Doctoral Dissertation (Shinshu University)

Study on the relationship between fabric bending rigidity and yarn properties

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Abstract

In this study, the relationship between fabric bending rigidity and yarn properties such as yarn bending rigidity and yarn torsional rigidity was investigated. The Cooper model was verified and the effect of crimp on yarn torsional rigidity was investigated. This study can be used to improve the simulation of textiles properties.

In Chapter 1, a background of the work on fabric and yarn properties was given.

Chapter 2 exposed a literature review of the previous studies and published papers on the subject of yarn properties and assessment and presented the general mechanical theories regarding bending properties of fabric as well as torsional and bending rigidity of yarns. The existing methods of assessment of this properties were also developed in this chapter.

In Chapter 3, the effect of yarn torsional rigidity on the Cooper model for fabric bending rigidity in any direction was verified. Five commercial fabrics were first used as experimental samples. Then, an additional five cotton fabrics with different weft densities were woven. The torsional rigidity of yarn from the bobbin and that of yarn directly extracted from fabric were measured with a yarn torsional tester. The bending rigidity of yarn from the bobbin was measured using the same pure bending tester as used in fabric bending testing. The bending rigidity of the fabric was calculated using torsional rigidities of yarns extracted from the fabric and showed better agreement with the experimental values than that calculated using the torsional rigidity of yarn from the bobbin. Indeed, measurements showed that the torsional rigidity of yarn from the bobbin was appreciably higher than the torsional rigidity of yarn from the fabric. This is due to the crimp in the yarn. The fabric bending rigidity was able to be predicted using the Cooper model with torsional rigidities of yarns extracted from the fabric.

In Chapter 4, following the previous chapter, the effect of crimp on torsional rigidity of monofilament and cotton spun yarns was investigated. Two kinds of polymeric monofilament yarns and four kinds of cotton spun yarns were examined. Different crimps were applied to the yarn

using an original crimp setting equipment. To fix the crimp, the polymeric monofilaments were treated with heat and the cotton spun yarns were treated with steam. The test samples were then produced following two protocols: with or without the application of weight. The yarn torsional rigidities with crimp were measured using a torsional measurement device and were compared with those without crimp. Almost no weight was applied to the cotton spun yarns to preserve the crimp during testing. The results with and without the application of weight were compared. For the monofilament yarns, the torsional rigidities of the crimped yarns had a linear relationship with the crimp ratio. For the cotton spun yarns, the torsional rigidities of the crimped yarns were smaller than those of the straight yarns. The smaller the yarn count, the smaller the yarn torsional rigidity. The effect of crimp on torsional rigidity differed according to the yarn counts. There was almost no difference in crimped yarn torsional rigidity between the straightened and non-straightened yarns after crimp setting. Therefore, there is a possibility that the change in yarn properties could have resulted from the bending of the fiber during crimp setting and not from the shape of the crimp afterwards.

In Chapter 5, the conclusions of this study were given. Recommendations for future work were also given.

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Chapter 1 : Introduction

Chapter 1: Introduction

1.1 Background

Today, it has become more than necessary to be able to predict the characteristics of textile in order to optimize the design and production of textile and decrease the costs by classifying the textile and garment. Previous studies have shown links between the yarn properties and the fabric properties based on the fabric structure and the properties of yarns used for. Moreover, the yarn and fabrics mechanics have a long history of studies and are quite well known. In fabric simulation, for example computerized textile simulation for design, the bending properties of fabric are important because they have an effect on the hand value and draping behavior. Therefore, the bending of fabric when designing products must be considered. The hand value has also been the subject of numerous studies to predict it, including studies about prediction of the hand from the weaving parameters. The hand and draping properties are directly linked to the bending properties of the fabric and yarn. If the fabric's bending properties could be predicted using only the yarn's bending properties, yarn could be appropriately selected according to the fabric's intended use.

Simulation of fabric properties using yarn properties have been widely investigated [1–3]. The bending, torsional, and tensile properties of the yarn are important for predicting the mechanical properties of the fabric [4–6]. Estimated or measured yarn tensile modulus are often use in current simulation. Bending and torsional moduli are calculated from tensile modulus with the hypothesis of its isotropy. However, yarns are discontinuous and also anisotropic, so bending and torsional moduli are independent from tensile modulus. Thus it is important to predict the bending property of fabric from the characteristics of yarns for fabric design to obtain more accurate simulation.

Pierce started to study the quantitative evaluation of fabric bending behavior, and developed the cantilever method to measure bending rigidity under low stress using cantilever. Using anisotropic Young's modulus for fabric, he also developed a model to estimate fabric bending stiffness in any direction [7]. When studying the bending behavious of fabric, Grosberg [8] distinguished the two terms - the bending rigidity and the frictional restrain couple - that composed the fabric bending behavior. Go et al.[9] elaborated a bending stiffness model neglecting the crimp effect. However, Cooper[10] demonstrated the influence of yarn torsional rigidity on fabric torsional rigidity by establishing a model that included both the torsional and bending rigidity of the yarn. Shinohara et al. [11], in the continuity of Cooper study, focused on the yarn torsional rigidity term and demonstrated its effect qualitatively on fabric bending rigidity in bias direction. Chapman and Hearle [12], using an energy method to predict bending properties of woven and nonwoven fabrics, corroborated the results previously obtained by Cooper.

As crimp also play a role in the yarn torsional rigidity, it was also studied. First, fiber crimp has been extensively studied in order to fully comprehend the geometrical structure and mechanical properties of fiber and yarn [13–15]. Meredith first developed a method to measure fiber crimp [16]. Following this, models of the geometry of fiber crimp were investigated [17]. Numerous studies have been carried out on yarn crimp geometry and its effect within the fabric based on Pierce's model [7, 18]. However, only a few studies have been conducted on the mechanical properties of crimped yarn.

Skelton[19] published an extensive study on the tensile, flexural, and torsional properties of crimped filaments. He developed theoretical models of saw tooth, rectangular, and circular-arc crimps, and verified his theory by measuring the torsional rigidity of circular-arc piano wire and nylon monofilament yarn extracted from a fabric using a torsional pendulum. However, the torque–twist curve was not obtained due to the measuring method used. Furthermore, this study was not conducted for common spun yarn with undulating crimp.

1.2 Purpose of this study

Starting from the yarn properties like its material, the pilling, bending rigidity or structural characteristics and using previous models linking it to the behavior of the fabric, a characterization of the fabric by correlating yarn characteristics affecting fabric properties could be possible. And starting from the fabric and using previous researches, the fabric properties could be linked to the parameters of the hand value established for the Kawabata Evaluation System. From this point, the yarn characteristics could be linked to the parameters for the hand value and a new textile model from the yarn to the handle could be suggested. It would allow improving the discrimination equation to distinguish cotton-like and silk-like textures made by Kawabata. This could be a useful tool to choose wisely the kind of yarn and establish a classification depending of the future use of the fabric. It also could give the opportunity to understand better the behavior of yarn inside the fabric structure.

1.3 Research Methodology

In this study, the relationship between fabric bending rigidity and yarn properties was investigated. Therefore, the effect of yarn torsional rigidity on fabric bending rigidity in any directions was verified experimentally. The fabric bending rigidity was calculated using measured yarn bending and torsional rigidities and compared the results with measured bending rigidity of fabric in several directions.

Following this study and in order to evaluate the effect of crimp on yarn properties, crimped yarns samples with various amplitudes and wavelengths were also made using original crimp setting equipment. Then, the torque–twist curves of straight and crimped yarns were obtained using a torsional tester and determined their torsional rigidities. The effect of crimp on yarn torsional rigidity was investigated by comparing the torsional rigidities of crimped and straight yarns.

1.4 Thesis Outline

In this study, an extensive study on yarn properties and their effect on fabric properties was led.

Chapter 1 is an introduction of the work lead in this thesis, as well as the methodology used and the problems encountered.

Chapter 2 exposed a literature review of the previous studies and published papers on the subject of yarn properties and assessment. It also presented the general mechanical theories regarding bending properties of fabric as well as torsional and bending rigidity of yarns. The existing methods of assessment of this properties were also developed in this chapter.

In Chapter 3, the effect of yarn torsional rigidity on the Cooper model for fabric bending rigidity in any direction was verified. The bending rigidity of thin fabric was calculated using torsional rigidities of yarns extracted from the fabric and showed better agreement with the experimental values than that calculated using the torsional rigidity of yarn from the bobbin. Measurements showed that the torsional rigidity of yarn from the bobbin was appreciably higher than the torsional rigidity of yarn from the fabric. This is due to the crimp in the yarn. The fabric bending rigidity was able to be predicted using the Cooper model with torsional rigidities of yarns extracted from the fabric.

In Chapter 4, following the Chapter 3 findings, the effect of crimp on torsional rigidity of monofilament and cotton spun yarns was investigated. Two kinds of polymeric monofilament yarns and four kinds of cotton spun yarns were examined. For the monofilament yarns, the torsional rigidities of the crimped yarns had a linear relationship with the crimp ratio. For the cotton spun yarns, the torsional rigidities of the crimped yarns were smaller than those of the straight yarns. The smaller the yarn count, the smaller the yarn torsional rigidity. The effect of crimp on torsional rigidity differed according to the yarn counts. There was almost no difference in crimped yarn torsional rigidity between the straightened and non-straightened yarns after crimp setting. Therefore, there is a possibility that the change in yarn properties could have resulted from the bending of the fiber during crimp setting and not from the shape of the crimp afterwards.

