Indian Journal of Fibre & Textile Research
Vol. 45, March 2020, pp. 40-48

Bending rigidity of yarns using beam method on a two-support configuration

Malek Alshukur[a] & Lisa Macintyre
School of Textiles and Design, Heriot-Watt University, UK

Received 31 May 2018; accepted 29 November 2018

This paper reports a simple, quick and reasonably accurate approach for measuring the bending rigidity of yarns. The beam method has been adapted and applied using a bending frame that has a fixed support and a simple support. The yarns are left to bend under the effect of their own weight. The accuracy and the precision of that bending frame are assessed over the time using an isotropic material and then compared against the ring-loop method and the KES-FB-2 pure bending tester. The findings show that the precision of this bending frame is acceptable. However, this bending frame gives at least 1.6 times greater values of bending rigidity than the KES-FB-2 pure bending tester, though the relationship between these two methods is linear and significant. Moreover, the spun yarns appear to have high levels of variability of the bending rigidity. This study is important as it overcomes the challenges faced while using other methods to measure the bending rigidity of yarn. It also provides a comprehensive account of the variation in this property. Further, it gives an indication of the highly non-uniform structure of spun yarns and the impact of yarn defects on the bending properties of yarns.

Keywords: Beam method, Bending stiffness, KES-FB-2 pure bending tester, Yarn flexural rigidity

1 Introduction

The bending rigidity, also known as the bending stiffness, flexural rigidity or flexural stiffness, is one of the mechanical properties of textiles. It has direct relationships with the ease of processing of textile fibres to make yarns, and then converting yarns into fabrics using weaving or knitting[1] with some properties of the final fabrics[2,3], such as drape, handle, crease and crease recovery.

The bending rigidity of yarn is related to the properties of the constituent fibres (fineness, bending rigidity, material type, etc.), yarn count, number of fibres in its cross-section, yarn twist level, yarn structure (fibre obliquity and inter-fibre friction), the spinning system used to make such yarns[1], and yarn compression properties[4]. Further, it is accepted that the minimum value of bending rigidity of a yarn is the sum of the values of bending rigidities of the constituent fibres[1,5].

With regard to the measurement of yarn bending rigidity, it is common to use the ring-loop method (also known as the weighted-ring stiffness test)[6], while a minority of researchers prefer to use the (quasi-static) beam method that benefits from the beam bending theory[4,6,7]. Both these methods are applied manually and they usually measure the total values of the (elastic) bending rigidity, including the coercive or frictional couple and bending recovery [8], which are the different components of bending rigidity. For ring-loop method, a circular loop or ring must be made of the yarn being tested. This loop is then suspended by a pin and loaded by a suitable point load. Due to the load, the circular loop deforms and changes shape to become similar to an ellipse[3]. Although this test was mainly designed for textile fibres[3], it was also applied for yarns[8]. However, if the yarn being tested does not bend in a linear fashion, the accuracy of this test is affected negatively[8]. Additionally, the application of this method occurs at the expense of neglecting the effect of yarn weight on the circular loop. Such an effect causes an additional, but an unaccounted, distortion[8].

In case of the beam method, yarns were treated as beams. This theory was applied on a zero-twist PET multi-filament yarn using a two-support beam system, that is, a beam simply supported at one end while fixed at the other end (a built-in support)[7]. The lengths of specimens were 10% higher than the distance between the supports to prevent the yarns from falling down. Further, a weight (point load) equal to 0.0041 g was placed on the yarns in the mid-distance between the supports. The value of the bending rigidity was calculated as the slope of the regression model of the coordinates of the point of maximum deflection[7]. It was found that the small angles of deflection gave

---

[a]Corresponding author.
E-mail: malekshukur@yahoo.com

the best results. Although not reported in the original work, based on the values of correlation coefficient (r=0.842) and the sample size (n=20), such a regression model was found significant at a significance level α=0.01. These results confirmed that the two-support beam configuration can be used to measure the bending rigidity of yarns. However, no results were reported on spun yarns made from short-staple fibres or long-staple fibres. Further, the researchers did not exclude the effect of 10% extra length added to the yarn specimens tested, and the change of location of the weight when the yarn bends. In another study, the beam method was also applied to measure the bending rigidity of low twist polyester filament yarn, using the principle of a beam fixed at both ends[9]. The same configuration was also applied to measure the bending rigidity of pulp fibres[10].

