The reliability of the newly developed bending tester for the measurement of flexural rigidity of textile materials

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Abstract. A new automated bending tester was developed in Ghent University, Belgium to reduce the human interference in the bending measurement. This paper reports the investigations made on the tester in order to confirm the reliability of its measurement. For that, 11 types of fabrics with different construction parameters were tested for their bending length and flexural rigidity using the new bending tester and the results were compared with that of the standard or manual bending tester, which were conducted in accordance with BS 3356:1990 standard method. Statistical analysis confirms that both measurements are strongly correlated with Pearson’s R ≥ 0.90 for all the measurements made. It means that the results from the new automated tester show good correlations with the standard measurement. Nevertheless, this prototype version of the new tester still needs to be adjusted to optimise the functionality of it and further investigations should be done to justify the robustness of the results.

1. Introduction

Bending behaviour of textile materials is a significant characteristic which largely determines the ability of fabrics to drape. Furthermore, it also influenced the formability, handle, flexibility, buckling behaviour, wrinkle resistance and crease resistance. The measurement of bending is often characterized by its bending or flexural rigidity and hysteresis. Several testing devices offer the function to test the bending rigidity of the fabrics. Not only that, they come with various principles of measurement such as pure bending principle, folded loop and cantilever methods [1], [2].

Pure bending tests are the most complex as compared to the others. Kawabata Evaluation System (KES) uses this principle in its bending measurement where the sample is mounted vertically on the device and the bending moment is measured as the sample is bent, enabled to obtain moment versus curvature results during the bending cycle [3], [4]. Using the same principle, the bending curvature could also be measured using Instron as reported by Kocik et al [5]. This pure bending method was also proposed and explained by other researchers in their publications [6]–[8]. Folded loop is another principle used to measure bending behavior. By folding a fabric back to itself, a loop-like structure is obtained and the height of the folded loop is measured as bending length is found to be proportional to it [1], [9]. A commonly used principle, cantilever deformation is a globally accepted principle which
was originally initiated by Peirce [10]. During the experiment, one edge of the fabric strip is fixed on a platform, glided with a ruler and deflected from the platform under its own weight as a cantilever. Then, the cantilever length is measured once it reaches a pre-determined deflection angle [11], [12]. Many researchers applied this principle and developed their own test method for the determination of bending. Sun introduced a tester which uses a cross-shaped specimen with a fixed strip length at the central part. The specimens are hanging on their own weight and their x and y coordinates are determined, thus drape angle could be measured [13]. The drape angle describes fabric drape, and the bending length and flexural rigidity can thus be calculated from it. The commercial testing instruments from Commonwealth Scientific and Industrial Research Organization (CSIRO), Fabric Assurance by Simple Testing (FAST) also uses the cantilever principle in its bending module with an optical device to detect the bending angle [14].

The cantilever method is applied in the standards which are commonly referred today such as EN ISO 9073-7 (European standard) and BS 3356-1990 (British standard). These standards use a manual bending tester to measure the bending length of the fabric samples. The whole procedure starts from placing the sample on the pathway, then sliding the fabric until the 41.5° line, and lastly taking the reading of the overhang length from the scale. All these are done by the operator. As this is prone to inaccuracies, an automated bending tester was developed which is still based on the cantilever principle. Still in prototype version, this equipment which was developed at Ghent University, Belgium introduces some automated approaches for the measurement [15]. Unlike the manual (standard) testing where the fabrics strip is bent by the operator until it reaches 41.5° from the plane platform, this movement was automated by using actuators. Also, the human eyesight which is used in determining the fabric when it reaches the angle is replaced by sensors. Hence, a constant movement can be achieved and inaccuracies of the measurement can be reduced.

This work aims to investigate the reliability of the newly developed bending tester. As it is meant to perform similarly as the manual tester, the results from both manual and the new automated tester were compared and analysed. The following section will discuss on the materials and methods used for this work. Then, the statistical analysis will confirm whether both results are equivalent to each other or not.