Finally, Chapter 5 summarized the studies of this thesis and gave suggestions of future work.

1.5 References

[1] X. Dai, Y. Li, and X. Zhang, “Simulating anisotropic woven fabric deformation with a new particle model,” *Textile research journal*, vol. 73, no. 12, pp. 1091–1099, 2003.

[2] M. Xiao and Z. Geng, “A model of rigid bodies for plain-weave fabrics based on the dynamics of multibody systems,” *Textile Research Journal*, 2010.

[3] G. Zhou, X. Sun, and Y. Wang, “Multi-chain digital element analysis in textile mechanics,” *Composites science and Technology*, vol. 64, no. 2, pp. 239–244, 2004.

[4] S. Inui, H. Okabe, M. Takatera, M. Hashimoto, and Y. Horiba, “A fabric simulation based on a model constructed from a lower level,” in *Computational Engineering in Systems Applications, IMACS Multiconference on*, vol. 1. IEEE, 2006, pp. 178–180.

[5] S. Inui, Y. Mesuda, Y. Horiba, and M. Kurihara, “Fabric weave form simulation based on the characteristics of yarn,” in *Biometrics and Kansei Engineering (ICBAKE), 2011 International Conference on*. IEEE, 2011, pp. 49–52.

[6] S. Kawabata, M. Niwa, and H. Kawai, “3—the finite-deformation theory of plain-weave fabrics part i: The biaxial-deformation theory,” *Journal of the Textile Institute*, vol. 64, no. 1, pp. 21–46, 1973.

[7] F. Peirce, “26—the “handle” of cloth as a measurable quantity,” *Journal of the Textile Institute Transactions*, vol. 21, no. 9, pp. T377–T416, 1930.

[8] P. Grosberg, “The mechanical properties of woven fabrics part ii: the bending of woven fabrics,” *Textile Research Journal*, vol. 36, no. 3, pp. 205–211, 1966.

[9] Y. Go, A. Shinohara, and F. Matsuhashi, “Viscoelastic studies of textile fabric (v) on the relationship between the bending behaviours of fabrics and fabric structures,” *Sen’i Gakkaishi*, vol. 14, no. 2, pp. 78–83, 1958.

[10] D. Cooper, “24—the stiffness of woven textiles,” *Journal of the Textile Institute Transactions*, vol. 51, no. 8, pp. T317–T335, 1960.

[11] F. Shinohara, A. Shinohara, and K. Sakaebara, “A theoretical study on the anisotropy of the bending rigidity of woven fabrics,” *J Textil Mach Soc Jpn*, vol. 32, no. 8, pp. T66–T71, 1979.

[12] B. Chapman and J. Hearle, “The bending and creasing of multicomponent viscoelastic fibre assemblies,” *J Text Ins*, vol. 63, no. 7, pp. T385–T412, 1971.

[13] R. Brand and S. Backer, “Mechanical principles of natural crimp of fiber,” *Textile Research Journal*, vol. 32, no. 1, pp. 39–49, 1962.

[14] J. Menkart and J. C. Detenbeck, “The significance of wool fiber crimp part i: A study on the worsted system,” *Textile Research Journal*, vol. 27, no. 9, pp. 665–689, 1957.

[15] M. Horio and T. Kondo, "Crimping of wool fibers," *Textile Research Journal*, vol. 23, no. 6, pp. 373–386, 1953.

[16] R. Meredith, "30—the torsional rigidity of textile fibres," *Journal of the Textile Institute Transactions*, vol. 45, no. 7, pp. T489–T503, 1954.

[17] R. Brand and R. Scruby, "Three-dimensional geometry of crimp," *Textile Research Journal*, vol. 43, no. 9, pp. 544–555, 1973.

[18] B. Olofsson, "49—a general model of a fabric as a geometric mechanical structure," *Journal of the Textile Institute Transactions*, vol. 55, no. 11, pp. T541–T557, 1964.

[19] J. Skelton, "38—the effect of planar crimp in the measurement of the mechanical properties of fibres, filaments, and yarns," *Journal of the Textile Institute*, vol. 58, no. 11, pp. 533–556, 1967.

Chapter 2: Literature review and general mechanical theories of fabric and yarn

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2.1 Introduction

The bending rigidity, also called flexural rigidity, is the pure moment required to bend a non-rigid structure in one unit of curvature.

In common theories of strength of material, for common material such as steel, several hypothesis are fixed. The material must be elastic, linear, homogeneous, isotropic, and the environment is quasi static, quasi isotherm and under small deformation. Under this hypothesis, the simplified law of Hooke to one dimension can be used, and therefore the bending rigidity B can be written as

$$B = E \cdot I \tag{2.1}$$

with E the tensile modulus and I the moment of inertia. In this case, the bending rigidity can be obtained using standardized methods such as the three-point or the four-point method.

For textile material, the bending rigidity can be descried as a function of the deflexion of a cantilever submitted to its own weight. Since textile material are not continuous, the moment of inertia is inexistant and therefore, 2.1 is not applicable. Furthermore, because of its anistropic properties, textiles material doesn’t fullfill the basic hypothesis of mechanical properties and therefore, their simulation is more difficult.

The quantitative evaluation of the bending behavior of woven fabric started with the work of Pierce [1], who developed a method of measuring bending rigidity under low stress, when investigating the ’hand of cloth’. This method consist in measuring the flexural rigidity of the fabric by using cantilever (Figure 2.1). This method test the fabric in pure bending. Others pure bending methods relying on gravity are used as well, like the heart loop method from Pierce [1] or Clark method[2], initially developed to measure the bending stiffness of paper. The work of Pierce on the bending behavior of textile was following by many others.

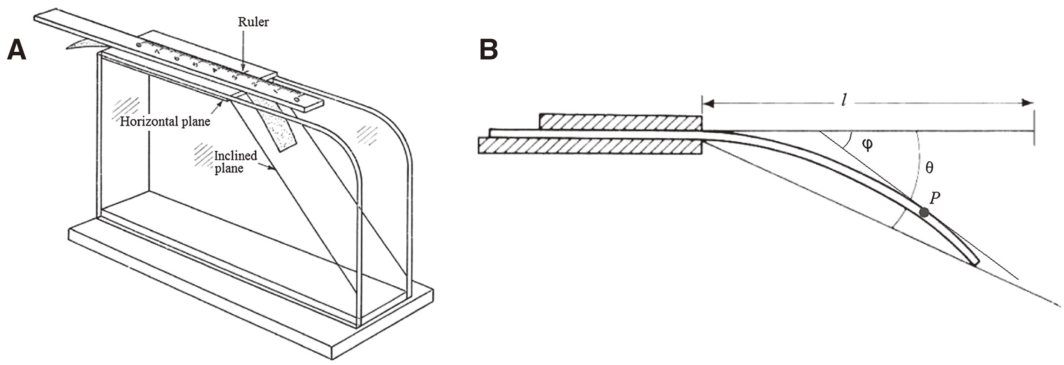


Figure 2.1: Pierce cantilever (source: American Journal of Botany, 2014[3])

As well as developing a measurement method for the flexural rigidity of textile, Pierce [1] also constructed a model that could be used to estimate a fabric's bending stiffness in any direction from the anisotropic Young's modulus for fabric. Grosberg [4] then showed that the fabric bending behavior depends on two factors: the bending rigidity and the frictional restraint couple. Go et al. [5] elaborated a bending stiffness model for woven fabric using the bending rigidity of yarn without torsional rigidity, and neglecting the crimp effect. Cooper [6] established a bending model for any direction taking into account the effect of the torsional rigidity on the bending behavior of fabric. Chapman and Hearle [7] also investigated a method of predicting bending rigidity using an energy method and ultimately obtained the same model as Cooper. Shinohara et al. [8] went further to explain the torsional component of Cooper's model. They showed the effect of yarn torsional rigidity on fabric bending in the bias direction qualitatively.

2.2 Measurement of bending rigidity of fabric and yarns

2.2.1 Cantilever

The structure itself of the fabric, an interlacement of yarns without rigid bonds, allow to it a important flexibility [9]. As mentioned in 2.1, Equation 2.1 can be used. However, as the moment of inertia I of a textile material is not possible to obtain due to its non continuous structure, measuring the bending rigidity B is equivalent to measuring the product $E \cdot I$. Therefore, using a classic Bernoulli-Euler theory for a moment-curvature relationship, for small movement [10]:

$$\frac{1}{r} = \frac{M}{E \cdot I} \tag{2.2}$$

with r the radius of curvature, M the bending moment, and $E \cdot I$ the bending rigidity. From Equation 2.2, the bending rigidity can be calculated, as it is possible to measure the bending moment and the radius of curvature.