When the beam method was investigated using the cantilever configuration, the bending behaviour of multi-filament yarns was found to be nonlinear because the displacement-curvature relationship was non-linear[4]. Additionally, these multi-filaments were subjected to large deformations while their cross-sections flattened, i.e. the strain-curvature relationship was also nonlinear. It was found that the deflection due to the bending rigidity was greater than the deflection due to the shear rigidity. Furthermore, when applying the theories of bending to model the deflection of those multi-filaments, there were differences between the theoretical and the experimental values. Therefore, the cantilever configuration was concluded to be not suitable to study the modelling behaviour of yarns[4].

The use of devices to measure and identify different components of yarn bending rigidity is a common practice. Example of those devices are the Kawabata's pure bending tester KES-FB-2, KES-FB2-S pure bending tester, KES-FB2-A pure bending tester, Shirley cyclic bending tester, and automatic yarn-bending tester[10], that was developed by B. M. Chapman in 1976[11]. These devices benefit from the concept of pure bending[8], that is, bending of yarn into a circular arc[12] in the absence of shear forces. However, these devices are mainly made to account bending rigidity in fabrics. Therefore, several problems and deficiencies arise when these are used to measure bending rigidity in yarns. For example, the pure bending tester KES-FB-2 gives only the average value of the bending rigidity of a sheet of 20 yarns without the value of standard deviation. Further, if there are differences in the yarn segments being tested, such as thickness, shape, symmetry, packing density (distribution of fibres), position of fibres within the yarn structure and size of fibre clusters, this device does not account for these differences. Furthermore, to use this device successfully, the sheet of yarns being tested should be prepared in such a way that all the yarns are tensioned at the same level. However, in reality, it is extremely difficult to achieve this condition. Moreover, this device measures the bending rigidity of yarns that have 11 mm length, while the Shirley cyclic bending tester uses 5 mm length of yarn specimens[8]. It is believed that these distances are too short and not suitable to show the impact of yarns medium-term and long-term periodical faults if they exist. The other devices are also found to have similar drawbacks. Therefore, researchers usually make use of both the manual methods and one of the devices[8] because these devices have higher sensitivity than the manual methods. Researchers usually compare the results of both approaches against each other.

To overcome the drawbacks of the manual methods and the devices, this study was aimed at optimising the application of the beam bending theory (beam method), using an accurate bending frame that has a two-support configuration. This bending frame was tested for accuracy, precision and consistency of measurements over a week. Additionally, the accuracy of such a bending frame was compared against other methods.

2 Materials and Methods

2.1 Theoretical Background

The yarns were configured as two-support beam systems as shown in Fig. 1; they were considered as statically indeterminate beams. Additionally, they were left to bend under their own weight without using a point load. Since the loading of this type of beam can be resolved into a bending moment and a shear force[12], the bending was not pure. Instead, due to the shear force, the bending moment varies from section to section along the beam axis. Consequently, the arc of curvature varies accordingly. The bending rigidity (B) for this kind of beam can be calculated using the following equation[13]:

$$\mathrm{B} = \frac{w(-2x^4+5\mathrm{L}x^3-3L^2x^2)}{48\mathrm{L}y} \quad \ldots (1)$$

where L is the distance between the jaws or the two ends of the beam or yarn; x and y, the coordinates

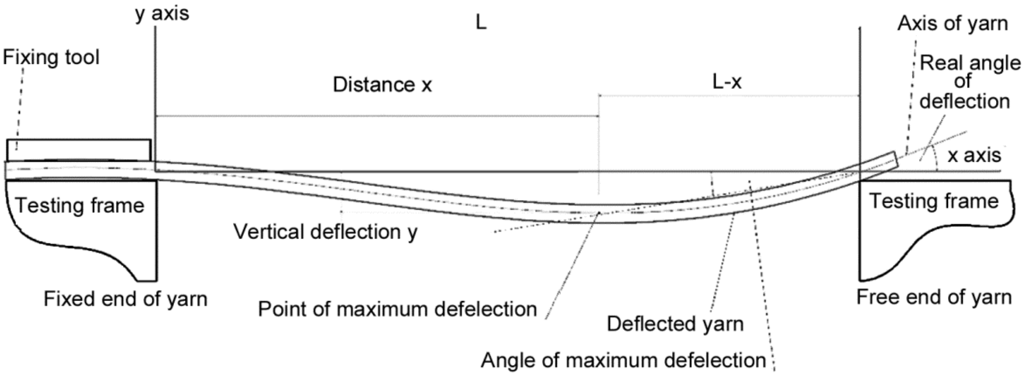

Fig. 1 — Schematic diagram of deflected yarn

of the point of maximum deflection, *y* always has negative values; and *w*, the total weight of the beam or yarn.

The bending rigidity of yarns can be calculated directly from Eq. (1) without using regression models as reported previously[7]. Further, the equation itself is simpler and easier to apply than a system of equations that are reported elsewhere[7]. Therefore, the configuration shown in Fig. 1 may be used to test the bending rigidity of yarn, although no work has yet been reported on it.