2. Materials and methods
A total of 11 fabrics were prepared to be tested using both testers. The fabrics have different fibre composition and some of them were imparted with water and oil repellent finish. The linear densities for most fabrics were around 20/2 Tex for warp and weft with 32x22 per cm fabric density. The fabrics were mostly woven with twill 2/1 structure, and only fabric K is single jersey knitted. Table 1 shows the details of the fabrics.

| Fabric | Fibre composition | Weight (g/m²) | Fabric | Fibre composition | Weight (g/m²) |
|--------|-------------------|--------------|--------|-------------------|--------------|
| A      | 50% nomex, 50% viscose | 269.18       | G      | 50% m-aramide, 48% lenzing FR, 2% carbon-based fibres | 262.82       |
| B      | 50% kermel, 50% viscose | 253.44       | H      | 70% m-aramide dope dyed, 30% viscose | 220.08       |
| C      | 70% kermel, 30% viscose | 228.74       | I      | 100% polyester    | 293.86       |
| D      | 50% nomex, 50% viscose | 253.56       | J      | 100% polyester    | 281.88       |
| E      | 69% nomex, 31% wool    | 242.72       | K      | 50% cotton, 50% polyester | 202.72       |
| F      | 50% m-aramide, 50% lenzing FR (flame retardant) | 268.64       |        |                    |              |

2.1. Bending measurement using manual tester
The manual bending measurement was performed based on BS 3356-1990 standard [16]. For this test, rectangular samples measuring 2.5 X 20 cm were prepared so that the length is parallel to the direction to be tested. Five warp and five weft pieces were tested for each type of fabric in this experiment. The samples were glided on the fixed-angle flexometer which is based on the cantilever principle.
According to Pierce[10], bending length $C$ is the length of the rectangular strip of material which will bend under its own mass to an angle of 7.1°. For ease of measurement, this method uses the cantilever length corresponding to the angular deflection $\theta = 41.5^\circ$, so that the bending length is half of the cantilever length as shown in the following equation. Hence, double the bending length or the overhang length was read from the ruler when the tip of the sample touched the red line of 41.5° on the apparatus (see Figure 1). The higher the bending length, the stiffer the fabric is.

![Figure 1. Schematic diagram of bending test according to BS 3356-1990 standard method](image)

Bending length $C$ is given by the formula (1), where we used $\theta = 41.5^\circ$, and $l$ is the sample overhang length at that angle. By using the appropriate mean value, the flexural rigidity ($G$) of the fabrics is determined in the standard using formula (2), where $C$ is the bending length (cm), and $M$ is the fabric mass (g/m²). In the standard method, the unit is not given in a standard unit (SI). With SI units, the flexural rigidity of a plate is the force couple (Nm) required per width (m) to bend the plate in one unit of curvature (1/m), and hence has general unit for a plate of Nm.

$$C = l \left(\frac{\cos(\theta/2)}{\theta \tan \theta}\right)^{1/3} = l/2, \quad (1), \quad G = 0.10 \text{ M C}^3 \text{ (mg cm)} \quad (2)$$

2.2. Bending measurement using automated tester

Next, the bending measurement of the same fabrics was done on the new automated bending tester (see Figure 2). The device performs exactly the same as the manual tester in terms of its measurement principles since it was manufactured purposely to mimic the function of the manual tester. With the aim to reduce the possible human errors during handling of the test, this automated tester let the process done by the actuators and sensors imparted into the device. The operator is still needed to place the sample onto the pathway, and also to take it out after the test it completed, but the sliding or the linear movement of the samples towards the red line of 41.5° is done by a linear actuator that is driven by a stepper motor. The motor has a step size of 1.8° and with the DRV8825 driver, it can be reduced to 0.05625° or 1/16th of the actual step size. For this set-up, only 1/4th of the step is applied, thus makes 0.45°. The actuator shall convert one step to a linear movement of 10 µm. The speed of the motor is set to 5 mm per second with a step frequency of 500Hz.

By using a laser beam which was pre-set at 41.5°, the determination of the bending length is done based on the laser interruption principle. Once the laser beam is interrupted, the sample will move back slowly, then move forward very slowly up to the interruption of the beam. This is necessary to take into account the bending hysteresis of the sample, as in the standard method where 8 ± 2 seconds are allowed before the scale is read from the manual tester. A light dependent resistor (LDR) is integrated and placed on the side of nylon platform just beneath the sample pathway as a target for the laser beam. It allows to determine if the laser shines unblocked at the pre-set angle. The adjustment of the angle is done by the stepper motor and with the same type of driver used in linear actuator, the precision of 0.05625° can be obtained. With this set-up, not only a single fixed value of angular deflection can be set, other overhang values at different angles can also be determined with the same device, allowing for a broader use of the automated bending tester. The results of overhanging length and bending length are automatically calculated and recorded in an excel sheet.
Some discrepancies are expected to come forward for the measurement using the automated tester. First of all, there is a possibility that the edge of the fabric which is placed on the glided path is not precisely positioned at the end of the path on the platform, allowing for an error of some mm. The same error can however be present in the manual tester. Next, the stepper motor determining the angle of the laser beam requires counterweights as the long arm on which the laser is mounted allows some angle dependent bending. This reduces the precision of the angle at which the laser beam is projected. Finally, the LDR can practically not be placed directly under the fabric, but instead is slightly lower, and hence the line on the manual tester is slightly higher. This will give rise to a constant error in the measurement. Note also that the automated tester will measure at the center of the fabric sample, while the manual tester has the operator standing at the side. For samples which have over the narrow width a transversal sagging (buckling) [17], this will also lead to differences between the devices. This effect should even out in the manual tester as we take the overall data, but five repeats might be too few for this. Better understanding of this phenomenon will give improved insight as where to put the light sensor for the detection of the bending angle.