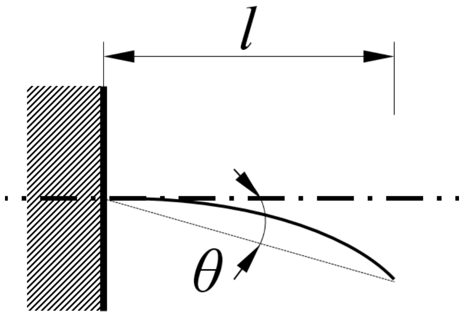


Figure 2.2: Pierce cantilever principle

From Figure 2.2, the bending rigidity can hereby be written as :

$$B = \frac{1}{\frac{\tan\theta}{\cos\frac{\theta}{2}}} \cdot \frac{pl^3}{8} \tag{2.3}$$

Where l is the length of the sample, θ the deflection angle of the sample, and p the weight per unit area of the sample.

In 1951, Abbot [11] studied various bending testing method existing at the time, between cantilever, heart loop, or flexometer. Cantilever method was determined to be the one returning the closest results to subjective assessment. However, as this technique is based on a standard elastic behavior, only the bending rigidity can be obtain using this method, as it can be defined as the proportionality between applied moment and curvature [12]. Therefore, others measurement methods were developed to take into account the non linearity of the textile material.

2.2.2 Pure bending tester

Pure bending tester by Isshi

Despite using the cantilever method, Pierce [1] already saw the limits of this measurement method. In 1959, Eg-Olofsson [13] developed an apparatus to measure the moment-curvature relationship. The principle was to submit the textile sample to a couple and therefore bend it to an arc of circle, while recording following a chosen time-schedule the bending moment and the curvature. Then, the bending rigidity is calculated using Equation 2.2.

In 1957, Isshi [14] developed an apparatus to measure the bending behaviour of fibers, yarns and fabric. This apparatus is considered as the ancestor to what will become the Kawabata Evaluation System FB2. This apparatus measure the behavior of fabric - or yarns - in pure bending, i.e. the curvature of the fabric is kept even throughout testing.

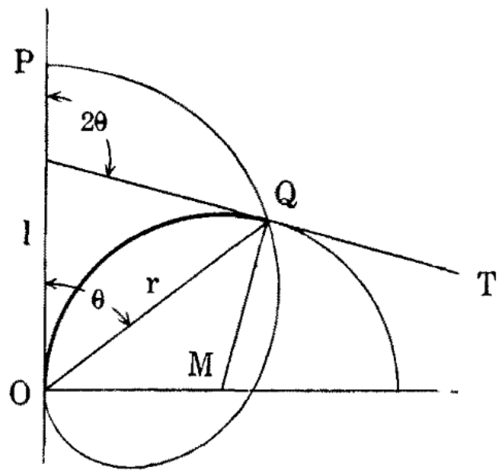


Figure 2.3: Pure bending measurement method [14]

Figure 2.3 represent a plane perpendicular to the direction of the sample width. The sample $\overline{OP} = l$ follows the path of the circle M and is bent to an arc $\widehat{OQ}$. Its center M is always on the line $\overline{OP}$ tangent of circle M. The origin is fixed in O, the initial line by $\overline{OP}$, the radius $\overline{OQ}$ by r, and the vectorial angle $\angle POQ$ by θ. Following this, Isshi developed Equations 2.4 and 2.5 :

$$r = 2\overline{MQ}\sin\theta \tag{2.4}$$

$$l = \widehat{OQ} = \overline{MQ}2\theta \tag{2.5}$$

Combining Equations 2.4 and 2.5 gives Equation 2.6.

$$r = \frac{l\sin\theta}{\theta} \tag{2.6}$$

If one extremity of the sample is fixed at O and the sample is bent in the shape of a partial cylinder, Equation 2.6 shows the set of all points of its other extremity P in the polar coordinate.

Isshi defined the curvature ρ of the sample in this specific case with Equation 2.7.

$$\rho = \frac{l}{\overline{MQ}} = \frac{2\theta}{l} \tag{2.7}$$

The other condition in which a sample takes the shape of a partial cylinder of any radius is if the angle of the directions of the tangents in contact with the circle M in O and Q is equal to 0 and 2θ to the initial line $\overline{OP}$, the directions of the sample at its both ends must coincide respectively with the directions of these tangents.

Kawabata Evaluation System FB2 Pure Bending Tester

On the same principle than Isshi, Kawabata[15] developed an apparatus - the Kawabata Evaluation System for Fabric FB2 - to test fabric and yarns in pure bending and measure the bending rigidity and the hysteresis.

The sample is fixed at one extremity, the origin on Figure 2.4, while the other extremity is fixed on a rotating clamp. The sample is then submitted to three bending cycles : (1), (2-3) and (4), following the equations shown on Figure 2.4, with

(1) from K =0 cm^{-1} to K =2.5 cm^{-1}

(2) from K =2.5 cm^{-1} to K =0 cm^{-1}

(3) from K =0 cm^{-1} to $K = -2.5$ cm^{-1}

(4) from $K = -2.5$ cm^{-1} to K =0 cm^{-1}

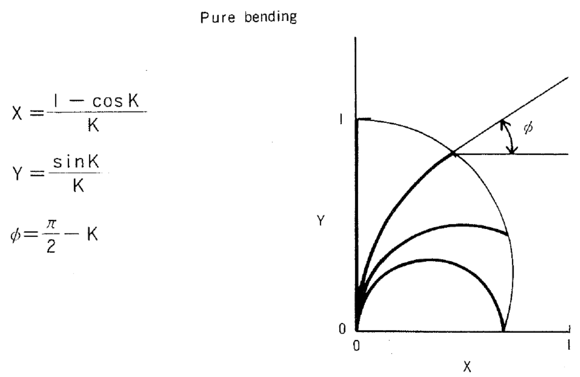


Figure 2.4: KES - FB2 Movement of the sample [15]

The bending moment M and the curvature K are measured continuously, and from them, the two following bending parameters can be obtained as shown in Figure 2.5.

- the bending rigidity B coefficient of the slope between 0.5 and 1.5 cm^{-1}
- the bending hysteresis 2HB measured at 0.5cm^{-1}

The bending rigidity and the bending hysteresis are measured:

- in forward direction (1) B+ and 2HB+
- in backward direction (3) B− and 2HB−

Average values B-MEAN of B+ and B− and 2HB-MEAN of 2HB+ and 2HB− are also given.

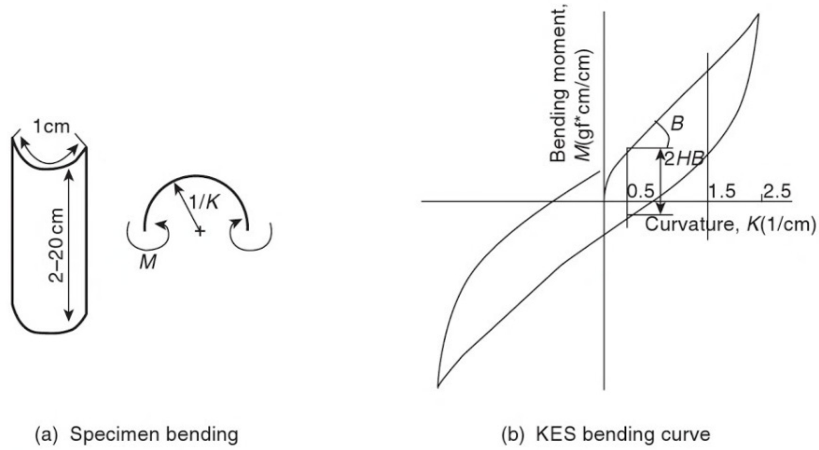


Figure 2.5: KES - FB2 Pure Bending test method [16]

2.3 Measurement of torsional rigidities of yarn

2.3.1 Mechanics

The torque is the force necessary to rotate an object around an axis. Mathematically, the torque $\vec{\Gamma}$ is defined as the cross product of the position vector $\vec{r}$ and the force vector $\vec{F}$ as shown with Equation 2.8

$$\vec{\Gamma} = \vec{r} \times \vec{F} \tag{2.8}$$

For textiles fibers, Meredith [17] described the torsional rigidity produced by a twist of one turn per cm Γ using Equation 2.9, with ϵ the shape factor, s the area of the cross-section and G the modulus of rigidity of the fiber. The shape factor is defined as the ratio between the torsional rigidity of a fiber of any cross section with the one of a similar fibre with a circular cross section.

$$\Gamma = \epsilon s^2 G \tag{2.9}$$

Platt et al. [18], using the force method, described the torque in twisted single yarns as a combination of fiber bending, fiber torsion and a combination of fiber bending and torsion. For the assumption of helical geometry and linear fiber elasticiy, they obtained expressions for the yarn torque due to fibre bending L_b (Equation 2.10) and fibre torsion L_t (Equation 2.11).

$$L_b = \frac{n_f B_f}{R} \frac{\ln(\sec^2 \theta_s - \sin^2 \theta_s)}{\tan \theta_s} \tag{2.10}$$

$$L_t = \frac{n_f B_f \sin^2 \theta_s}{R \tan \theta_s} \tag{2.11}$$

Where n_f is the number of fibers in yarn cross-section, B_f the fiber bending rigidity, R the yarn radius and θ_s the yarn-surface helix angle.