2.2 Bending Frame

To apply the Beam Method, a suitable testing frame was developed as shown in Fig. 2. This bending frame was improved to increase its accuracy by incorporating two plates. The first plate has a sharp edge and was attached vertically on the left jaw of the frame. This sharp edge aids in improving the nature of the simple support for the free ends of the yarns being tested. The second plate was placed on top of the right jaw to make sure that the two jaws of the test frame have the same horizontal level. A pressure peg was also used at the right jaw of the frame to aid in creating a built-in support and to maintain constant pressure on the fixed yarn end.

To measure the coordinates of the point of maximum deflection, a Fujifilm FinePix HS20 EXR camera was used to take images of the yarns after being bent. These images were then analysed using “analySIS FIVE®” software. To get comparable results, the test was conducted in a conditioned laboratory that has standard atmospheric conditions. Additionally, to get clear images of the yarns, the test was conducted in a well-illuminated area of that laboratory. The camera was set at the “EXR Auto Focus” mode. Additionally, to increase the accuracy and sensitivity of the measurements, the number of pixels of the images were maintained as high as possible by selecting the “Fine” mode. To ease the process of mounting the specimens on the bending frame, the camera base was kept at 11 cm away from the test frame. Further, to make sure that the camera captures all the space between the jaws of the bending frame, the “Zooming-in” technique was used while taking the shots. The distances in the images were converted from pixels to millimetres using a calibrated ruler, mounted in the vicinity of the yarns while taking the images. Twenty specimens were taken for each yarn tested. Since the camera lens has a concave shape, the specimen lengths measured by the image analysis technique was slightly different from the real values. However, these differences were accounted for using a Correction Factor (ε).

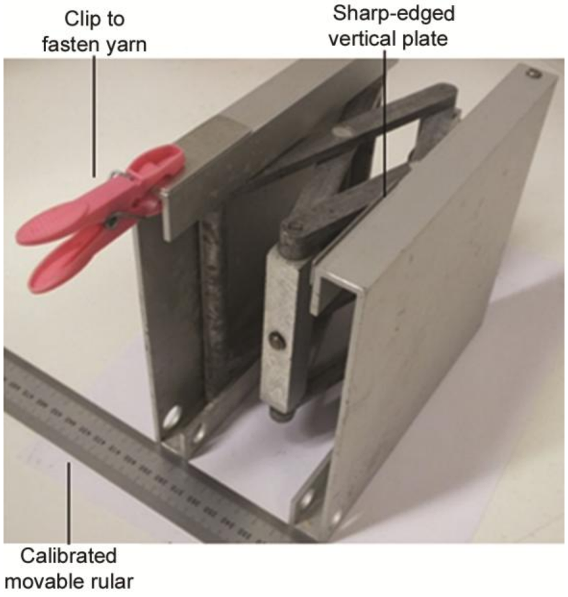

Fig. 2 — Simple bending frame used in this study

Therefore, all measured values of the specimen lengths, and the coordinates *x* and *y* of maximum deflexion were multiplied by (ε). This Correction Factor is given by the following equation:

$$\varepsilon = L_{set}/L_{measured} \quad \ldots (2)$$

where L_{set} (mm) is the distance set between the jaws; and $L_{measured}$, the measured value of the distance between the jaws, as they appear in the photos, after converting from pixel to mm.

2.3 Testing Precision, Accuracy and Reliability of Bending Frame

The bending frame was tested to define its precision, accuracy and reliability over time. The precision of this frame was tested using plastic strips as isotropic materials that are expected to have low variability. This procedure aided in giving an idea about the variability that may result from the bending frame itself. The plastic strips were prepared by cutting a flat, A3-sized plastic sheet using a manual guillotine (rexel SmartCut A525pro). The dimensions of the plastic strips were 4×110 mm. The thickness of the strips was 0.13 mm. The number of specimens for this test was 20.

The accuracy of the bending frame was tested against the KES-FB-2 pure bending tester (Kawabata's device) and the ring-loop method using a Ne=2/2/3 core-spun sewing thread. Five sheets of twenty specimens each were prepared as stipulated in the manual of the KES-FB-2 pure bending tester and tested using the same device. Following this, the total average and total standard deviation of those sheets were calculated. Similarly, five subgroups of the sewing thread (each having three threads) were tested on the bending frame, while another five subgroups (each having three threads) were tested using the ring-loop method. Following this, the total average and the total standard deviation of the subgroups were calculated. The total average values and total values of the standard deviation of the three methods were compared against each other.

