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Evaluating the Bending Rigidity of Flat Textiles with the Use of an Instron Tensile Tester

Abstract
The purpose of this work is to verify the possibility of using an Instron tensile tester for evaluating those mechanical properties of flat textile fabrics which are responsible for their handle properties. A method of evaluating the bending rigidity of woven fabrics was developed. The method consists in axially compressing samples fixed at both ends and placed in a vertical position, which leads to their buckling. The bending rigidity was determined on the basis of the critical maximum force occurring at buckling, and the curvature of the buckled sample which appears as result of the action of this force. The results obtained by this method were compared with those obtained with the use of the FAST system. The good compatibility of both these methods was proved by the correlation coefficients.

Key words: *handle, mechanical properties, bending rigidity, bending moment, curvature, buckling, buckling length.*

Introduction

One of the basic attributes of clothing accepted by the client is that it should ensure him a feeling of comfort over the time of using this clothing. In accordance to the definition given in [1], comfort is the physiological and physical harmony of a human being with his environment. Apart from aesthetic aspects, comfort depends on sensorial feelings which results from the contact between human skin and the clothing worn, as well as on physiological feelings. These latter are caused by the clothing's ability to ensure the required heat protection, the possibility to lead water vapour and carbon dioxide out from the skin's surface, and to protect the skin against noxious activity of the surrounding environment. The factors which define the comfort created by clothing can be divided into factors, which are related to sensorial comfort, and those which describe physiological comfort. Sensorial comfort is connected with stimulating the feeling sensors, which are displaced on our body, by the contact arising between human skin and the clothing material. The stimulation degree of the feeling sensors depends to a great degree on the mechanical properties of the textile product. The set of features of the fabric destined for clothing which decisively influences the sensorial comfort felt by the user is historically described by a factor called handle.

For a long time, handle has been estimated by the organoleptic method. The producers and users of flat textile products try to formulate in words the impression of touching the flat textile product. Such estimation is a subjective method, which does not analyse the core of the problem connected with the influence of factors creating the particular sensations. This was why in the 1930s investigations were commenced into an objective measurement of the features which are decisive for handle. Peirce was a forerunner of such investigations. His works connected with determining the bending rigidity and compressibility of flat textile products should be mentioned [2]. At the turn of the 1960s, researchers from the Swedish Textile Institute (TEFO) [3-8] carried out intensive investigations into thismatter. These research works led to determining the dependencies between the features of flat textile products subjected to bending, buckling, shearing, and compressing, and the susceptibility of these products to manufacturing clothing. Lindberg [8] was the first who applied the theory of buckling to estimating the behaviour of fabrics in the clothing manufacturing process. Kawabata and Niwa [9-13] were followers of Peirce and the Swedish researchers, who since 1968 have conducted research into handle. These investigations have been crowned by the design and construction of a measuring system which serves for objective estimation of handle. Theoretical considerations based on the laws of mechanics and statistics preceded the construction of the particular modules. The aim of these research works was to select measurable physical features using statistical methods, which would be decisive on handle as a sensorial feeling acknowledged by the user during the contact of the fabric with human skin. The effect of these investigations was to develop a measurement system, which is composed of several devices enabling the tests of tensile and shearing properties, pure bending, compressing, surface roughness, and surface friction.

The FAST system (Fabric Assurance by Simple Testing) is another system designed for analysing the handle properties of fabrics. Postle developed it in Australia.

However, the FAST system is intended rather for controlling production processes than for an objective evaluation of the sensorial properties of fabrics. In this system, compressing, bending, extension and dimensional stability tests are performed [14].

The problem of handle has been also analysed at the Institute of Textile Metrology of the Technical University (TU) of Łódź [15-23], and at present it is being continued at the Department of Textile Metrology of the Faculty of Engineering and Marketing of Textiles, TU of Łódź. An assumption accepted for these investigations was linking the meaning of handle with the susceptibility (ability) of fabrics to form pleats. A pleat is formed as a consequence of stability loss which depends on the fabric's bending rigidity. The bending rigidity, in turn, is one of the basic parameters which are decisive for the handle of flat textile products. A lower value of bending rigidity supports the positive impression of sensorial comfort, and is at the same time a feature of fabrics which are susceptible to the formation of pleats. The importance of bending rigidity for estimating the technological

Table 1. Characteristics of fabrics used for testing.

