EXPERIMENTAL TESTING AND FINITE ELEMENT SIMULATION OF TH-7 BENDING TEST OF SPORTS BRA TEXTILES

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Abstract: *The measurement of mechanical properties of textiles is essential for Finite Element (FE) simulation and virtual garment try-on software. For the determination of bending, the TH-7 device, developed by Technical University of Liberec, Faculty of Textile Engineering, was used. It offers testing of specimens in different shapes. Circular shaped specimens with a diameter Φ = 5 cm were cut from three fabrics used in the Anita momentum sports bra. These specimens were subjected to the bending test in directions from 0° to 360° turned by every 22.5° both up and down. The shape of the specimen during testing was recorded using video. From the measured bending force F_m [mN] the bending rigidity B [Nm^2/m] was calculated as described in literature. The value of bending rigidity was verified in FE simulation of TH-7 bending test by comparing resulting specimen shape and bending force. None of the bending tests proposed in literature seems to provide correct values for Young's modulus E, whereas the simulation of non-linear behaviour requires a more complex approach of piecewise linear modelling.*

Keywords: *bending force, bending rigidity, material properties, knitted fabrics, anisotropy.*

1 INTRODUCTION

Bending rigidity is an important mechanical property of textile fabrics. Therefore, several different procedures and devices for measuring bending behaviour have been proposed in literature. ASTM D1388 proposes the Cantilever test (Option A) and Heart Loop test (Option B) [1] which both subject the specimens to their own weight. They provide limited information about the mechanical behaviour due to the fixed amount of bending and, moreover, they don't include force measurement. The KES-FB (Kawabata Evaluation System) pure bending tester suggests that the fabric is subjected to bending only, which is not thoroughly correct in case of horizontal clamping of fabric. In addition, this device is rather expensive [2]. Yet, the advantage over Cantilever and Loop tests is the ability to detect the non-linear bending behaviour by measuring the relationship between bending momentum and curvature [2]. In the Czech standard ČSN 80 0858 "Testing of stiffness and resiliency of textile fabrics" a similar bending tester is used [3]. The TH-7 bending tester is a much cheaper and more practical device, as it allows the measurement of small specimens in both bending directions (up and down) in one cycle, directly providing bending hysteresis. In addition, good correspondence to the KES-FB was proven [4].

In sports bras, mainly knitted fabrics are used for the construction of cups and wings. The loop structure of knitted fabrics leads to an anisotropic, usually orthotropic, mechanical behaviour, which has to be taken into account when choosing the direction in which the fabrics are sewn. Due to the assumption of orthotropic behaviour, material properties of knitted fabrics have to be tested in several directions. The idea of using circular shaped specimens was first mentioned by Peirce [5]. Circular shape has the advantage of reducing curl and moreover the benefit that the stiffness can be measured in any direction using only one specimen. This significantly reduces the amount of required specimens compared to using rectangular ones [4].

2 EXPERIMENTAL

2.1 Specimens

Fabric samples of the required size of the Anita momentum sports bra were available for the wing (5), cup (6) and cup liner (7) fabric (see Figure 1).

Loop structure was analysed under the microscope to determine the type of knitting for each sample. Wing fabric (5) is a single layered warp knit mesh with fillet, three guide bar structure (one elastan thread) (see Figure 2a). Cup fabric (6) is double layered, the outer layer is a 2 layer rip structure (weft knit with tuck) and the inner layer is standard plush to make the cup more comfortable (see Figure 2b). Cup liner fabric (7) is double layered, with locknit (charmeuse) outer layer and tricot inner layer to provide high strength in machine direction (see Figures 2c and 2d).

Figure 1 Unstitched Anita momentum sports bra, machine direction of samples indicated by arrow

From these three samples, three circular shaped specimens each with a diameter Φ = 5 cm were cut. The specimens were marked with lines at every 22.5° with the machine direction as 0°.

Thickness was measured according to EN ISO 5084 [6] and density was calculated as weight per unit area divided by thickness (see Table 1).