After Hickie and Chaikin[19] demonstrated the possibility to calculate the mechanical strain of fibers in torsion using the helical-yarn geometry, Postle et al.[20] described the total yarn torque L as the sum of the yarn torque component due to fibre bending L_b, the yarn torque component due to fibre tension L_θ and the yarn torque component due to fibre torsionL_t as written in Equation 2.12, and elaborated the yarn torque component due to fibre tension L_θ term shown in Equation 2.13.

$$L = L_b + L_\theta + L_t \tag{2.12}$$

$$L_\theta = \pi R^3 E_f e_y \frac{\ln(\sec^2 \theta_s - \sin^2 \theta_s)}{\tan^3 \theta_s} \tag{2.13}$$

Where E_f is the Young's modulus of the fiber and e_y the yarn strain. They also established that the torque due to fiber bending is in fact negligible for small twist angles.

2.3.2 Measurement of the torsional rigidity

One of the earliest and most common method to measure the fiber and yarn torque is the torsion pendulum [17]. However, the results can be distorted by a damping factor [20]. Measurements using a torsional tester, such as a galvanometer, are also common [21]. Kawabata Evaluation System KES-YN1 is also commonly used to measure the yarn torsional rigidity [22–24].

Kawabata Evaluation System YN-1 for yarn torque

To obtain torsional rigidity, a KES-YN1 yarn torsional tester (Kato Tech Co. Ltd. Kyoto, Japan) was used as shown in Figure 2.6. This device gives a measurement of the torque and the twist angle by measuring the resistance of the sample when rotating one extremity while the other is fixed. The movable part of the apparatus then makes a 6π rotation in one direction followed by a 12π rotation in the other, and returns to the original position while the device registers the torque and twist angle. Torsional rigidity is obtained from the mean of the two slopes between 2π and 4π in the forward rotation, and -2π and -4π in the backward rotation. The torsional rigidity Γ_{mes} is then calculated using the sample length l. The rotating speed was set at 12 degree/s. The forward torsional rigidity was used during this study. The torsional rigidity Γ_{mes} during forward rotation is given by Equation 2.14.

$$\Gamma_{\mathrm{mes}} = \frac{L_{4\pi} - L_{2\pi}}{\frac{2\pi}{l}} \tag{2.14}$$

where, $L_{4\pi}$ and $L_{2\pi}$ are the torques at 2π and 4π, respectively.

Figure 2.6: KES - YN1 Torque tester

2.4 References

[1] F. Peirce, “26—the “handle” of cloth as a measurable quantity,” *Journal of the Textile Institute Transactions*, vol. 21, no. 9, pp. T377–T416, 1930.

[2] J. d. Clark, “Determining the rigidity, stiffness and softness of paper,” *Paper Trade J*, vol. 100, no. 13, pp. 41–44, 1935.

[3] P.-Y. T. Henry, “Bending properties of a macroalga: Adaptation of peirce’s cantilever test for in situ measurements of laminaria digitata (laminariaceae),” *American journal of botany*, vol. 101, no. 6, pp. 1050–1055, 2014.

[4] P. Grosberg, “The mechanical properties of woven fabrics part ii: the bending of woven fabrics,” *Textile Research Journal*, vol. 36, no. 3, pp. 205–211, 1966.

[5] Y. Go, A. Shinohara, and F. Matsuhashi, “Viscoelastic studies of textile fabric (v) on the relationship between the bending behaviours of fabrics and fabric structures,” *Sen’i Gakkaishi*, vol. 14, no. 2, pp. 78–83, 1958.

[6] D. Cooper, “24—the stiffness of woven textiles,” *Journal of the Textile Institute Transactions*, vol. 51, no. 8, pp. T317–T335, 1960.

[7] B. Chapman and J. Hearle, “The bending and creasing of multicomponent viscoelastic fibre assemblies,” *J Text Ins*, vol. 63, no. 7, pp. T385–T412, 1971.

[8] F. Shinohara, A. Shinohara, and K. Sakaebara, “A theoretical study on the anisotropy of the bending rigidity of woven fabrics,” *J Textil Mach Soc Jpn*, vol. 32, no. 8, pp. T66–T71, 1979.

[9] T.-W. Chou and F. K. Ko, *Textile structural composites - Volume 3*, 1st ed. North Holland, 1989.

[10] A. C. Ugural and S. K. Fenster, *Advanced mechanics of materials and applied elasticity*. Pearson Education, 2011.

[11] N. Abbott, “The measurement of stiffness in textile fabrics,” *Textile Research Journal*, vol. 21, no. 6, pp. 435–441, 1951.

[12] T. K. Ghosh and N. Zhou, “Characterization of fabric bending behavior: a review of measurement principles,” *Indian Journal of Fibre and Textile Research*, vol. 28, no. 4, pp. 471–476, 2003.

[13] T. Eeg-Olofsson, “7—some mechanical properties of viscose rayon fabrics,” *Journal of the Textile Institute Transactions*, vol. 50, no. 1, pp. T112–T132, 1959.

[14] T. Isshi, “Bending tester for fibers, yarns and fabrics,” *Journal of the Textile Machinery Society of Japan*, vol. 3, no. 2, pp. 48–52, 1957.

[15] S. Kawabata, *The Standardization and Analysis of Hand Evaluation*, 2nd ed. Textile Machinery Society of Japan, 1980.

[16] Y. Li and D. X. Dai, *Biomechanical engineering of textiles and clothing*. Woodhead Publishing, 2006, 428p.

[17] R. Meredith, “30—the torsional rigidity of textile fibres,” *Journal of the Textile Institute Transactions*, vol. 45, no. 7, pp. T489–T503, 1954.

[18] M. M. Platt, W. G. Klein, and W. J. Hamburger, “Mechanics of elastic performance of textile materials part xiii: torque development in yarn systems: singles yarn,” *Textile Research Journal*, vol. 28, no. 1, pp. 1–14, 1958.

[19] T. Hickie and M. Chaikin, “81—the configuration and mechanical state of single fibres in woollen and worsted yarns,” *Journal of the Textile Institute Transactions*, vol. 51, no. 12, pp. T1120–T1130, 1960.

[20] R. Postle, P. Burton, and M. Chaikin, “41—the torque in twisted singles yarns,” *Journal of the Textile Institute Transactions*, vol. 55, no. 9, pp. T448–T461, 1964.

[21] W. D. Freeston, M. M. Platt, and G. Butterworth, “Mechanics of elastic performance of textile materials part xvii: Torsional recovery of filaments and singles yarns, and plied-yarn balance,” *Textile Research Journal*, vol. 36, no. 1, pp. 12–30, 1966.

[22] H. Kimura, M. Matsumoto, Y.-I. Matsumoto, and K. Fukushima, “Structure of novel composite single yarn from polypropylene staple fibers,” *Journal of Textile Engineering*, vol. 58, no. 3, pp. 27–34, 2012.

[23] W.-S. Lo, K.-F. Choi, and T. Lo, “Measurement of yarn bending and torsion rigidities of naturally curved yarns part 1: Monofilament yarn in helical shape,” *Textile Research Journal*, vol. 80, no. 18, pp. 1875–1886, 2010.

[24] H. WY, “A study of yarn torsional property and its effects on knitted fabric,” Ph.D. dissertation, Institute of Textile and Clothing, The Hong Kong Polytechnic University, Hong Kong, 2011, phD Thesis.

Chapter 3 : Verification of the effect of yarn torsional rigidity on fabric bending rigidity in any direction

Chapter 3: Verification of the effect of yarn torsional rigidity on fabric bending rigidity in any direction

3.1 Introduction

Simulation of fabric taking into account the mechanical properties are very important due to the increase of computer aided design for fabric. In clothing and furniture areas, the hand value and the drape are two primary properties that have to be take into account in the choice of a fabric.

Those two parameters are directly linked to bending properties of the fabric and the yarn. If the fabric bending properties could be predicted with only yarn bending properties, appropriate yarn selecting for the future use of the fabric will be possible. Additionally, fabric is an anisotropic material, and thus its properties must be considered in all directions.

Numerous studies have measured the bending rigidity and bending hysteresis of fabric. The quantitative evaluation of the bending behavior of woven fabric started with the work of Peirce [1], who developed a method of measuring bending rigidity under low stress. Grosberg [2] showed that the fabric bending behavior depends on two factors: the bending rigidity and the frictional restraint couple. Pierce was the first to construct a model that could be used to estimate fabric bending stiffness in any direction from the anisotropic Young's modulus for fabric. Go et al. [3] elaborated a bending stiffness model for woven fabric using the bending rigidity of yarn without torsional rigidity, and neglecting the crimp effect. Cooper [4] established a bending model for any direction taking into account the effect of the torsional rigidity on the bending behavior of fabric. Chapman and Hearle [5] also investigated a method of predicting bending rigidity using an energy method and ultimately obtained the same model as Cooper. Shinohara et al. [6] went further to explain the torsional component of Cooper's model. They showed the effect of yarn torsional rigidity on fabric bending in the bias direction qualitatively. However, the effect of yarn torsional rigidity on fabric bending rigidity has not been clarified experimentally. Yarn bending and torsional rigidities have to be measured to validate the model.

