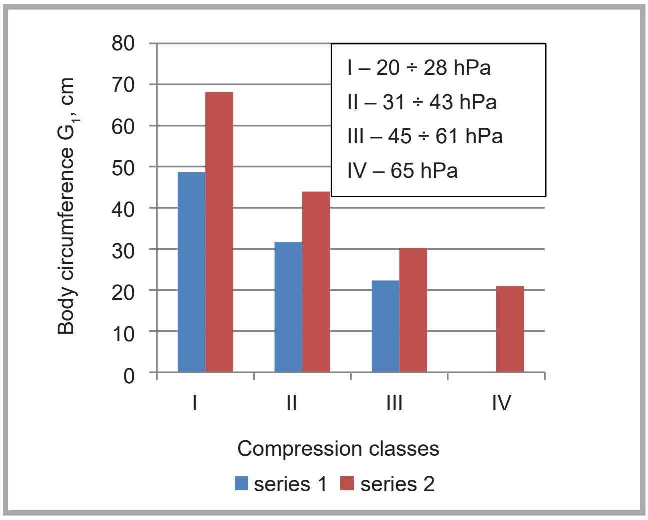

Figure 15. *Extreme values of body circumferences G_{1max} for particular compression classes. Series 1 – for the lower limit of compression class, series 2 – for the upper limit of compression class*

rigidity along the experimental curve. Determination of fabric suitability for a particular compression class was performed for the example of a weft-knitted fabric plated with elastomeric yarns (***Figure 12***). According to the procedure described above, value dF/dε in the initial part of the graph stays at a more or less constant level up to a relative elongation ε of 1.3 (***Figure 13***).

Due to the risk of excessive deformation of the compression fabric, e.g. because of excessive elongation when the product is put on and during the non-rest period of its use, the maximum elongation value, equal to 0.85 of useful elongation ($\varepsilon_{max} = 0{,}85 \cdot \varepsilon u$), was adopted for the analysis.

Based on the value of force F determined for the maximum permissible elongation ($\varepsilon_{max} = 0{,}85 \cdot \varepsilon_u$) adopted and Laplace's law, it is possible to determine fabric suitability for a particular compression class according to the equation which defines the maximum value of circumference G_{1max} at which the type of compression fabric tested can still be used.

$$\frac{2 \cdot \pi \cdot F}{P_{max} \cdot s} > G_{1max} < \frac{2 \cdot \pi \cdot F}{P_{min} \cdot s} \qquad (6)$$

where:
F – force in a fabric strip of width s at maximum elongation, corresponding to the elongation value ($\varepsilon_{max} = 0{,}85 \cdot \varepsilon u = 1{,}1$), which equals $F = 217$ cN/cm for the analysed knitted fabric,
P_{min}, P_{max} – pressures for the lower and upper values in particular classes.

A graphic illustration of determining the maximum lengths of circumferences G_{1max} for the lower and upper values in the 1st compression class is shown in ***Figure 14***, whereas ***Figure 15*** illustrates the maximum values of body circumferences G_1 for particular compression classes for the example of a weft-knitted fabric plated with elastomeric yarns.

Conslusions

1. The model interpretations of experimental results conducted and the conditions of use of compression products justify introducing the relation between force and relative elongation to the design process, calculated on the basis of force values determined in the relaxation phase, when the process of fabric stretching stops in the sixth hysteresis cycle for individual stretching ranges.
2. Introducing the relationship between the force and elongation of the knitted fabric based on force values determined in the relaxation phase, when the process of stretching the knitted fabric stops, for different stretching ranges eliminates the causes of errors in the design of compression products, as it takes into account differences in the relations between values F and εin dependence on the stretching range and rheological properties of the fabric tested.
3. The assessment of the suitability of knitted fabrics with elastomeric threads for particular compression classes based on the procedure of determining usefulelongation and on Laplace's law allows to calculate the maximum lengths of body circumferences G1 at which the variant of compression fabric tested can still be used.

❑

Acknowledgements

This research was financially supported by the Polish National Centre for Research and Development Project No. 244972, Agreement nr PBS3/B9/46/2015.

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❑ ***Received 04.09.2017 Reviewed 20.03.2018***