2.2 Experimental TH-7 bending test

The circular shaped specimens were clamped in the TH-7 bending tester (see Figure 3). Measuring range was set to 40 mN. For each direction, 10 cycles of 90° up and down bending were performed and filmed to analyse the deformed shape during the bending test.

The measured bending force F_m [mN] was output as mean value for the 10 cycles and averaged for three specimens per sample, for each direction as well as up and down separately. This bending force can be converted into the bending rigidity B [Nm^2/m] (1), where sample width s = 50 mm and the constant κ = 0.0334 [m²] as described in [4]. Instead of bending rigidity of unit width B [Nm^2/m], bending rigidity for sample width B_s [Nm²] (2) was used for further calculations:

$$B = \kappa \cdot \frac{F_m}{s} \tag{1}$$

$$B_s = \kappa \cdot F_m \tag{2}$$

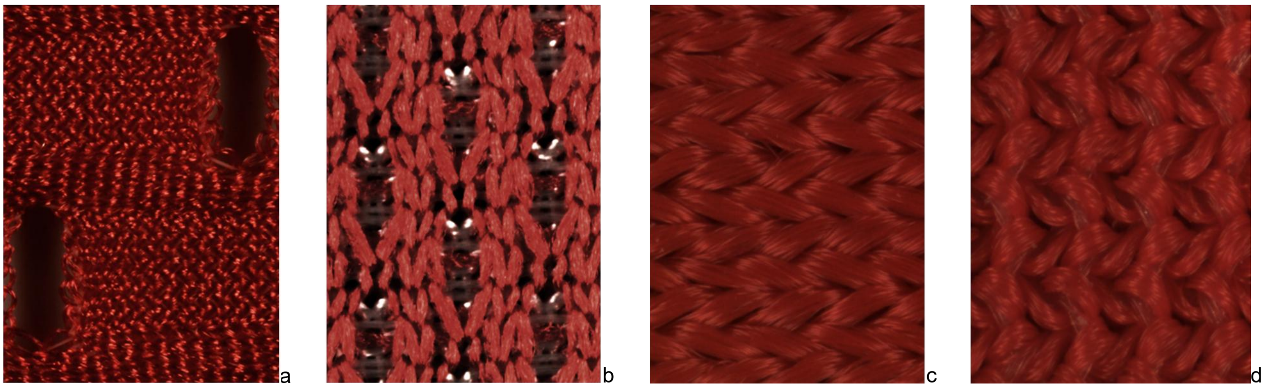

Figure 2 a) Sample 5 (back) b) Sample 6 (face) c) Sample 7 (inner layer, face) d) Sample 7 (outer layer, face); machine direction up

Table 1 Specifications of sports bra samples

sample	description	weight per unit area M [g/m²]	thickness T [mm]	density ρ [t/mm³]
5	wing	245.8	0.85	$2.892 \cdot 10^{-10}$
6	cup	266.3	1.25	$2.131 \cdot 10^{-10}$
7	cup liner	367.4	1.00	$3.674 \cdot 10^{-10}$

Figure 3 Specimen clamped in the TH-7 bending tester, front and side view

2.3 FE-modelling of TH-7 bending test

FE models were pre-processed in MSC Patran 2016. The fabric was modelled as a semi-circle corresponding to the free bending length of the sample in the test using standard PSHELL shell formulation with linear CQUAD4 and CTRIA3 elements. The sensor jaws were modelled as half cylinders fixed to one node by RBE2 constraints (see Figure 4).

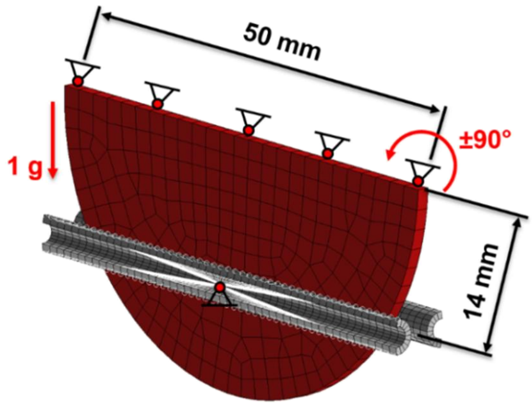

Figure 4 FE model of TH-7 bending test (shell thickness display) with boundary conditions and load case

