D. Truncyte,
*L. Papreckiene,
M. Gutauskas

Kaunas University of Technology,
Faculty of Design and Technologies,
Department of Clothing and
Polymer Products Technology
Studentu str.56, 51424 Kaunas, Lithuania

*Faculty of Fundamental Science,
Department of Mathematical Research in Systems
Studentu str.50, 51424 Kaunas, Lithuania
E-mail: Dainora.Truncyte@stud.ktu.lt

Behaviour of Textile Membranes while Being Pulling Through a Hole by the Constrained Method

Abstract
The behaviour of woven and knitted fabrics while they are pulled through a circular hole is analysed. The relations between the resistance parameters to pulling (force and work) and the consistent pattern of the change of geometrical parameters of the membrane have been determined. It has been shown that the H-P curve reflects the geometrical transformations of the specimen at all stages of deformation.

Key words: *textile, membrane, pulling through the hole, textile specimen geometry.*

■ Introduction

After some period in the science of testing textile materials, a method based on the principle of pulling a disc-shaped specimen through a hole was adapted again. The influence on the fabrics of technological treatments such as washing and finishing with stiffeners and softeners can be evaluated. Also, their influence on the variation in the parameters of fabric drape, hand, etc. can be determined.

The first devices described in scientific research [1, 2] were not sufficiently comprehensive in the factors tested. The hole used to test the fabric had different, not standardised forms, and the tests performed did not allow the various types of textile materials to be compared [3, 5]. Besides, during the tests with the specimens of various thicknesses (the role of which is the most important in experiments of this type) the researchers had to use pads with holes of different sizes. Furthermore, the production of such pads is rather complicated.

A few years ago, methods of pulling a constrained fabric through holes based on the same principle were improved. The behaviour of the disc-shaped specimen during the test was limited by the plate fixed parallel to the pad [6, 12]. When the sample was pulled through the relatively small hole in the centre of the pad, the additional resistance due to the fabric friction into the limiting plates had to be overcome. This method was more comprehensive, as it permitted the following aspects to be considered:
■ the distance h between the limiting plates could be regulated with a precision better than 0.05 mm (Figure 1);
■ the number of pads with holes of various sizes could be minimised;
■ the behaviour of various fabrics and their parameters could be compared.

When the radius r of the pad hole is changed and the distance h between the pad and the supporting plate is adjusted, testing regimes for measuring the mechanical properties of textile materials of all types can be selected.

Compared to the other methods of pulling a fabric specimen through a hole, this limitation of the testing regime allowed us to narrow down the literature survey, by not analysing unrestrained pulling (when the specimen is freely placed in a space between two limiting plates), as was dealt with in earlier research works from Alexandria University, and others [1 - 5].

Constrained pulling methods have only been widely investigated in Germany (JTV-Griff-Tester) [6, 7] and in Lithuania (KTU-Griff-Tester) [8 - 17] since 2000.

This article shows the consistent patterns of the behaviour of the specimen, which are only related to the change in the geometrical parameters of the specimen and the restriction rate.

Extensive testing of various types of textile fabrics with the KTU-Griff-Tester device showed that the statistical part of the test is very acceptable. For example, for textile hand evaluation, applying the constrained pulling to 5 - 8 specimens
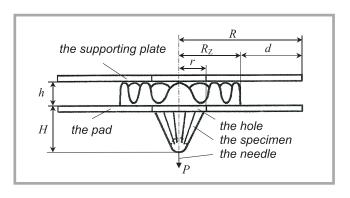
is enough. This number of specimens always vouches for a safe level of bias from an average value of 5%. The values of particular statistical rates are not shown, because only the general peculiarities of geometrical behaviour of the specimen are analysed in this article.

Analysis of textile materials using the above-mentioned method showed that it is possible to forecast the test results of the constrained specimen when pulled through the limiting plates. At the beginning of the pulling, the edge of the specimen takes the form of a sinusoid curve in contact with the pad and the supporting plate.

With the increase of the punch height H (Figure 1), the projection radius R_z of the specimen decreases, and the waves of the sinusoid change into a more rectangular shape and their number increases; they finally break down and, with the increase of their number, fill up the space between the limiting plates.

After the estimation of the test series, the test regimes were optimised [8, 9]. The hole radius r and the distance h were matched, so that while pulling the specimen with the thickness δ it would not jam in either the pad hole ($\pi r^2 \geq 2\pi R\delta$) or between the limiting plates ($2\pi rh \geq 2\pi R\delta$).