The bending length C, and flexural rigidity G, from both devices were then compared and analysed by using Pearson’s R statistical analysis tool. This analysis method is very useful to check the reliability of the new bending tester where the R value close to 1 means both devices give comparable results which signify the newly developed device is as reliable as the manual. The following section will tabulate the results.

### 3. Results and discussion

The overhang length l of the fabric samples measured by the manual tester was recorded by the operator for every side and direction of the samples. Then, C and G were calculated based on the formula mentioned in the previous section. For automated tester, l and C were already recorded by its built-in system. Only G needed to be computed, based on the weight of the materials.

The C and G obtained from the manual bending tester and the new automated tester were compared and analysed. Pearson’s R correlation analysis was conducted to the results from both devices to determine the relationships between them.

| Compared indices from standard bending method and automated bending tester | Pearson’s R |
|------------------------------------------------------------|-------------|
| Warp C-Inside                                              | 0.96        |
| Warp C-Outside                                             | 0.98        |
| Warp G-Inside                                              | 0.95        |
| Warp G-Outside                                             | 0.98        |

**Figure 2. Automated bending tester**

The image shows an automated bending tester setup with the platform, LDR placement, and laser beam illustrated.
The results in Table 2 show that all the indices have R values equals to or more than 0.90, while the p-value was found to be less than 0.001. These high R values which are close to 1 mean that the correlation between the indices from both devices are very strong and almost all data could be represented by the fitted regression line. If we considered together all the data for warp and weft, and also outside and inside, we still can obtain an overall R=0.96 and R=0.95 for C and G respectively. Figure 3 illustrates the scatter plots of the overall C and G showing the spread of the data close to the regression line.

| Weft       | C-Inside | 0.92 |
|------------|----------|------|
|            | C-Outside | 0.97 |
|            | G-Inside | 0.90 |
|            | G-Outside | 0.96 |

Figure 3. Plots for the overall results for bending length C and flexural rigidity G

From the results, it was found that the regression line has a slope of 0.8, instead of the expected value close to 1. The fixed offset is as expected as the laser beam points at the LDR, and not at the exact base of the fabric, so a 0 bending length of the manual tester, would still register as a bending length of some mm. The slope discrepancy means a systematic error is present in the linear stepper motor or in the angle stepper motor. The linear displacement was found to be exact. Hence, an investigation was made to confirm the degree of the angle made by the beam. For this, it was found that at 41.5° the true angle of the laser beam is slightly less by 1 to 2°. The reason for this difference are the counterweights needed to avoid bending of the arm on which the laser beam is mounted. The counterweights however overcompensate somewhat the weight of the laser beam. This finding explains why the automated tester measures always a shorter bending length than the manual tester, with the discrepancy increasing as the bending length increases. Fixing this issue with the automated bending tester is needed, but requires a new design of the laser mount.

4. Conclusions

The aim of this work was to perform investigations in order to confirm the reliability of the new automated bending tester. 11 types of fabrics with different construction parameters were tested for their bending length C, and flexural rigidity G using the device. The same fabrics were also tested by using the standard tester or the manual tester, according to the BS 3356:1990 standard method. Both results were compared and analysed. The results yield Pearson’s correlation R≥0.90, with p-value less than 0.001, for warp and weft, outside and inside, which indicate a strong positive linear relationship between both methods. This means that the results from the new automated tester show good correlations with the standard measurement. However, there are still possibilities on the new tester that require adjustment so that the correlation level can be further increased, specifically with regard to the laser mount and LDR placement. For instance, a fixed laser beam could be installed at 41.5° instead of the one on the moving arm. The placement of LDR could also be adjusted to correctly position at the
edge of the platform or the software might take into account the angle differences made and just give the filtered result. A better calibration method is also needed to ensure the consistency of the measurement. Furthermore, having an additional number of operators to perform the standard bending tests independently will reduce the uncertainty arising from a single operator and thus would make the results more reliable.

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