The measurement of yarn properties is difficult owing to the small torque and bending moment in addition to unevenness. The first yarn bending measurement was carried out by Pierce [1] employing a cantilever method also used for fabrics. Saxl [7], Horio and Onogi [8] and other researchers have developed methods of measuring the bending rigidity of yarns. A pure bending tester for fabric and yarn was developed by Isshi [9], opening the door for the development of a modern apparatus. The Kawabata Evaluation System (KES) FB-2 for pure bending is currently used to test fabric and yarns [10].

The yarn torque can be measured using a torsion pendulum but the results can be distorted by a damping factor [11]. Measurements using a torsional tester, such as a galvanometer, are also common [12]. Furthermore, KES-YN1 is used to obtain the yarn torsional rigidity [13–15].

The simulation of fabric properties using yarn properties is carried out around the world [16–21]. When simulating fabric bending behavior, it is important to take into account yarn properties such as tensile, transverse compression, bending and torsion properties. Current simulations use the estimated or measured yarn tensile modulus, while bending and torsional moduli are calculated from a tensile modulus assumed to be isotropic. However, yarns are discontinuous and anisotropic, and bending and torsional moduli are thus independent of the tensile modulus. It is necessary to include those effects in a future model in realizing a more accurate simulation.

In this study, the effect of yarn torsional rigidity on fabric bending rigidity in any direction was verified experimentally. The fabric bending rigidity was calculated using the measured yarn bending and torsional rigidities and the results were compared with the bending rigidity of fabric measured in several directions. Furthermore, the effect of crimp on the torsional rigidity of yarn was also discussed.

3.2 Theoretical

Cooper [4] proposed a mathematical model with which to calculate the bending rigidity of woven fabric in any direction according to the yarn bending rigidity and torsional component. Shinohara et al. [6] then clarified the model to get the torsional component from the yarn torsional rigidity and yarn density.

In Cooper's model, the bending rigidity in warp and weft is estimated using the relation :

$$B_f = nB_y \tag{3.1}$$

where B_f is the bending rigidity of the fabric in N·cm^2/cm, n is the yarn density in the testing direction in yarns/cm, and B_y is the bending rigidity of a yarn in N·cm^2. However, as fabric are anisotropic, it is necessary to estimate the bending rigidity in any direction.

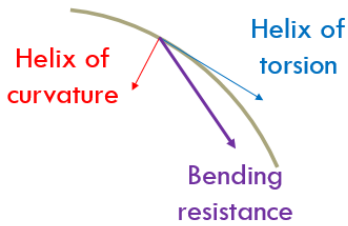


Figure 3.1: Helices of curvature and torsion composing the bending resistance

If the hypothesis of the yarn able to react independently to any deformation applied to the fabric as a whole is considered true, then the resistance of the fabric to bending can be defined as the sum of the resistances offered by the individual yarns. In this case, when the fabric is bend, an helix of torsion and an helix of curvature compose the bending resistance as shown on Figure 3.1. As the couple can be defined as

Couple = strain $\times$ number of yarn strained $\times$ effective rigidity per yarn

Cooper determined the helices of curvatures and torsion in warp and weft with the systems 3.2 for warp direction and 3.3 for weft direction.

$$\text{Warp}\begin{cases} B_1 \cdot \cos^3 \alpha \\ J_1 \cos^2 \alpha \sin \alpha \end{cases} \tag{3.2}$$

$$\text{Weft}\begin{cases} B_2 \cdot \sin^3 \alpha \\ J_2 \cos \alpha \sin^2 \alpha \end{cases} \tag{3.3}$$

Where J is the effective torsional rigidity per yarn of the warp and weft assemblies as they exist in the fabric structure and 1 and 2 refer to the warp and weft direction respectively. Therefore, Cooper established Equation 3.4 for the bending rigidity of the fabric to be estimated in any direction:

$$(B_f)_\alpha = B_{f1} \cdot \cos^4 \alpha + B_{f2} \cdot \sin^4 \alpha + (J_1 + J_2) \cos^2 \alpha \sin^2 \alpha \tag{3.4}$$

Where α is the angle of the fabric from the warp. Shinohara et al. [6] then explained the J term by showing that it could be defined as $J = J_y \cdot n$, where J_y is the yarn torsional rigidity in N·cm^2/2π. Therefore,

$$(B_f)_\alpha = B_{y1} \cdot \cos^4 \alpha + B_{y2} \cdot \sin^4 \alpha + (n_1 \cdot J_{y1} + n_2 \cdot J_{y2}) \cos^2 \alpha \sin^2 \alpha \tag{3.5}$$

However, Cooper and Shinohara et al. did not provide an experimental verification with the torsional rigidity of yarn. When the same yarn is used for both warp and weft, Equation 3.5 can be simplified as

$$(B_f)_\alpha = B_y \cdot (n_1 \cos^4 \alpha + n_2 \sin^4 \alpha) + J_y \cdot (n_1 + n_2) \cos^2 \alpha \sin^2 \alpha \tag{3.6}$$

where B_y is the bending rigidity of the yarn and J_y is the torsional rigidity of the yarn.

3.3 Experimental

To verify the relationship between yarn rigidities and bending properties of a fabric in various directions, yarn bending and torsional rigidities were measured and the fabric bending rigidity was calculated using Equation 3.6 and compared the results with the bending rigidity of fabric measured in several directions. To investigate the effect of crimp, the torsional rigidity of straight yarns from a bobbin the one of crimped yarn extracted from fabric were compared.

3.3.1 Measurement of yarn torsional rigidity and fabric and yarn bending rigidities

Yarn torsional rigidity

To obtain torsional rigidity, a KES-YN1 yarn torsional tester (Kato Tech Co. Ltd. Kyoto, Japan) was used as shown in Figure 3.2. This device allows the measurement of the twist angle and torque of the yarn. In the tester, the yarn is placed between two clamps, one movable and one fixed. The movable part of the apparatus then makes a 6π rotation in one direction and then a 12π rotation in the other, and returns to its original position while the device registers the torque and twist angle. Torsional rigidity is obtained from the mean of the two slopes between 2π and 4π in forward rotation and between -2π and -4π in backward rotation. The rotating speed was π/15 s^{-1}. An example of a torque–twist angle curve is shown in Figure 3.3. The asymmetry is due to the nature of the yarn. The torque will be higher when rotating in the direction of the twist, because it increases the twist, while rotating in the opposite direction of the twist will untwist the yarn. To minimize yarn tension in the torsional test, the yarn sample was submitted subjected only to the weight of the clamp (0.342 g) and its own weight during the testing process. The effective sample length was 3 cm. To test crimped yarns, an additional weight of ($0.2T_{tex}$+4) cN was added, where T_{tex} is the yarn count in tex, when making the 3 cm length yarn samples to obtain a constant crimp according to the Japanese Industrial Standards (JIS) for testing fabrics (JIS L1096:2010 [21]). Figure 3.4 shows a sample layout. For bobbin yarn, to guarantee a constant length for all samples, a preload equivalent to the weight of 200 meters of yarn was applied when making a sample. Then, after 24 hours under the standard conditions (temperature of 20$\pm$1°C and relative humidity of 65% $\pm$ 5%), the yarn torsional rigidity was measured. Twenty-five samples for each kind of yarn were prepared and then tested.