Figure 1. The principle scheme of the KTU-Griff-Tester; h - distance between the pad and the supporting plate, r - radius of the pad hole, R - radius of the specimen, H - the punch height, R_Z - radius of the specimen projection on the plate, d - radial distance R - R_Z, P - force.

Thus:

$$\begin{cases} r \geq \sqrt{2R\delta}\,; \\ h \geq \dfrac{R}{r}\delta. \end{cases} \qquad (1)$$

where:
r – the radius of the pad hole;
R – the radius of the specimen;
δ – the thickness of the specimen.

The aim of this research was to establish the relation between the parameters of the change of the sample geometric parameters and mechanical parameters of the specimen's resistance to the pulling-off. Especially the resisting force (P), the work of pull (A), and the deformation of pull (H) i.e. the displacement of the pulling rod were considered. These relations were established during analyses of the pull-off curves H-P.

In our research, the radius of the disc-shaped specimen was $R = 56.5$ mm, the radius of the pad hole of $r = 10$ mm. The optimal distance between the limiting plates if the values of r are different can be calculated from equation (2):

$$h = k\delta \qquad (2)$$

where k is a coefficient, depending on the hole radius r and determined experimentally.

The values of r and k are presented in Table 1. For our tests we accepted as an optimal distance $h = 5.6\ \delta$.

Table 1. Relationship between r and k.

r, mm	7.5	10.0	12.5	15.0	20.0
k	7.5	5.6	4.5	3.8	2.8

◼ Methodology

The investigations were performed using the KTU-Griff-Tester, an original, specially-prepared device. The pull-off curve H-P was recorded, and the specimen's view was fixed in the various stages of the test. The velocity of pulling the specimen during all the tests was set to 100 mm/min.

The objects of investigations were 10 knitted and woven fabrics; their structure, thickness and other parameters are presented in Table 2. As the investigated fabrics differ greatly in terms of fibre composition and structure, the influence of the different kinds of fabrics on the obtained results is not discussed. The main objective of the research is to show only the general behavioural tendencies of any kind of textile membrane, but not the numeric values of a particular fabric's resistance to pull parameters which undoubtedly depend on many factors.

As the thickness δ of all the tested materials was less than 1 mm, only one pad with the hole radius equal to $r = 10$ mm was needed.

Four test zones were distinguished while watching the digital images recorded by a camera.
1. At the beginning of the process, when R_Z is still close to the radius R of the specimen, and the distance d of the specimen contour from the pad edge is small, the waved surface of the three-dimensional space is formed from the flat specimen and the specimen contacts the pad and the upper plate only through the segments of the specimen's circumference and the radii which are related to the waves' amplitudes. The line of the sample edge acquires a sinusoid form (Figure 2.a).
2. After the contact with the limiting plates, the specimen waves flatten and transform into rectangular wrinkles (Figure 2.b); the area of the specimen's contacts with the limiting plates increases, as does the pull-off power when the fabric is close to isotropic. If great anisotropy is a characteristic of the material, then the wave formation begins at the stiffer axis of the fabric, and the specimen projection in the pad plane takes the form of a Cassini oval [13, 15, 17].
3. Later the severe transformations begin: the number of waves N still increases;
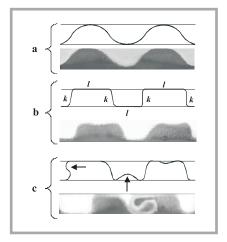

Figure 2. The change of the wave forms between the limiting plates: a - initial stage; b - intermediate stage, and c - the breakdown stage.

the waves break down (Figure 2.c) minimising the contact area of the specimen and the plates and decreasing of the pulling force. The 'waves', which have a trapezoidal or rectangular form, suffer from the compression load (force) and bends. Here two different situations are observed. When the wall l contacting with the pad or supporting plate bends, two new waves are formed. When the vertical or leaning wall k bends, then a fold which overlaps the adjacent waves occurs. The pulling process then starts to follow the 'hitchy' regime.
4. At the end of the process, when $R_Z < 0.3\ R$, the area of the contact of the specimen part above the pad & below the plate, and the volume it occupies between the plates reaches the maximum values. The pull forces reach their local maximum in the shape of a peak as well.

Table 2. Initial parameters of the materials investigated.