Fabric	Raw material	Mass per 1 m² m_p, g/m²	Thickness H, mm	Thread number per 10 cm		Linear density of yarn Tt, tex		Weave
				weft	warp	weft	warp	
A	PET	194.3	0.45	250	448	36,5	18,0	2_3 Z
B	Wool	353.8	1.78	94	112	186	162	3_3 Z Shetland
C	Wool/PET	272.9	0.54	242	318	-	-	2_2 Z
D	Wool	307.9	0.90	228	450	41,0	38,0	diagonal
E	Cotton/PET	117.2	0.28	238	310	21,0	21,0	plain weave

Table 2. Characteristics of fusible interlinings.

Marking of insert	Kind of insert	Mass per 1 m² M_p, g/m²	Adhesive graduation, mesh	Adhesive spread, g/m²
1	nonwoven with deposited PA paste	55	13	-
2	insert knitted with PA powder	67	17	10 - 12
3	insert knitted with PA powder	73	17	10 - 12
4	insert woven with PA powder	99	17	12 - 16
5	insert woven with PA powder	144	28	20 - 22

Table 3. Characteristics of fused panel systems.

Kind of combination fabric-insert	Mass per 1 m² m_p, g/m²	Thickness H, mm
A1	245.5	0.73
A5	333.1	0.78
B2	460.3	2.02
B3	430.6	2.06
C4	364.9	0.92
D2	395.8	1.15
E1	172.8	0.56
E5	255.8	0.65

usefulness and usability of woven fabrics led us to begin an attempt to determine the specimen's bending rigidity by means of measuring buckling with the use of an Instron tensile tester.

The bending test we proposed was performed by axially compressing a sample fixed at both ends, which led to its buckling. The bending rigidity was determined on the basis of the critical maximum load appearing at the moment while the sample lost its stability and of the sample curvature at this very moment. The curvature was determined by recording the sample's image and the choice of the sample's axis equation at the moment of buckling. At the same time, identical samples were sent to the Faculty of Mechanical Engineering, University of Maribor, to be examined using the FAST system. The results obtained were compared with those determined by the Instron tensile tester.

Experimental Part

Materials tested

The tests were carried out with selected types of fabrics made from various kind of fibres and characterised by different structures. Additionally the fabrics were reinforced with stiffening interlinings. In order to characterise the pure fabrics, the fusible interlinings, and the fused panel systems, the basic parameters such as mass, thickness, warp and weft counts were determined; all of them are presented in Tables 1-3.

Measurement procedure

The axial compressing of samples was performed by an Instron tensile tester, while the records of the shapes of the buckled samples were obtained with a CCD Elemis KK 35 camera with 6V12 (6-12 mm) lens and a computer-equipped Framegrabber image acquisition card.

25 mm × 250 mm strips of fabric were cut out in the direction of warp and weft in order to prepare the samples for testing; 10 samples for each direction were tested. To create identical, reproducible test conditions, after cutting the samples were conditioned in a room with a temperature of 20°C and of 65% humidity, where they remained for 48 hours.

The selected samples were axially compressed with the use of the Instron tensile tester, acting on the basis of elongation constant over time. Considering that the buckling of samples occurs under very small forces, it was possible to use a measuring head designed for stretching tests. The lower end of the sample was fixed in the tester's clamp, which was fastened to a crossbar which moved in the upper direction over the measurement. The upper end of the sample was fixed to one end of a stiff tension member, whose second end was fastened by an articulated joint to the tester's crossbar with the measuring head. In this way, the forces occurring over the measurement which compressed the sample caused the measuring head to discharge. An outline diagram of the sample's fastening system (a part of the measuring system) is presented in Figure 1.

A diagram of the changes in the compressing force as a function of the crossbar movement in an upwards direction was recorded over the measurement. The analysis of the diagrams obtained allowed us to state that the shape of the curves depended on the length of the compressed sample tested; this phenomena was also observed during previous research works [16]. At a relatively large sample length, called the buckling length, which is different for various kinds of