Linear elastic material MAT1 for course fitting and stress-dependent MATS1 for piecewise linear fitting were assigned to the fabric. Considering the bending rigidity of a thin structure being the product of Young's modulus *E* and area moment of inertia *I* [mm^4] (3, 4), Young's modulus *E* [MPa = N/mm²] can be derived from the bending rigidity for sample width B_s [Nm²] calculated from the experimental TH-7 bending and from the measured thickness *T* [mm] of the sample (5).

$$B_s = E \cdot I \tag{3}$$

$$I = \frac{s \cdot T^3}{12} \tag{4}$$

$$E = \frac{12 \cdot \kappa \cdot F_m}{s \cdot T^3} \tag{5}$$

Poisson ratio *v* was used from previously performed tensile test. For the Teflon sensor jaw properties were assigned, including a friction coefficient μ = 0.05 in the fabric-jaw contact. The clamped top row of nodes of fabric was rotated by ±90° in steps of 2° in accordance with the TH-7 measurement procedure. Inertial load was included to account for the influence of gravity. The solver MSC Nastran Implicit Nonlinear analysis (SOL 400) was used for achieving the numerical results.

3 RESULTS AND DISCUSSION

3.1 Experimental TH-7 bending test

Textiles usually exhibit hysteresis behaviour under bending loading, which can be measured when bending the specimen consequently in both directions. Figure 5 shows exemplarily the hysteresis loop for sample 6 obtained by TH-7 bending test at 0° orientation as the arithmetic mean of 10 cycles averaged for three specimens.

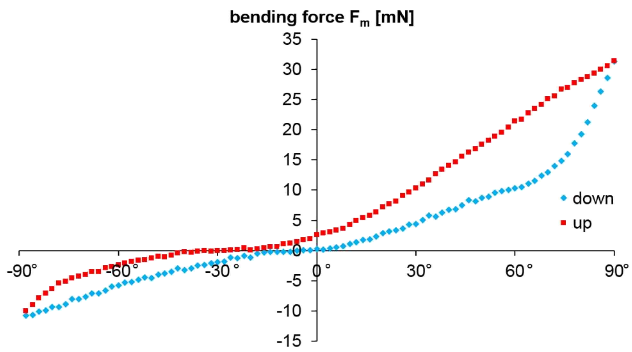

Figure 5 Hysteresis loop obtained by TH-7 bending test (sample 6, degree 0° = machine direction)

The anisotropic mechanical behaviour obtained by subjecting the same specimen to bending in several directions can be evaluated and depicted in a polar diagram.