Fabric type	Fabric symbol	Fabric nature	Knit (weave) type	Density, cm⁻¹ Wale (warp)	Density, cm⁻¹ Course (weft)	Surface density, g/m²	Thickness, mm
Knitted fabric group	T11	Cotton	Rib 1×1 knitwear	$P_{h'} = 11$ $P_{h''} = 11$	17	183	0.72
	T12	Viscose, elastane	Plain jersey	5	30	248	0.64
	T13	Acetate, polyamide	Double jacquard	14	$P_{vd} = 5$ $P_{vk} = 10$	152	0.60
	T14	Polyester	Warp-knitted lock-knit (cord-tricot)	14	14	142	0.49
	T15	Polyamide	Brushed warp-knitted laid-in	24	20	179	0.99
	T52	Polyamide, elastane	Plain jersey	15	24	202	0.52
	T96	Cotton	Two-thread fleecy	15	19	234	0.96
Woven fabric group	A43	Wool, polyester	Twill	40	22	199	0.43
	A45	Flax	Twill	40	22	210	0.45
	A87	Wool, polyester	Fancy twill	37	24	393	0.87

The four zones can be found in the pulling curves H–P (Figure 3 and Figure 9, curve II):

a) the part of the curve to the first local maximum (peak P_1), which shows the increase of the pull force due to the increase to the specimen's contact with limiting plates;

b) the curve part from the point P_1 to the point P_2, relative to the break down of the waves;

c) the part of the curve between P_2 and the second local maximum (peak P_3), which shows the compression of the specimen;

d) the sudden descent to the value $P = 0$ at the end of the process, which shows the end of the process (the sample is pulled – through).

Thus in zone (a), the sinusoids are forming and acquire trapezoidal or rectangular shapes, and the contact area with the limiting plates increases intensively (as does the force P). In zone (b), the trapezoidal and rectangular walls suffer due to compression load and bends (breakdowns). Here, we can observe in the curve the deformation process in the form of the 'hitchy' regime. Zone (c) shows the multiplexing of the geometrical forms which appear, and which are similar to the pressing. Visible air-gaps between the waves disappear. The pulling forces increase to the local maximum value (peak P_3). In zone (d), the outer contour of the specimen reaches the pad hole. The specimen leaves the pad hole, but not at the same time. The stiffer areas pass the pad hole first, and the softer ones lag behind due to the anisotropy specific for example to a knitted fabric.

■ Results and discussion

The dependence of the change of the wave number N of the 10 specimens of different thickness and the radius of the part of the specimen which has not yet withdrawn was investigated. The exact number of the waves shown in the specimen pictures diverges only insignificantly from the value calculated by the Equation 3 [14]:

Into this expression we can put $R_Z = 0.9\,R$; $0.8\,R$; $0.7\,R$; $0.6\,R$; $0.5\,R$; $0.4\,R$; and $0.3\,R$.

In the same cases, the distance of the specimen edge from the pad edge (Figure 1) can be expressed thus:
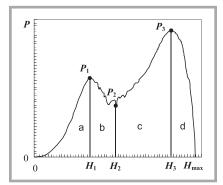
$$d = R - R_Z \qquad (4)$$

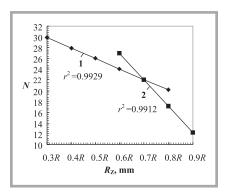**Figure 3.** *The pull curve H–P.*

Figure 4. *Example of the dependence of the wave number N on the parameter R_Z.*

When the distance d increases, the number of the waves N increases as well. The N values of the tested objects when $R_Z = 0.9\,R$; ...; 0.3 R, or considering that $d = R - R_Z$ when $d = 0.1\,R$; … ; 0.7 R, are presented in Table 3.

While testing each specimen, it may be observed that these points placed according to the $R_Z - N$ coordinates fall on two or three sections of straight lines (Figure 4 and Figure 5). The change of

the directions can be noted every time when $R_Z = 0.7\,R$, and also occasionally in the interval between 0.3 R and 0.5 R. Thus the dependence N on the parameter R_Z, can be expressed much simpler than in equation (3), by the equations of the straight lines different at various intervals.

The break of the line at the point $R_Z = 0.7\,R$ allows us to make a presumption for the reason of the sharp change in the specimens' geometrical shape.

The analysis of the data R_Z and N (Figure 5) shows that the actual number of the waves increases at first, and with the value between 0.5 R and 0.7 R it stabilises or begins to decrease. This can be related to the breakdown of the waves and the merging of the adjacent waves. It means that the assumption about the form of the specimen contour close to the sinusoid [14] is right, and not only at the initial deformation stage.

As the textile materials are characterised by high deformability and anisotropy, the highest value of height H may be greater than R.