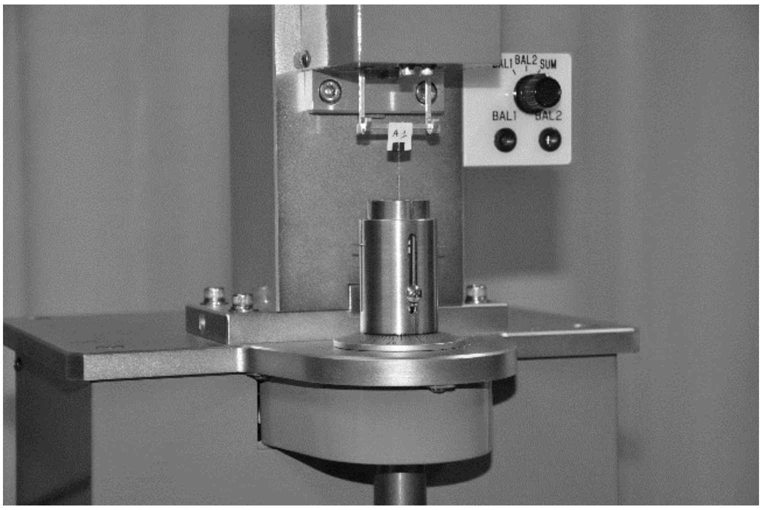


Figure 3.2: Yarn torsional testing with a KES-YN1 device

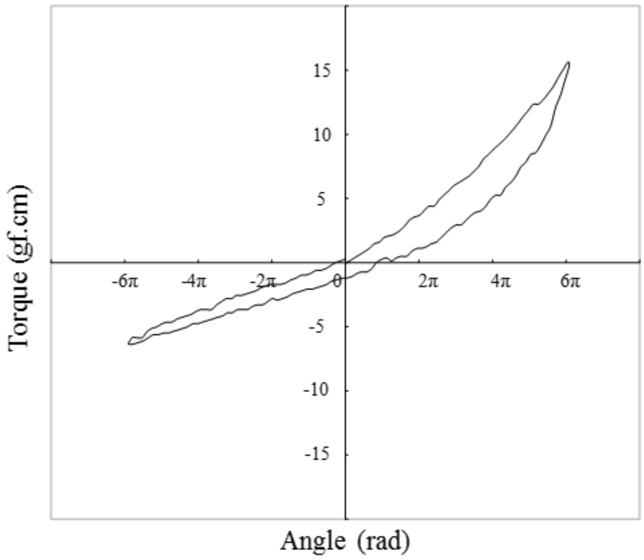


Figure 3.3: Typical torque curve for spun yarn

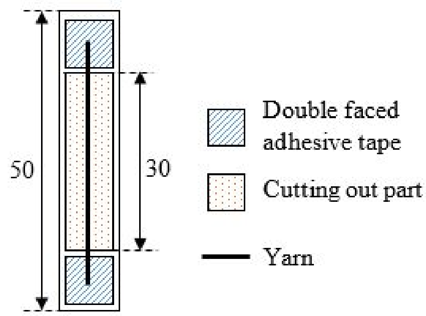


Figure 3.4: Torsional rigidity sample layout

Fabric bending rigidity

A Kawabata KES-FB2 pure bending tester (Kato Tech Co. Ltd., [10]), as shown in Figure 3.5 was used to measure the bending rigidity of the fabric samples. The bending rigidity is obtained from the mean of the two slopes between curvatures of 0.5 and 1.5 cm−1 in the forward direction and between −0.5 and −1.5 cm−1 in the backward direction. For the fabric bending measurement, 20-cm × 20-cm samples were prepared along the warp, along the weft, and at 22.5°, 45°, and 67.5° from the warp (0°). Five samples were made for each testing direction. Then, after conditioning the samples for 24 hours under the standards conditions, the samples were tested and the bending rigidity of the samples was measured five times in a row.

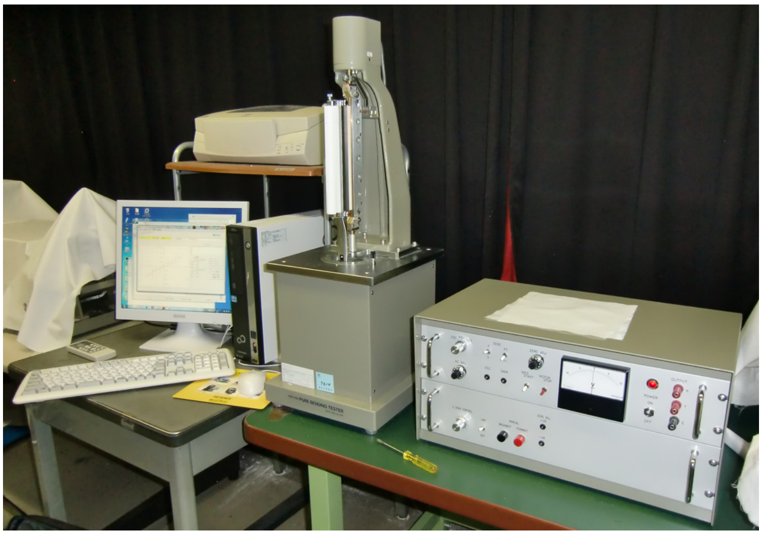
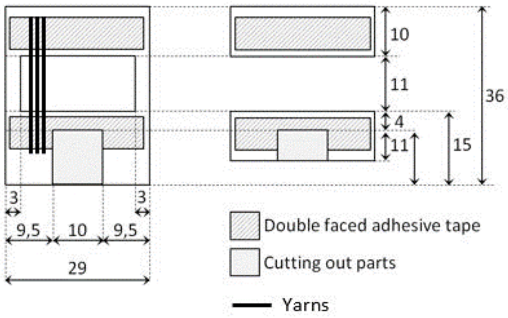


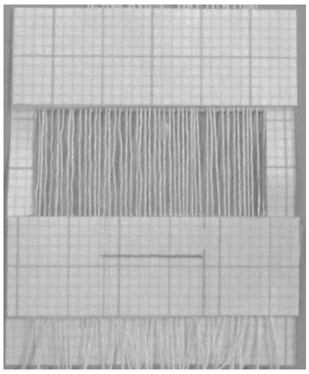
Figure 3.5: Kawabata KES-FB2 pure bending tester

Yarn bending rigidity

Yarn bending rigidity was also measured using the Kawabata KES-FB2 pure bending tester (Kato Tech Co. Ltd., [10]) shown in Figure 3.5. As cotton yarn has low bending rigidity and does not have a homogeneous structure along its length, the bending rigidity for a single yarn is thus difficult to obtain. To increase the accuracy of the measurement, multiple yarns distributed with density of 10−20 yarns/cm over 2 cm are tested together as shown in Figure 3.6. Like for the yarn torsional rigidity samples, a weight equivalent to 200 m of the yarn was applied during the placing of the yarn to guarantee a constant length for all yarns. To obtain more accurate measurements, 100- and 200-yarn samples distributed on 10 cm as shown in Figure 3.7 were also tested. As the two displayed a similar accuracy, samples of 100 yarns were prepared for samples A2 to E2. An example of a cotton spun yarn typical bending rigidity curve is shown in Figure 3.8. Fifteen samples per kind of yarn were prepared. After being conditioned for 24 hours under the standard conditions, the samples were tested.

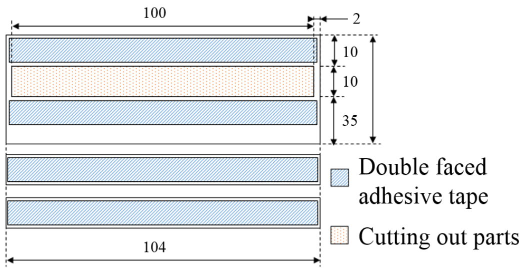


(a) Yarn bending sample layout

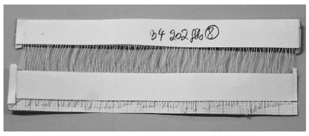


(b) Yarn bending sample (before test)

Figure 3.6: Yarn bending samples for a 2 cm width



(a) Yarn bending sample layout



(b) Yarn bending sample (after test)

Figure 3.7: Yarn bending samples for a 10 cm width

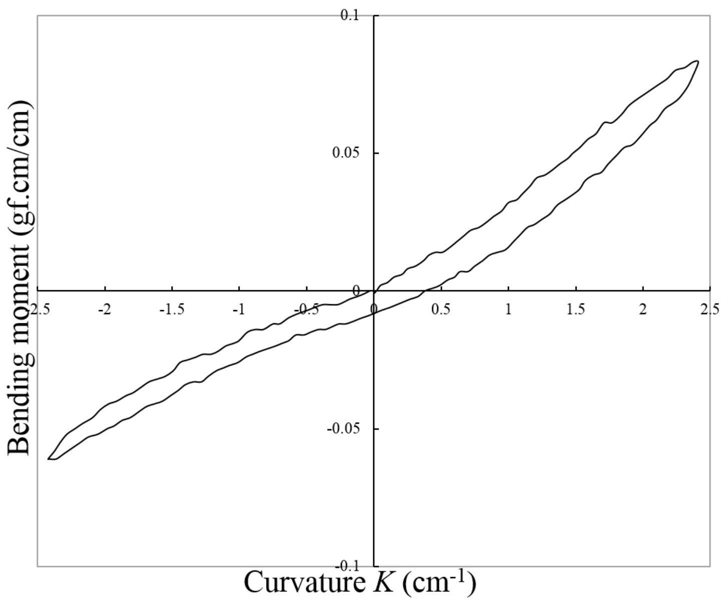


Figure 3.8: Typical bending moment curve of yarn (20 yarns/cm)

3.3.2 Test materials

Ten kinds of plain woven cotton fabric samples were prepared, as shown in tables 3.1 and 3.2. The fabrics for samples A to E were commercial products. For samples A to E, extracted yarns from the fabric for yarn were used for testing. In yarn bending tests, 2 cm-wide samples were used for samples A to E, and 10 cm-wide samples were used for samples A2 to E2. The fabrics for samples A2 to E2 were made using the same cotton non-sized yarn in warp and weft, and using the same weaving loom. Only the weft density was changed for each sample. For samples A2 to E2, both raw yarn from a bobbin and extracted yarns were used in testing the torsional and bending rigidities to compare the crimp effect.

Table 3.1: Fabric and yarn specifications for samples A to E.