To check the reliability of the bending frame over the time, the statistical process control (SPC) technique was used and applied using an $\bar{x}$-SD control chart. For this, 70 plastic strips were prepared using the aforementioned guillotine and their dimensions were 100×4 mm. These specimens were divided into 14 subgroups of 5 specimens each, and two subgroups were tested per day. The specimens of each subgroup were tested successively for bending. The test was conducted over seven days to test all the 14 subgroups of plastic strips. The $\bar{x}$-SD control chart for the testing process was drawn using the data collected from the subgroups. Since the specimens were cut manually on the guillotine, variation in the dimensions of the specimens was inevitable. To reduce the impact of this variation or the variation in the linear density on the results, the specific bending rigidity (g mm^2 tex^{-2}) was used to plot the $\bar{x}$-SD control charts. Although this procedure is not ideal, it proved to be practical and reasonably accurate.

2.4 Yarn Materials and Procedures for Testing Yarns

The yarns tested were made of different materials (pure or mixed), such as (soft) textured acrylic, natural wool, lambswool, combed cotton, blended lambswool/cotton, blended wool/polyamide, blended lambswool/viscose, blended wool/cotton, blended wool/nylon and blended linen/cotton. Further, the yarns were singles, two-ply and three-ply, while the resultant linear density of these yarns was chosen between R72 tex and R195 tex. The yarns were also made on various spinning systems, i.e. the carded short spinning system, the combed short spinning system, the woollen system or the worsted system, while the multi-filaments were textured.

Before conducting the test, the yarns were preconditioned in an oven at 47 C° for 5 h. Following this, they were conditioned in a standard atmosphere for a minimum of 48 h as stipulated in the BSI ISO Standard 139:2005[14]. While conducting the test, each yarn specimen was securely fixed at the right jaw of the testing frame, while left as such on the sharp edge of the left jaw so that it remains free from any type of fastening, as shown in Fig. 1. Additionally, each yarn specimen was left to bend under its own weight for approximately 2 min. This is because, using a longer time does not change the vertical distance of deflection *y*, i.e. it cannot alter the results. An image of the yarn specimen after being bent was taken using the digital camera. Following this, the yarn specimens were removed and their weight was measured using a digital scale (Oertling) with 0.0001 g sensitivity. Since the yarns were different in thickness, material and type, it was not possible to test all of them using the same test length. Each yarn was tested at a length suitable to its properties so as to have small angle of deflections. These testing lengths were predefined using initial measurements. In all cases, both specimen length and weight was accounted for as per Eq. (1).

To prevent the free ends of the yarns from falling down while conducting the test, the yarn specimen length was increased more than the distance between the jaws of the bending frame by 2 − 4 mm. However, such an increase in the specimen length was not considered while measuring the weight of specimens. In another study, the researchers increased the length of the yarn specimens by 10% more than the distance between the jaws, without clarifying its inclusion in their calculations or weight measurements[7].

3 Results and Discussion

3.1 Precision of Bending Frame

The results of testing the plastic strips at fixed length (110 mm) are given in Table 1. It is found that the average value of bending rigidity is 225.97 g mm^2 and the standard deviation is 12.66 g mm^2, thus the CV% is 5.6. This indicates that the variation in bending rigidity of the plastic strips is relatively high, while the precision of any measurement tool is vital to obtain consistent measurements. It is believed that this variability has resulted from the material used rather than from bending frame. In particular, this variability is believed to be originated from both the variation in weight of plastic strips and the variation in width of plastic strips. Table 1 shows that the variation associated with the linear density is CV%=2.24. Additionally, Eq. (1) indicates that the bending rigidity is proportionally related to the ratio w/L, which stands for the weight of plastic strip per unit length, i.e. the linear density of the plastic strips. Consequently, since L is constant, the variability of the weight (w) results in a variation similar to the variation in bending rigidity.

To account for the variation in the bending rigidity due to the variation in specimen width, it is recognised that the widths (b) of plastic strips are set manually on the guillotine. Consequently, any variation in this dimension will lead to a similar variation in the bending rigidity of the strips. This is because the bending rigidity (B) is equal to EI, where E is Young' modulus of bent material and I is the second moment (moment of inertia) of the cross-section of bent material with respect to its neutral axis[13]. Further, since we have plastic strips of rectangular cross-section having width b and depth (or height) d, the second moment of the cross-section is calculated with respect to the centroid axis (the neutral axis x) using the following equation[13]:

Table 1 — Results of testing the plastic strips at a specimen length of 110 mm

Specimen number	Distance (x) corrected mm	Deflection (y) corrected mm	Weight (w) g	Bending rigidity (B) g mm^2	Linear density tex	$B_i - B_{average}$ g mm^2
1	63.28	2.31	0.0719	224.37	653.64	-1.608
2	61.38	2.29	0.0728	228.56	661.82	2.589
3	60.74	2.30	0.07	218.44	636.36	-7.535
4	58.07	2.27	0.0704	219.97	640.00	-6.003
5	62.86	2.40	0.0712	213.80	647.27	-12.177
6	63.16	2.33	0.0705	218.10	640.91	-7.877
7	57.84	2.33	0.0694	210.97	630.91	-15
8	64.55	2.34	0.0696	214.32	632.73	-11.652
9	61.16	2.34	0.0746	229.08	678.18	3.111
10	61.38	2.37	0.0716	217.21	650.91	-8.767
11	60.63	2.17	0.0723	239.05	657.27	13.077
12	65.30	2.29	0.0721	226.63	655.45	0.661
13	63.36	2.33	0.0731	226.16	664.55	0.184
14	61.95	2.18	0.0714	235.76	649.09	9.782
15	63.34	2.35	0.0714	219.02	649.09	-6.956
16	65.15	2.33	0.0701	216.62	637.27	-9.354
17	59.63	2.12	0.0711	239.74	646.36	13.771
18	58.97	2.16	0.0708	233.61	643.64	7.641
19	56.70	2.17	0.0685	221.90	622.73	-4.078
20	64.26	2.02	0.0746	266.17	678.18	40.199
		Average		225.97	648.82	Not relevant
		SD		12.66	14.52	Not relevant
		CV%		5.60	2.24	Not relevant

$$I_x = \frac{1}{12} b\, d^3 \qquad \ldots (3)$$

This means that the second moment of the cross-section (I) has a proportional relationship with the width of the plastic strips (b). Therefore, any variation in this dimension will be reflected in the variation of (I) and eventually in the bending rigidity. The evidence gathered so far by testing an isotropic material (plastic strips) does not indicate that the bending frame lacks precision.

3.2 Reliability of Bending Frame

The reliability of the bending frame is the precision of measurements over the time, which can be obtained via control charts. The control chart (Fig. 3) indicates that the values of average and standard deviation (SD) of the specific bending rigidity (g mm^2 tex^{-2}) of the 14 subgroups (tested over a week) are acceptable. This is because the changes in their values over the time are within the acceptable range, i.e. between the Upper Control Limit (UCL) and the Lower Control Limit (LCL). These control limits are set at 1.5 × SD (g mm^2 tex^{-2}). The total average value of specific bending rigidity is found 412.284 ×10^{-6} g mm^2 tex^{-2}, while the standard deviation is 28.26 ×10^{-6} g mm^2 tex^{-2}; the CV being 6.85%. This variation may be due the variation in bending rigidity of plastic strips and the variation in their linear density, which is given as a quadratic term in the equation of specific bending rigidity. This is because the average value of their linear density is 640.94 tex, and the standard deviation is 20.51 tex; the CV is 3.20 %. Additionally, the average value for the bending rigidity (B) of the plastic strips is found to be 169.20 g mm^2; the SD is 12.69 g mm^2 and the CV is 7.50 %. Further, although it is not possible to account for the variation in dimensions of the specimens, it is thought to have its own impact, as explained above. Therefore, the low value of CV% of specific bending stiffness indicates that the bending frame is reliable to test conventional textile yarns.

3.3 Accuracy of Bending Frame

A summary of the results of testing a sewing thread on the bending frame, the KES-FB-2 pure bending tester (Kawabata's device) and the ring-loop method are given in Table 2. These results indicate that the KES-FB-2 pure bending tester give substantially smaller average values than the other two methods. Additionally, the ring-loop method gives higher mean values of the bending rigidity than the beam method. On comparing the results of the bending frame and the KES-FB-2 pure bending tester, the plot shown in Fig. 4 indicates linear relationship between these two methods of measurement as shown below:

Result of bending frame = 0.1588 + 1.605 × result of KES-FB-2 pure bending tester ... (3)

This relationship is found to be significant at a significance level α=0.01 because the p-value of the ANOVA testing is 0.007. Further, the standard error (SE) is 0.833 g mm^2, which is small. However, the coefficient of determination (R^2) is 67.1%, while adjusted R^2 is 62.4% due to the dispersion of the points