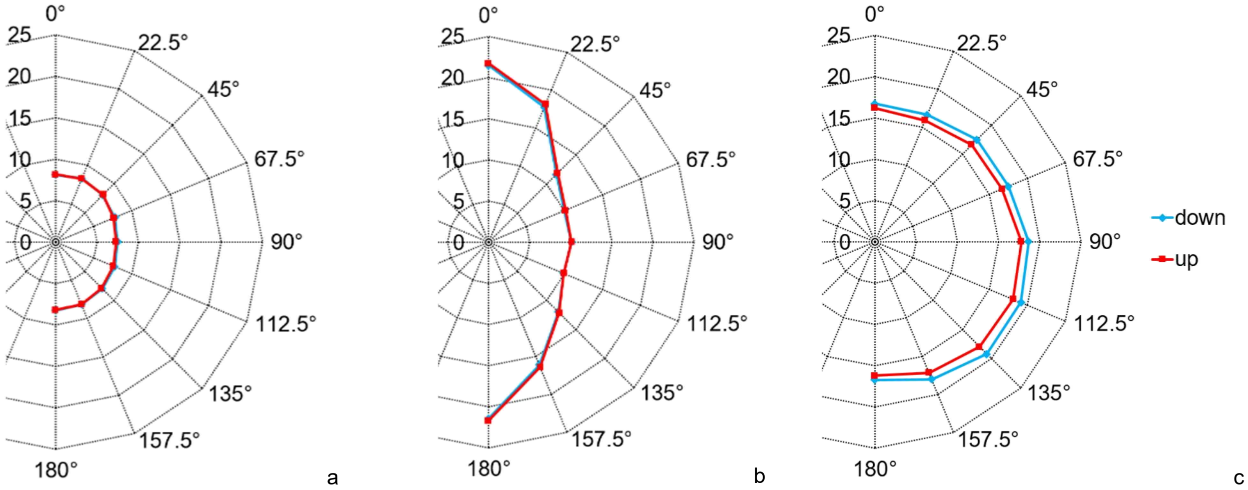

Figure 6 Polar diagram of bending rigidity *B* [Nm²/m] at +90° bending a) Sample 5 b) Sample 6 c) Sample 7

The highest value of bending rigidity *B* [Nm²/m] for +90° bending was chosen for comparison of the three samples. Due to symmetry, specimens were measured only for directions from 0° to 157.5°. The data could be copied to the other half of the polar diagram as mentioned in [4] or simply omitted (see Figure 6).

Sample 6 shows far more anisotropy than samples 5 and 7, while sample 7 shows the greatest deviation between up and down bending direction. For all three samples, the measurement for directions from 0° to 90° would be sufficient as the first and second quadrant are very similar.

3.2 FE-modelling of TH-7 bending test

Table 2 shows the mechanical properties used for the FE simulation of the TH-7 bending test for the three sports bra samples. Young's modulus E calculated from TH-7 bending test for bending direction 0°, and previously performed tensile test in machine direction are compared. It can be concluded that TH-7 bending test overestimates Young's modulus by a factor of 1000. Therefore, FE simulation had to be performed with values obtained by tensile test to gain comparable bent shape. Based on the resulting values for horizontal bending force F_m, Young's modulus was fitted for 0° to +90° bending, which can be approximated by linear material behaviour.

The resulting bent shape from experimental TH-7 bending test and FE simulation are compared in Figure 7 exemplarily for sample 6 in machine direction (0°). The shell elements representing the sensor jaws were modelled with offset in order to show the outer surface contacting with the specimen.

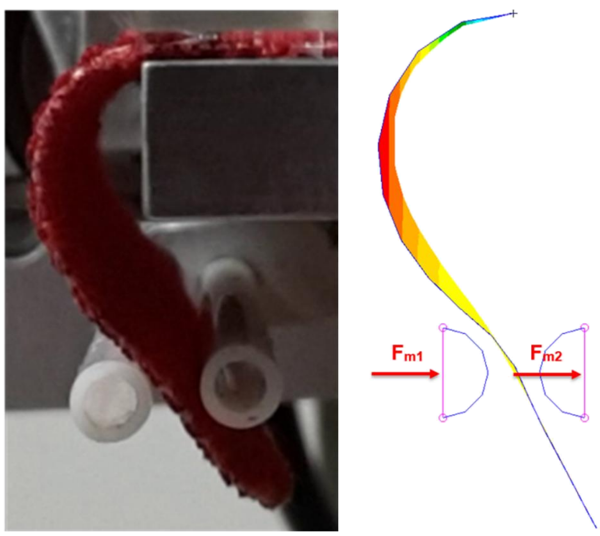

Figure 7 Comparison of bent shape at bending angle +90° of sample 6, a) TH-7 test b) FE simulation

Table 2 Mechanical properties of sports bra samples for FE simulation

sample	thickness T [mm]	density ρ [t/mm³]	Young's modulus E [MPa]		Poisson ratio ν [-]
			TH-7 test	tensile test	
5	0.85	$2.892 \cdot 10^{-10}$	158.791	0.165	2.416
6	1.25	$2.131 \cdot 10^{-10}$	421.603	0.409	2.022
7	1.00	$3.674 \cdot 10^{-10}$	321.480	0.332	0.409

The nearly linear material behaviour for bending direction up could be coarsely approximated by Young's modulus *E* = 0.147 MPa. The non-linear material behaviour for bending direction down was taken into account by piecewise linear modelling defining stress-dependent MATS1 material. The stress values were calculated from resulting maximum strain for the respective bending angle and adjusted to resulting bending force F_m at the sensor jaw. The sum of horizontal bending forces F_m at both sensor jaws for FE simulation was compared with the measured values for +90° bending (see Figure 8); the procedure for -90° bending was identical. Fluctuations in FE result occur due to stick-slip at the contact of specimen and sensor jaw.