	Sample				
Characteristic	A	B	C	D	E
Weave	Plain weave				
Material	Cotton				
Area density (g/m^2)	148.8	156.7	81.0	134.0	47.9
Warp weave density (ends/cm)	28	24	28	21	20
Weft weave density (picks/cm)	23	24	26	21	14
Warp crimp (%)	4.8	9.3	3.5	7.0	1.7
Weft crimp (%)	21.0	10.0	7.0	10.0	7.0
Warp yarn count (tex)	30	30	16	30	14
Weft yarn count (tex)	30	30	14	30	14
Origin	Commercial product				

Table 3.2: Fabric and yarn specifications for samples A2 to E2.

	Sample				
Characteristic	A2	B2	C2	D2	E2
Weave	Plain weave				
Material	Cotton				
Area density (g/m^2)	111.8	129.1	130.9	140.2	150.4
Warp weave density (ends/cm)	23.6				
Weft weave density (picks/cm)	19.7	23.6	27.6	31.5	35.4
Warp crimp (%)	21.8	15.6	16.9	12.4	11.7
Weft crimp (%)	12.7	14.7	16.5	16.7	18.5
Warp yarn count (tex)	20				
Weft yarn count (tex)	20				
Origin	Produced product				
Yarn twist(tpm)(twist factor)	1069 (K=5.0)				
Fiber average length(mm)	36.6				
Fiber average fineness (tex)	0.15				

3.4 Results and Discussions

3.4.1 Samples A to E

Description of the estimation methods

In order to estimate bending rigidities using Cooper[4] and Shinohara et al.[6] model in any direction, three different estimation methods were calculated. As the samples were commercial samples, yarns in warp and weft directions presented different properties and therefore, Equation 3.5 was used.

I Equation 3.5 with measured yarn torsional and bending rigidities

II Equation 3.5 with measured bending rigidity and estimated yarn torsional rigidity.

III Equation 3.5 with estimated yarn torsional and bending rigidities values from fabric bending rigidity.

Estimation of yarn torsional rigidity Using Equation 3.5 and knowing B_{y1} and B_{y2}, the sum of torsional rigidities $(n_1 \cdot J_{y1} + n_2 \cdot J_{y2})$ can be estimated from the experimental values of fabric bending rigidity in bias direction (45°).

Estimation of yarn bending rigidity Using Equation 3.1, and knowing n in both warp (1) and weft (2) direction, the bending rigidities of the warp and weft yarns were calculated from the experimental values of fabric bending rigidity in warp (0°) and weft (90°) directions.

Then the results obtained with Methods I, II and III were compared to the experimental fabric bending rigidity values. Table 3.3 shows experimental and calculated bending rigidities of fabric in all directions for samples A to E. The torsional rigidities of the yarn in warp and weft direction for samples A to E can be found on Table 3.4.

Results and Discussion

Samples A, C and E Figures 3.9 to 3.11 shows the results for samples A, C and E. Small differences can be observed, but the theoretical model still gave results close to the experimental values of fabric bending rigidity, especially in the case of the sample E. Thus, in those cases,

Table 3.3: Calculated and experimental values of the bending values (mN.cm^2/cm)

Angle (°)	Method	0°	22°	45°	67°	90°
A	I	0.79	0.789	0.732	0.595	0.515
	II	0.79	0.76	0.673	0.566	0.515
	Exp	0.79	0.783	0.673	0.574	0.515
B	I	1.844	2.683	1.499	1.605	1.735
	II	1.844	1.966	2.065	1.889	1.735
	Exp	1.844	1.869	2.065	1.932	1.735
C	I	0.976	0.873	0.647	0.451	0.378
	II	0.976	0.891	0.682	0.468	0.378
	Exp	0.976	0.775	0.682	0.463	0.378
D	I	1.615	1.422	1.116	1.038	1.073
	II	1.615	1.643	1.559	1.26	1.073
	Exp	1.615	1.533	1.559	1.292	1.073
E	I	1.515	1.309	0.822	0.348	0.155
	II	1.515	1.254	0.712	0.293	0.155
	Exp	1.515	1.359	0.712	0.268	0.155

Table 3.4: Measured torsional rigidities of yarns for samples A to E

Sample	Torsional rigidity (μN·cm^2/2π)			
	Warp		Weft	
	Mean	SD	Mean	SD
A	34.20	3.78	28.93	4.22
B	6.14	0.47	3.92	0.38
C	32.02	8.42	12.99	0.91
D	7.41	1.29	1.03	0.08
E	65.95	2.50	21.30	3.40

Cooper and Shinohara et al. model can be used to estimate bending values in any direction just using the yarn properties.

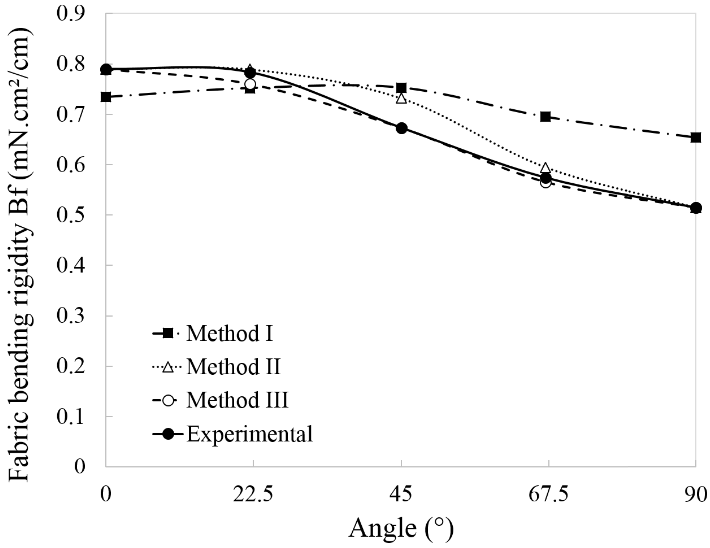


Figure 3.9: Comparison of experimental and calculated bending rigidities for Sample A

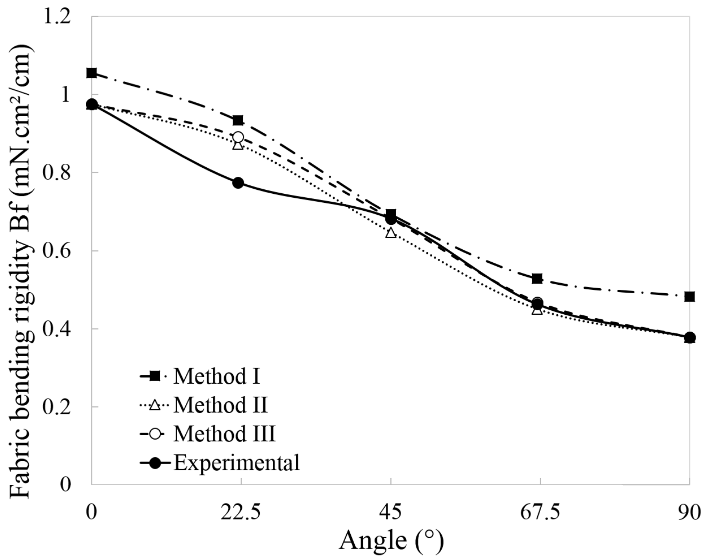


Figure 3.10: Comparison of experimental and calculated bending rigidities for Sample C

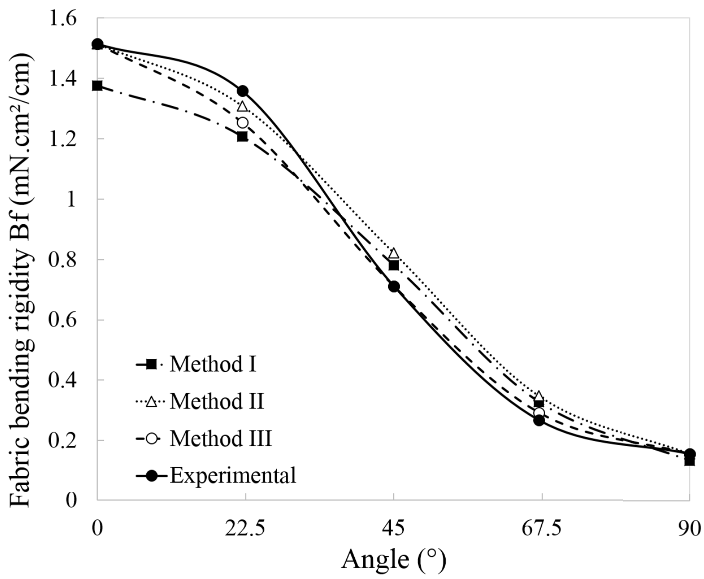


Figure 3.11: Comparison of experimental and calculated bending rigidities for Sample E

Samples B and D For Sample B and D however, shown respectively on Figures 3.12 and 3.13, the method II with estimated yarn bending value did not fit the experimental values. Cooper and Shinohara et al. model with measured yarn torque present large differences from the experimental values. Of course, method III, which use fabric bending properties to get yarn bending properties is very close from the experimental values.

With the method I, with measured yarn bending and torsional values, the difference is even bigger. However, in this case, it can be observed that the theoretical curve and the experimental one are just shifted from each other. It is the same for sample D. Both samples shared a important stiffness and density.

In a first time, it was questioned if the sizing effect could cause such differences, taking into account the similarities between both samples.