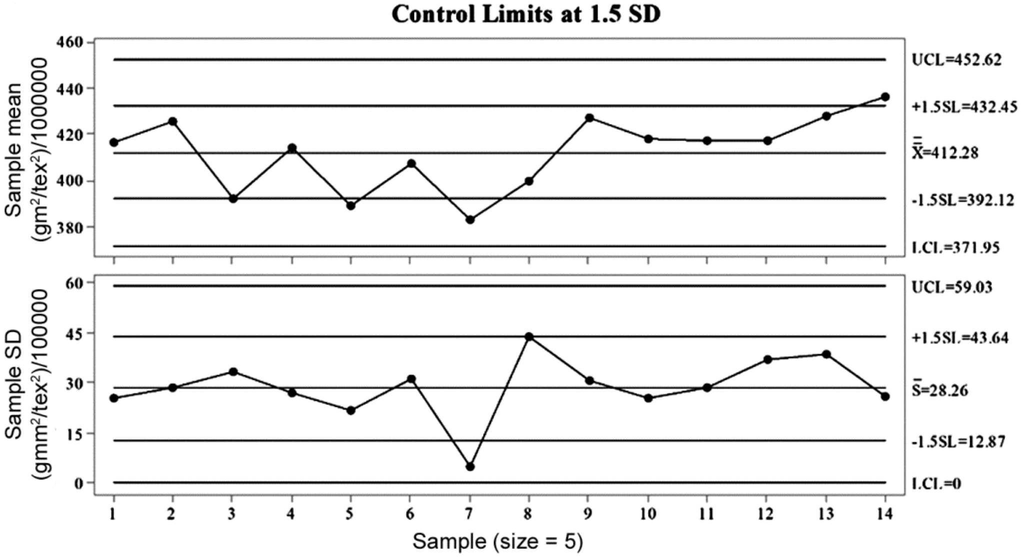

Fig. 3 — $\overline{X}$ -SD control chart for testing process using bending frame

Table 2 — Results of testing the sewing thread using bending frame, KES-FB-2 pure bending tester and ring-loop method

Method	Statistic related to bending rigidity	Values
Kawabata's pure bending tester KES-FB-2	Averages of thread sheets	1.6, 1.6, 1.4, 1.45, and 1.35 g mm^2
	Grand average value	1.48 g mm^2
	SD of the averages	0.115 g mm^2
	CV% of sheets	7.78
Bending frame	Averages of thread subgroups	2.447, 4.100, 6.031, 6.204 and 7.127 g mm^2
	Average of all individual measurements	5.182 g mm^2
	SD of averages	1.884 g mm^2
	CV% of averages	36.35
Ring-Loop method	Averages of thread subgroups	6.933, 8.824, 6.568, 6.348, and 6.153 g mm^2
	Average of all individual measurements	6.965 g mm^2
	SD of averages	1.079 g mm^2
	CV% of averages	15.49

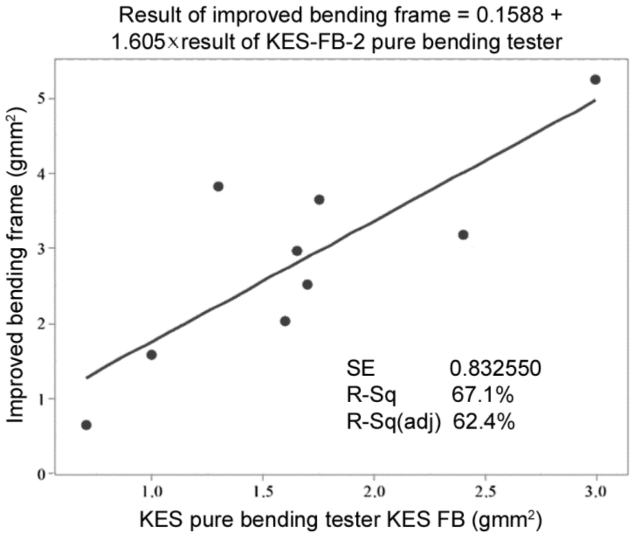

Fig. 4 — Comparison between bending frame and KES-FB-2 pure bending tester

around the regression line. It is thought that the difference between these two methods may originate from the fact that the KES-FB-2 pure bending tester accounts for only one component of the bending rigidity (elastic bending rigidity). However, the bending frame of this research accounts for the total bending effect.

Since there are differences between the results of ring-loop method and bending frame, these differences are tested for significance using a 2-sample t-test at a significance level α=0.05. The results of this t-test show a p-value of 0.015, which indicates that the difference between the ring-loop method and the bending frame is indeed significant. Further, Levene's Test is also conducted to compare the variations that have resulted from both the ring-loop method and the bending frame. The p-value of this test is 0.120, which shows that the variations of both methods are not statistically different. It is thought, however, that the difference in the average values of both methods is related to the configuration of the sewing thread while conducting the test. In particular, if the loops are not perfectly circular, the findings resulting from ring-loop method are not exactly accurate. In practice, due to yarn internal stresses, flexing sewing threads or any other type of yarn to make perfect circular loops is extremely difficult to achieve. Furthermore, the impact of the thread or yarn faults on the deflection is minimised when the yarns or threads are forced to bend as loops. In contrast, the impact of thread faults or yarn faults is normally increased when the yarns or threads are levelled between the jaws of the bending frame. The relationships between yarn configurations while conducting bending testing, and the impact of yarn faults on the test are worthy of further investigation; however, these are beyond the scope of this study.