Figure 6 shows the change in the average parameters values due to the punch height H (see Figure 1). The initial radius of the specimen is $R = 56.5$ mm; therefore all straight lines start from one point. The lean angle of the lines shows the different intensity of test objects of average shift R_Z in the space between the limiting plates:

$$R_Z = \frac{R_Z^v + R_Z^h}{2} \qquad (5)$$

$$N = \frac{4\sqrt{2}}{h}\sqrt{3\left(2R^2 - RR_z\right) - \left(4R - R_z\right)\sqrt{2R^2 - RR_z}},$$

Equation 3. *Number of the waves shown in the specimen pictures.*

Table 3. *Dependence of the wave number N on the fabric thickness δ and parameter R_z.*

Fabric symbol	Thickness δ, mm	The number of waves N, when R_Z						
		0.3R	0.4R	0.5R	0.6 R	0.7R	0.8R	0.9R
T15	1.0	30	28	26	24	22	18	12
T96	0.96	31	30	27	25	23	19	13
A87	0.87	34	33	30	28	25	20	14
T11	0.72	42	40	37	34	31	25	17
T12	0.64	46	44	41	38	34	28	19
T13	0.60	49	47	43	40	36	29	20
T52	0.52	58	55	51	47	43	35	23
T14	0.49	61	57	52	48	44	35	24
A45	0.45	67	64	59	54	49	40	27
A43	0.43	70	66	62	56	51	42	28
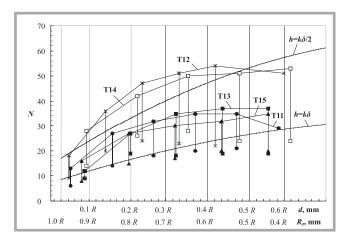
Figure 6. Scheme illustrating: a) the way of determining the values of the average parameter R_Z, and b) the dependence of those values on the punch height H.

Analysing transformations of the disc shape specimen in the space h between the limiting plates, we see not only the change of linear values but also of the following relations:

a) the relation between the outer circumference $L_Z = 2\pi R_Z$ and the initial circumference of the specimen $L_0 = 2\pi R$;

$$T_L = L_0/L_Z \qquad (6)$$

b) the relation between the area $S_Z = \pi\{R^2 - [R - (R_Z - r)]^2\}$, which shows the outer part of the specimen that fits in the zone S_P (Figure 7) and the area of the pad & the supporting plate that is in contact with the waved specimen $S_P = \pi(R_Z^2 - r^2)$;

$$T_S = S_Z/S_P \qquad (7)$$

c) the relation between the average specimen volume $V_Z = S_Z \cdot \delta$ and the volume $V_P = S_p \cdot h$ of the relative part of the space h.

$$T_V = V_Z/V_P \qquad (8)$$

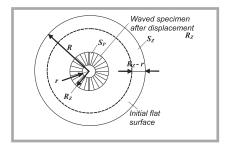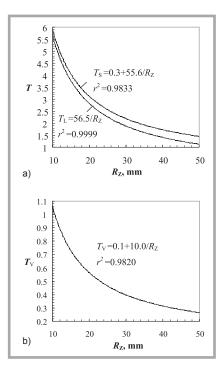

Figure 7. View of the pad with a hole of the diameter r and the specimen pulled through.

Table 4. Calculated geometrical parameters of the specimen.

d, mm	6.5	16.5	26.5	36.5	46
R_Z, mm	50	40	30	20	10.5 ≈ r
$T_L = L_0/L_Z$	1.13	1.41	1.88	2.83	5.38
$T_S = S_Z/S_P$	1.22	1.66	2.33	3.43	5.49
$T_V = V_Z/V_P$	0.22	0.30	0.42	0.62	0.99

These relative values designated T and lettered with relative indexes T_L, T_S, T_V are listed in Table 4 and presented as dependencies of R_Z in Figure 6. These theoretical rates are not related to the fibre composition or the structure of investigated fabrics. The rates clearly show examples of the degree of filling spaces in various pulling zones (according to shift) and they characterise the specimen coiling in the space h measured by time of pulling.

When the parameter d changes d = 0.1 R; 0.2 R; ... ; 0.8 R or R_Z = 0.9 R; 0.8 R; ... ; 0.2 R, the ratio T_S of the specimen area S_Z and the area of the pad S_P, also changes and at the end of the test, when R_Z = 10.5 mm (r = 10 mm), it approaches the value of 5.49. Then the specimen contour wrinkles more than five times. The typical values of the T_L, T_S, and T_V specific for all fabrics tested, are listed in Table 4 and presented in Figure 8, as was already mentioned above.