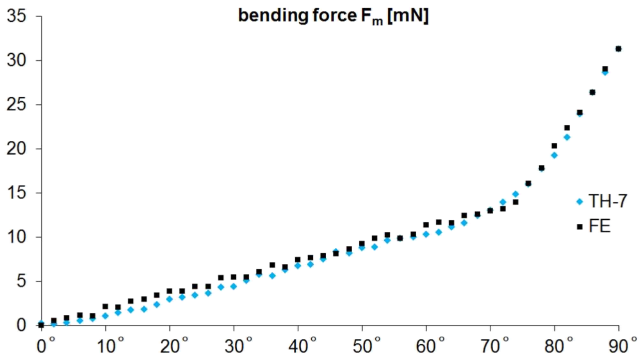

Figure 8 Comparison of horizontal bending force F_m of sample 6 in TH-7 bending test and FE simulation

4 CONCLUSIONS

The TH-7 bending test provides a fast and cheap option to measure the mechanical properties of fabrics. The proposed finite element calculation allows an evaluation of the required Young's modulus for each measured direction. Using this procedure the orthotropic properties of the fabric required for a mechanical analysis of can be derived. Therefore, a numerical procedure has been performed for the verification of Cantilever bending test [7]. None of the bending tests proposed in literature seems to provide correct values for Young's modulus *E*. The proposed bending rigidity [4] seems to calculate unreasonably high values. The constant κ = 0.0334 m² was calculated by a simple discrete model of continuous bending curve [4] to match TH-7 results with KES-FB results. We suppose that this constant considers using bending force F_m in [mN] rather than in [N] as mentioned in [4]. The assumption of using bending rigidity as a value for FE simulation should be rejected, only tensile tests are able to provide the necessary material properties for simulation when assuming linear behaviour.

The measured bending force F_m is a function of the bending angle. There is no advice given in [4] on which value at which bending angle to use for the calculation of bending rigidity. Considering the non-linear behaviour of knitted textiles requires piecewise linear fitting defining nonlinear (stress-dependent) material properties adjusted to the resulting bending force F_m at the sensor jaw for the respective bending angle. This procedure is time-consuming, but it allows for realistic bending simulation of sports bra fabrics in one direction. In addition, hysteresis behaviour cannot be taken into account in MSC Nastran solvers.

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5 REFERENCES

1. ASTM D1388-14 Standard Test Method for Stiffness of Fabrics, 2014
2. Naujokaityte L., Strazdiene E., Fridrichova L.: Comparative analysis of fabrics' bending behavior testing methods, Tekstil 56(6), 2007, pp. 343-349
3. ČSN 80 0858 Zkoušení tuhosti a pružnosti plošných textilií (Testing of stiffness and resiliency of textile fabrics), 1974
4. Fridrichová L.: A new method of measuring the bending rigidity of fabrics and its application to the determination of the their anisotropy, Textile Research Journal 83(9), 2013, pp. 883-892, https://doi.org/10.1177/0040517512467133
5. Peirce F.T.: 26 – The "handle" of cloth as a measurable quantity, Journal of the Textile Institute Transactions 21(9), 1930, pp. T377–T416, https://doi.org/10.1080/19447023008661529
6. EN ISO 5084 Textiles - Determination of thickness of textiles and textile products, 1996
7. Hassmann M., Stöger S., Mentel N., Krach W.: Bending behaviour of sports bra fabrics: Experimental and finite element simulation of ASTM D1388 Cantilever test, Vlákna a Textil (Fibres and Textiles) 24(1), 2017, pp. 73-77