3.4 Results of Yarn Testing

The results of testing conventional textile yarns for bending using the bending frame are given in Table 3. It is observed that the CV% is in the range 23.76 − 52.51%, which indicates that the variability of bending rigidity of the yarns is high. Although the bending frame is confirmed to be sufficiently accurate for testing an isotropic material, using it to test conventional textile yarns unveils extremely high variability for the bending rigidity of the yarns. The reasons for the high variability of the bending rigidity of yarns are explained below:

(i) Spun yarns are not homogeneous in structure[5] and several types of defect may exist within their structure, because of the raw material and the manufacturing processes. In particular, these defects such as thin places, thick places, slubs, neps, piecings,

Table 3 — Results of testing the yarns on bending frame

Yarn sample	Test length mm	Resultant linear density tex	Bending rigidity			p-value	
			Average g mm^2	Standard deviation, g mm^2	CV%	t-test	Leven's Test
Soft acrylic	50	R72/2	0.650	0.154	23.76	0.000	0.034
Lambs wool/cotton	65	R120/2	3.662	1.774	48.46	0.077	0.945
Combed cotton	50	R126/3	1.579	0.774	48.99	0.458	0.533
Natural wool	75	R195/2	5.249	1.601	30.49	0.000	0.905
Lambs wool	60	R120/2	2.518	0.966	38.34	0.000	0.533
Wool/polyamide	60	R120/2	3.183	1.671	52.51	0.005	0.413
Lambs wool/viscose, (60/40)	65	R120/2	3.835	1.033	26.93	0.001	0.001
Wool/cotton (50/50)	80	R 163/2	8.636	4.324	50.07	0.484	0.862
Wool/nylon	60	R 120/2	2.963	1.212	40.90	0.020	0.477
Linen/cotton	55	R 144/2	2.029	0.872	42.97	0.014	0.802
Lambs wool 1/12s	45	83	0.549	0.229	41.24	0.043	0.952

fly, knots, snarls, loops and crackers, affect the bending rigidity locally along the yarn axis.

(ii) Due to the change in packing density of fibres length-wise and width-wise within the yarn structure, the volume density and the linear density of yarn change along the yarn structure. This leads to variations in the distribution of mass in the spun yarn structure along the different yarn segments (longitudinal mass variation). In other words, the weight of spun yarns is not uniformly distributed along the yarn axis. Consequently, the value of bending rigidity changes along the yarn axis. Further, other type of variances in the spun yarn structure may be reflected in the physical and performance characteristics of yarns[5], including their bending stiffness.

(iii) During the test, some yarns bent in a three-dimensional configuration instead of bending in a vertical plane because of torsional forces. This 3D configuration affects the value of bending rigidity of the yarns. This unmeasured configuration indicates internal stresses within those yarns. These stresses, in turn, may have originated either during the winding-in process of the yarns on packages or due to leaving yarns on packages for a long period of time. Subsequently, these internal stresses affect the yarns during unwinding them off the packages, and make them curved in a space instead of the ideal bending state in a two dimensional plane.

(iv) The yarns tested are one single yarn (yarn 11), one three-ply yarn (yarn 3) and the remaining two-ply yarns (Table 3). Obviously, these yarns have different cross-sectional shapes. Therefore, the value of the second moment of inertia (I) changes, depending on the direction of bending, whether in the width direction or in the height direction of the cross-section. Such changes in this parameter directly affect the bending rigidity (EI), whereas an ordinary beam has one value of (I) when testing it for bending. It is found that at the point of maximum deflection, the cross-section of the yarns being tested sometimes bent in the width direction, while in other occasions it bents in the depth or height direction. Consequently, this entails changes in the value of second moment of inertia of the cross-section, which is accounted for part of the changes in the bending rigidity.

(v) Further, theoretically, in case of beam configuration, the point of maximum deflection should normally be located at a distance equalling to 3L/8 from the simple support of the yarn (i.e. the left jaw of the bending frame). Additionally, the value of maximum deflection[15] should be $wL^2/187EI$. However, in the case of plied yarns, in particular two-ply yarns, there is a high chance of having an unbalanced plied yarn structure. Such an unbalanced yarn structure may result in a shift of location of the point of maximum deflection along the axis x. This shift is unpredictable and can be in the direction of the simple support or the direction of the built-in support. Such a shift results in a change to the values of both the deflexion and the bending rigidity.