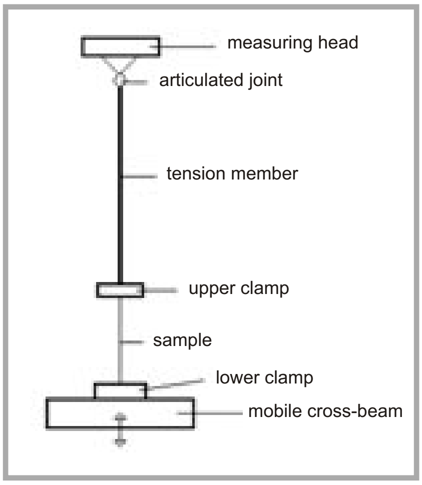

***Figure 1.** Diagram of the sample's fastening system.*

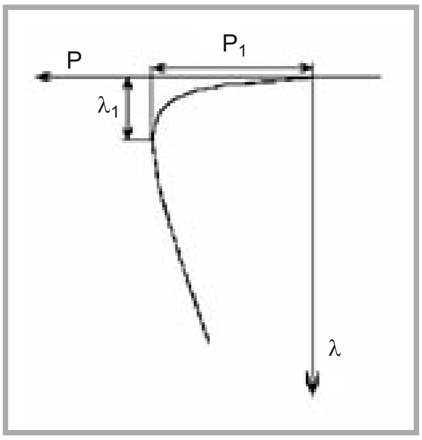

Figure 2. *Example record of force as a function of compressing the sample with determination of maximum force and buckling length.*

fabrics, the diagrams have been obtained with a force maximum characteristic for buckling (Figure 2). The buckling length changed within the range from 30 mm to 200 mm for the woven fabrics tested within the scope of this investigation.

If some minimal jamming eccentricity occurs (which cannot be ruled out), the curves load vs. displacement are then characterised by a maximum force whose value depends not only on the sample's slenderness ratio but also on the fastening eccentricity [8}. The curve maxima, such as those shown in Figure 2, are related to the limited load value P_1 which the sample can transfer to the moment of stability loss. Beyond the displacement limit determined by the point related to the maximum force, any further deflection increase takes place at decreasing load. The maximum force related to the buckling of the ample was accepted as the force value taken for calculating the maximum bending momentum occurring in the sample.

The shape of the axis of the buckled samples was recorded by photographing. The lens of the camera fixed on a tripod was at the same level as the Instron clamps, at a plane parallel to the plane formed by the clamps. The photograph was taken at the moment corresponding to the maximum force value. In order to obtain better visibility, the photographs were taken against a contrasting background. Examples of shapes of the buckled samples are shown in the photographs presented in Figure 3.

The photographs obtained of the buckled samples characterised by different shapes were transformed into a binary image. Next, the axes of the objects and the co-ordinates of the curvature points were also determined in binary images. On the basis of the co-ordinates of these points, the equations of the buckled sample's axes were determined using the NCSS statistical program.

Theoretical Considerations

The bending rigidity of samples was calculated from the relationship

$$EI = M_g \rho \qquad (1)$$

where:
EI - the bending rigidity,
ρ - the curvature radius,
M_g - the bending momentum.

The curvature radius was determined from equation (2):

$$\frac{1}{\rho} = \frac{d^2y}{dx^2}\left[1+\left(\frac{dy}{dx}\right)^2\right]^{-\frac{3}{2}} \qquad (2)$$

If the value of the curvature is small, we can assume that

$$\frac{1}{\rho} \cong \frac{d^2y}{dx^2} \qquad (3)$$

The elaboration procedure of the bending momentum M_g depends on the way in which the sample is fastened. The sample's fastening and measuring system presented in Figure 1 does not enable the actual clamping system to be explicitly defined at once. The samples are directly fastened in the clamps. But the real boundary conditions depend on the stiffness of the neighbour tension members of the measuring system; moreover, for the fastening system applied, the tension member fastened and articulated to the measuring head influences the actual boundary conditions. Apart from that, if we consider that the samples are compressed in the clamps, local narrowing occurs at the edges of the clamps, which may also influence the boundary conditions. All these circumstances led us to propose the following method for verifying the actual kind of samples' fastening. According to the proposed model solution, as the point of departure for the description of the axis of the buckled sample, it is accepted that transversal loads do not occur, and that the general solution of the differential equation (4) is valid:

$$EI\frac{d^4y}{dx^4} + P\frac{d^2y}{dx^2} = 0 \qquad (4)$$

By accepting that $k^2 = P/EI$, equation (4) takes the form:

$$y = A \sin kx + B \cos kx - Cx+D \qquad (5)$$

where:
A, B, C, D, k - coefficients of the equation which describes the sample axis,
P - the axial force compressing the sample, and
EI - the bending rigidity of the sample.

The parameters of equation (5) were chosen for every sample on the basis of empirical points taken from the buckling diagrams.