The volume ratio T_V at the end of the process reaches 0.99 (Figure 8). Thus the wrinkles of the rest part of the sample completely fill up the space between the limiting plates.

The total area S of the contact areas of the specimen and the pad consists of 2 N parts (Figure 9). The area of one of the mentioned areas with the given values of the parameter R_Z can be calculated from the following equation:

$$\frac{1}{2N}S = \frac{1}{2}(LR_z - lr); \qquad (9)$$

where L and l are the greater and smaller arcs of the defined section. The relation between their lengths is expressed by the equation

$$\frac{L}{R_z} = \frac{l}{r}. \qquad (10)$$
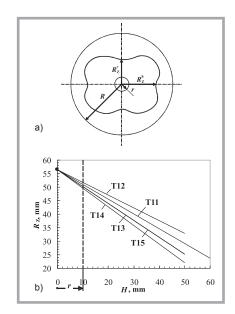
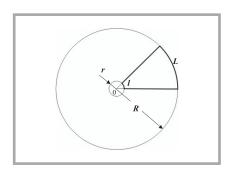Figure 8. Dependence of ratios: a) of T_L, T_S and b) T_V on the R_z.

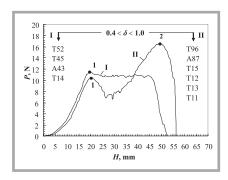Figure 9. Contact of one specimen's section with the supporting plate.

Figure 10. *Typical pulling curves: r = 10.0 mm, h = 5.6 δ; (0.4 < δ < 1.0); δ - of the particular fabric samples is given in Table 3.*
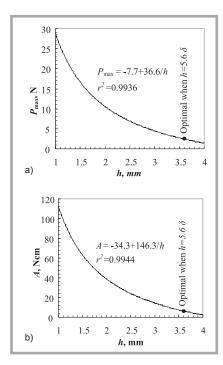

Figure 11. *Dependence of the resistance parameters: a) force P_{max}, and b) work A on h, for fabric T12, and r = 10.0 mm.*

Then, the whole area is as follows:

$$S = 2N \frac{1}{2} \left(LR_z - \frac{L\,r}{R_z} r \right) = N \frac{L}{R_z} \left(R_z^2 - r^2 \right) \quad (11)$$

The analysis of the pulling curves (Figure 10) showed that the shape of those curves (when r = constant) depends on the thickness δ of the specimen. The pulling curve acquires a 'saddle' shape with two peaks 1 and 2 if the thickness δ of the specimen is close to the upper interval limit (0.4 < δ < 1.0, for the radius of the pad hole r = 10.0 mm). The curve has one peak at the beginning of the curve if the thickness δ of the specimen is close to the bottom limit of the mentioned interval. This was verified by testing 10 types of fabrics (see Figure 10). The first peak (peak 1 on curve I and II) is concerned with the beginning of the test process and

related to the space between the plates limited by the value h. The second peak (peak 2 on curve II) is concerned with the ending of the test process and limited by the diameter r of the pad's hole. In the case of the same pad, the thicker fabric demands greater effort to be pulled through the hole, whereas the thiner fabric hardly take the shape of a waving sheet.

Two parameters of the pulling curves the force P_{max} and the work A of pulling the specimen through the hole diverge from the optimal value of $h = k\delta$ when parameter h is minimised according to the law $y = a + b/x$. In this case, $y = P_{max}$, or $y = A$, and $x = h$ (Figure 11).

The distance between the limiting plates h can be reduced in cases when a lack of machine sensitivity is observed during the pulling test, or when investigations of one technological parameter (such as washing) on the textile's hand are carried out for one particular fabric.

■ Conclusions

1. While sliding in the space between the limiting plates in the direction of its centre, the textile membrane deforms into waves of a sinusoid shape. The stability of these waves depends on the space between the limiting plates size. When $h \geq (R/r) \cdot \delta$, the sinusoid-shaped waves break down and acquire the shape of waves of different width. The waves become more even when h decreases.

2. The theoretical and experimentally-determined number of the waves calculated by the scheme proposed in this work shows good correlation during the whole deformation process.

3. The analysis of the geometric shape of the specimen has shown that the curve $H–P$ while being pulled through the central hole indicates the geometric transformation of the specimen during all the stages of deformation. On the basis of an analysis of the relations between the resistance parameters (force P and work A) and the specimen's geometric forms we can state that the curve $H–P$ may be divided into 4 zones.

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