(vi) The error of sampling and the error of measurement may also affect the results and the variation obtained, though a great care has been taken to minimise these errors.

All these reasons may cause high values of CV% of bending rigidity of spun yarn. It is worth noting that a previous study [8] conducted on a two-ply cotton spun yarn (R96/2 tex) using the weighted-ring stiffness test demonstrates that the CV% of the deflection of that yarn is as high as 12.7%. Although this variability is concerned with the deflexion of yarn instead of its bending rigidity, it gives an indirect indication about the high variability of the bending rigidity of spun yarns. The present study, however, shows the variation in bending rigidity of yarns using the SD or the CV% as direct measures.

4 Conclusion

The use of a simple form of the two-support beam system as a method for measuring the bending rigidity of yarns has been studied. The bending frame has a simple support at one end and a fixed support at the other end. This bending frame has a sharp plate to improve the nature of simple support of the yarns at the free end. Further, the digital image analysis is adapted to measure distances on this bending frame, while the yarn is left to bend due to its own weight. Before testing yarns, the precision of this bending frame is checked using plastic strips as isotropic materials. Although there is a variability in the dimensions of the plastic strips, the variability in their bending rigidity is found to be CV of 5.6 %. This value is acceptable for the variability of the bending rigidity. Following that, the precision of the bending frame is checked over a week by testing plastic strips and the CV% of their specific bending rigidity is found as low as 6.85. This value is also acceptable as it is found between the UCL and the LCL. Moreover, the results of this two-support bending frame are compared with the KES-FB-2 pure bending tester (Kawabata's device) and the ring-loop method. The bending frame gives slightly lower values than the ring-loop method. However, the KES-FB-2 pure bending tester results in at least 1.6 times smaller values of bending rigidity than the values of the bending frame. This relationship is found linear and significant at α=0.01.

When the bending frame is used to measure the bending rigidity of yarns, the variations in results are found to be high for all yarns. The origin of this variation is believed to be related to the variability of structures of these spun yarns and due to the various types of yarn defects. Since the uniformity and evenness of the yarn structure have a direct impact on the variability of the yarn bending rigidity, it is suggested to use the latter as an indicator to assess the uniformity and evenness of the yarn structure in future studies.

References

1 Lawrence C A, *Fundamentals of Spun Yarn Technology* (CRC Press LLC, New York), 2003, 362.

2 Park J W & Oh A G, *Text Res J*, 76 (2006) 478.

3 Morton W E & Hearle J W S, *Physical Properties of Textile Fibres* (Woodhead Publishing Limited Cambridge, England), 2008, 414.

4 Cornelissen B & Akkerman R, Analysis of Yarn Bending Behaviour, *Proceedings, ICCM-17-17th International Conference on Composites Materials* (Institute of Materials, Minerals and Mining, Edinburgh, UK) 2009.

5 Goswami B C, Martindale J G & Scardino F L, *Textile Yarn: Technology, Structure, and Applications* (John Wiley & Sons, New York), 1977, 97.

6 Elder H M & El-Tawashi M, *J Text Inst*, 68 (1977) 188.

7 Ghane M, Sheikhzadeh M, Halabian A M & Khaburi S, *Fibres Text East Eur*, 16 (2008) 30.

8 Abbott G M, *J Text Inst*, 74 (1983) 281.

9 Ghane M, Sheikhzadeh M, Khaburi S & Ghaeli I, *Fibres Text East Eur*, 17 (2009) 51.

10 Fischer W J, Lorbach C, Jajcinovic M, Hirn U & Bauer W, Measured and calculated bending stiffness of individual fibers, *Proceedings, Progress in Paper Physics Seminar 2014* (North Carolina State University, Raleigh, North Carolina, USA) 2014.

11 Dhingra R C & Postle R, *J Text Inst*, 67 (1976) 426.

12 Case J, Chilver L & Ross C T F, *Strength of Materials & Structures*, 4th edn (Arnold: Hodder Headline Group, London), 1999, 299.

13 Beer F P, Johnston E R & Dewolf J T, *Mechanics of Materials* (McGraw-Hill, New York, USA), 2006, 562.

14 *BSI ISO Standard 139: Textiles- Standard Atmospheres for Conditioning and Testing* (British Standards Institution), 2005.

15 Paine R, *Mechanical Engineer's Reference Book*, edited by E H Smith, 12th edn (Butterworth-Heinemann, Oxford), 2000, 1/5.