The determined parameter k was accepted as the basis for verification of the actual kind of sample fastening. We stated that the coefficient k was near 2π/l (where l is the sample's length) for 16 of the 23 tested samples. Such a value of the coefficient k entitles us to accept the assumption that while carrying out the tests we have proposed, we are dealing with compressing samples which are fixed at both ends. According to Timoshenko's considerations [23], for the elaboration of the bending rigidity we accepted that the maximum bending momentum occurs at the point related to the maximum curvature of the dependency force vs. displacement, and can be calculated from equation (6):

$$M_g = \frac{a \cdot P}{2\cdot\left(1-\frac{\alpha}{4}\right)} \qquad (6)$$

where:
a - the ordinate related to the point of the

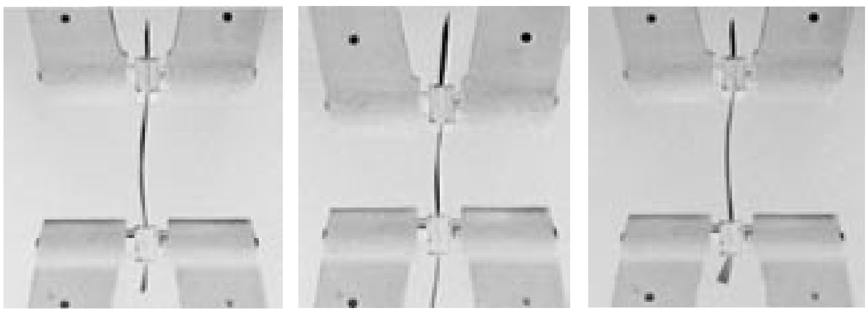

Figure 3. *Examples of the specimen at the moment of buckling.*

Table 4. Results of evaluation of the bending rigidity, using two different testing methods (B - bending rigidity calculated according to the methods used by the FAST system, EI - bending rigidity according to the Instron tensile tester method).

Kind of fabric	Ao	Aw	Bo	Bw	Co	Cw	Do	Dw	Eo	Ew	A1w	C4o	C4w	E1o	E1w	E5o
INSTRON EI , μNm^2	8.9	7.1	36.6	10.3	14.8	28.6	14.3	19.7	9.8	5.8	15.8	23.2	77.3	15.7	54.2	192
FAST B, μNm	8.3	29.1	47.0	32.0	30.4	24.8	29.5	21.9	7.8	7.0	162	96.2	285	22.6	121	617

maximum curvature of the dependency (the maximum ordinate),

P - the force at which the buckling occurred, related to the recorded curvature ($P=P_1$, Figure 2).

The coefficient α was calculated from equation (7).

$$\alpha = \left(\frac{kl}{\pi}\right)^2 \quad (7)$$

Test Results and Discussion

While elaborating the proposed method of measuring the bending rigidity of textile samples with the use of the Instron tensile tester, we followed the analysis of mechanical features during the elastic buckling of the rods. The samples' buckling moment was identified with the moment when the compressing force achieved its maximum value. The bending momentum was calculated as for the fixed samples. On the basis of an analysis of the diagrams obtained during the buckling tests, and an analysis of images recorded of the axis of buckled samples, the bending momenta were determined according to equation (6), and the curvature radii according to equation (3). Next, the bending rigidity for each tested sample was calculated from equation (1). The results obtained were compared with those obtained by the FAST system. The results of all the calculations are listed in Table 4.

The research results listed in Table 4 enabled us to carry out a correlation analysis between the data obtained by the samples' bending rigidity measurements with the use of both methods discussed. The correlation coefficient between the measurement results of both methods equals r=0.960. The linear regression equation between the results obtained by the FAST method and the Instron tensile tester method was also calculated, and the following form was obtained:

$$\hat{y} = 0.283 \cdot x + 6.0 \quad (8)$$

As the curvilinear coefficient R=0.9604, which means that $R^2=r^2$, it can be accepted that the dependency considered is linear. On the other hand, as the methods analysed do not have the same measure, they cannot be accepted as commensurable and interchangeable. Taking into consideration the very random variability of the results within the group of samples belonging to the same fabric, it seems advisable to carry out broader investigations with more differentiated test material, especially within the range of samples of higher stiffness.

Conclusions

- The Instron tensile tester can be used for determining the bending rigidity of flat textile products.
- The test results obtained with the use of the Instron tensile tester are characterised by a significant linear correlation with the results obtained by the FAST system.

References

1. *Multi-author work, Metrologia Włókiennicza, vol. IV, WNT, Warszawa, 1973.*
2. *Peirce F.T., Handle of Cloth as a Measurable Quantity, J. Text. Institute, vol. 21, pp. 377-416, 1930.*
3. *Eeg-Olofsson T., A Contribution to the Experimental Study of the Bending Properties of Fabrics, Göteborg-Chalmers, Tekniska Högskala 1957.*
4. *Eeg-Olofsson T., J. Text. Institute, vol. 50, p. 112, 1959.*
5. *Olofsson B., Model Studies of Relationships Between Geometry, Fine Structure and Mechanical Properties of Worsted Fabrics, Cirtel, vol. 4, 1965.*
6. *Olofsson B., Ogucki N., A. Theory of Elasto-Plastic Buckling, Text. Res. J., vol. 36, pp. 295-309, 1966.*
7. *Lindberg J., Behre B., Dahberg, Text. Res. J., vol. 31, p.99, 1961.*
8. *Lindberg J., Westerberg L., Svensson R.T., Wool Fabrics as Garment Construction Materials, J. Text. Institute, vol. 51, pp. 1475-1492, 1960.*
9. *Kawabata S., Niwa M., Kawai H., The Finite-Deformation Theory of Plain-Weave Fabrics, Part I. The Biaxial-Deformation Theory, J. Text. Institute, vol.64, pp. T21-46, 1973.*
10. *Kawabata S., Niwa M., Kawai H., The Finite-Deformation Theory of Plain-Weave Fabrics. Part II. The Uniaxial Deformation Theory, J. Text. Institute, vol. 64, pp. 47-61, 1973.*
11. *Kawabata S., Niwa M., Kawai H., The Finite-Deformation Theory of Plain-Weave Fabrics. Part III. The Shear-Deformation Theory. J. Text. Institute, vol.64, pp.62-85, 1973.*
12. *Kawabata S., Niwa M., Chapter 10. Objective Measurement of Fabrics Hand, Modern Textile Characterization Methods, ed. by Mastura Raheel, Marcel Decker, pp. 329-354, 1996.*
13. *Kawabata S., Niwa M., Chapter 7, Recent Progress in the Objective Measurement of Fabric Hand, Macromolecular Concept and Strategy, ed. Okamura S., Ranby B., Ito Y., Springer Verlag, pp. 329-354, 1996.*
14. *De Boos A. G., Tester D.H., The FAST Approach to Improved Fabric Performance, CSIRO, Division of Wool Technology, Australia, Textile Objective Measurement and Automation in Garment Manufacture, ed. George Stylos, Ellis Hovood, 1991.*
15. *Pryszcz M., Buckling of woven fabrics (in Polish), M.Sc. thesis, IMWiO, Technical University of Łódź, 1987.*
16. *Żurek W., Kocik M., Pryszcz M., Buckling of woven fabrics (in Polish),. Przegląd Włókienniczy 43/4, 1989.*
17. *Skalska J., Buckling of woven fabrics (in Polish), M.Sc. thesis, IMWiO PŁ, 1989.*
18. *Ruszkowska A., Investigation into susceptibility of a surface to felt creation (in Polish), M.Sc. thesis, Institute of Metrology, Nonwovens, and Clothing (IMWiO), Technical University of Łódź, 1992.*
19. *Żurek W., Kocik M., Skalska J., Susceptibility to felt creation (in Polish), Proceedings of the ArchTex'97 Conference 'Textiles - Design and Maintenance', Łódź 1997.*
20. *Ziółek A., Investigation of nonwoven properties over their axial compression (in Polish), Report of the Institute of Metrology, Technical University of Łódź, 2001.*
21. *Bulzacka K., Estimation of the sensorial comfort factors of clothing layer systems (in Polish), M.Sc. Thesis, Institute of Metrology, of Łódź Technical University of Łódź, 2002.*
22. *Kocik M., Krucińska I., Geršak J., Ziółek A., Bulzacka K., Graczyk M., Jakubczyk J., Application of Instron Tensile Tester for Analysis of Bending Rigidity of Flat Textiles, 4th International Conference IMCEP 2003, Maribor, Slovenia, 9-11 October 2003, p. 24.*
23. *Timoshenko S.P., Gere J.M., Teoria stateczności sprężystej, Arkady, Warsaw, 1963.*

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