Thus, a new set of samples was made with fabric from sample D and washed suppress the sizing effect. After the samples for 24h under the standards conditions, they were tested using KES FB2. The results are shown on Figure 3.13. A slightly difference from the previous experimental values can be observed. However, it doesn't explain the difference between the model and the experimental values. Therefore, the sizing effect can be put aside. During this experiment, yarn extracted from the fabric was used to test the yarn properties. Hence, crimp may also play a role in those results.

It can also be observed from table 3.4 that the torsional rigidities of warp and weft yarn for samples B and D are significantly lower than for samples A, C and E. Thus, Cooper and Shinohara et al. model might not be applicable for fabrics composed of yarns with low torsional rigidities. However, it can be stated that for this two samples, the Cooper and Shinohara et al. model give an underestimated value of the fabric bending rigidity. Even if the theoretical values are shifted from each other, Cooper model can't be used in those cases.

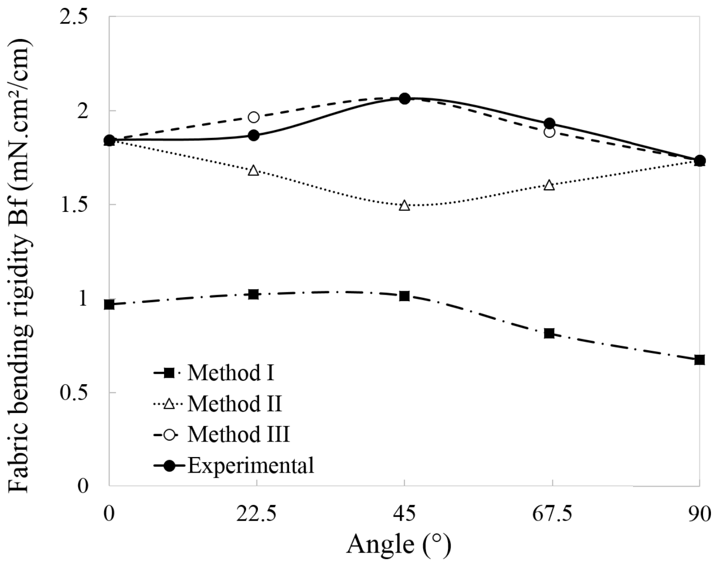


Figure 3.12: Comparison of experimental and calculated bending rigidities for Sample B

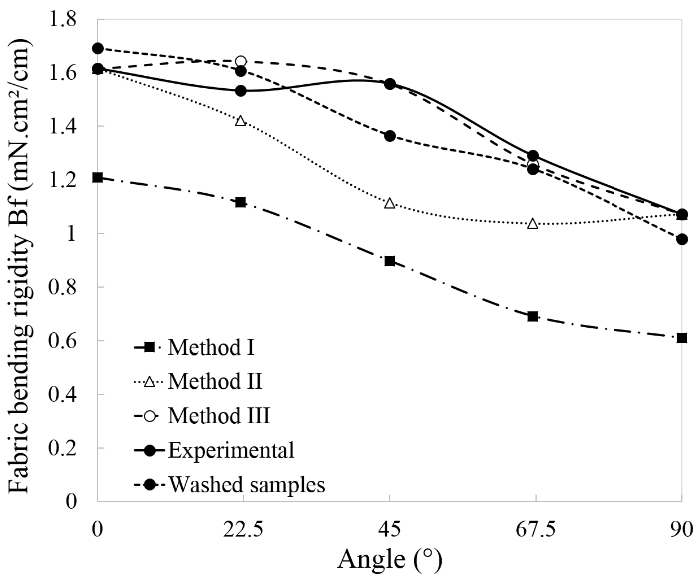


Figure 3.13: Comparison of experimental and calculated bending rigidities for Sample D

3.4.2 Samples A2 to E2

Description of the estimation methods

Following the results obtained for commercially acquired fabric, it was decided to redo the experiment with lab-made samples with the same yarn in warp and weft directions. Therefore, in this case, Equation 3.6 can be used. In order to estimate bending rigidities using Cooper and Shinohara et al. model in any direction, the same three methods than previously were used. An additional fourth method was also used.

I Equation 3.6 with measured yarn torsional and bending rigidities

II Equation 3.6 with measured bending rigidity and estimated yarn torsional rigidity.

III Equation 3.6 with estimated yarn torsional and bending rigidities values from fabric bending rigidity using Equation 3.1.

IV Equation 3.6 with estimated yarn torsional and bending rigidities from measured fabric bending rigidity of sample C2.

Estimation of yarn torsional rigidity Using Equation 3.6 and knowing n_1, n_2 and B_y, the torsional rigidity J_y was estimated from the experimental values of fabric bending rigidity in bias direction (45°).

Estimation of yarn bending rigidity Using Equation 3.1, and knowing n in both warp (1) and weft (2) direction, the bending rigidities of the warp and weft yarns were calculated from the experimental values of fabric bending rigidity in warp (0°) and weft (90°) directions.

Estimation of yarn bending and torsional rigidities from sample C2 The torsional and bending rigidities were estimated using the same methods than previously but using only experimental fabric bending rigidities in bias and warp/weft directions from sample C2. Then, the estimated values were combined with the n_1 and n_2 values of the other samples with Equation 3.6 to estimate the bending rigidities of samples A2, B2, D2 and E2.

Table 3.5 gives the measured bending rigidities of yarns. Figure 3.14 compares the torsional rigidities of yarns extracted from the fabric with the torsional rigidity of bobbin yarn. The torsional rigidities of yarns extracted from fabric are very similar among all produced samples, even if the weft density differs. However, there was a large difference from the torsional rigidity of yarn taken directly from the bobbin. This could be due to crimp.

Table 3.5: Measured bending rigidities of cotton yarn (samples A2 to E2) ($\mu N \cdot cm^2$)

Sample \ Bending rigidity of one yarn	Mean	SD
A2-E2 (from bobbin)	1.609	0.003

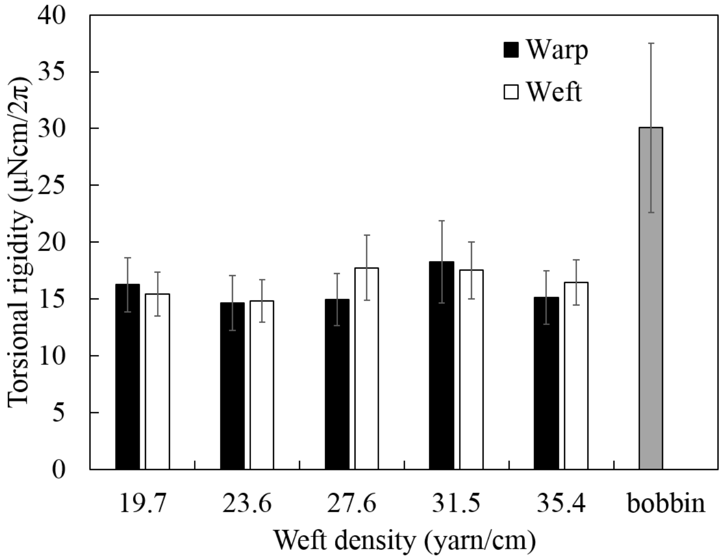


Figure 3.14: Measured torsional rigidities of yarns extracted from fabric for samples A2 to E2

Results and Discussion

With the measured values of yarn properties, Equation 3.5 was verified. Two measurements of each yarn's torsional rigidity were used to calculate the fabric bending rigidities: one for yarn directly taken from the bobbin and the other for yarn extracted from each fabric sample in both the warp and weft. The experimental and calculated fabric bending rigidities are compared in Figures 3.15 to 3.19.

Errors in warp and weft direction are due to the measured yarn bending rigidity, due to the yarn torsional rigidity being not affected by the bending rigidity in the yarn direction. Samples C, D and E have good agreement in yarn directions, but samples A2 and B2 are slightly different. Figure 3.20 shows bending rigidity per yarn calculated from fabric bending rigidity using Equation 3.1, and measured yarn bending rigidity from the bobbin for samples A to E. It was found that the calculated yarn bending rigidities of lower weft densities are lower than those of higher density

fabrics, especially in the weft direction. Samples A and B had the lowest weft density, and their calculated bending rigidities of yarn were lower than the measured yarn bending rigidity. This caused the difference in the calculated fabric bending rigidities for warp and weft directions.
In bias directions of samples A2 to E2, the calculated bending rigidity with yarns extracted from the fabric had better agreement than that with the yarn taken from the bobbin. In the calculation of bending rigidity with yarn from the bobbin, the error was a maximum in the 45° direction. This error is clearly explained by the J_y value in Equation 3.6. Figure 3.14 shows that yarn torsional rigidities extracted from fabric were significantly lower than yarn torsional rigidity of yarn from the bobbin. This could be due to the crimp effect.
If the torsional rigidity of yarn directly extracted from the bobbin is measured, the fabric bending rigidity can be calculated before weaving. However, the results show that better results are obtained using the torsional rigidity of extracted yarns. Therefore, Cooper and Shinohara et al. model might intrinsically include the crimp effect.

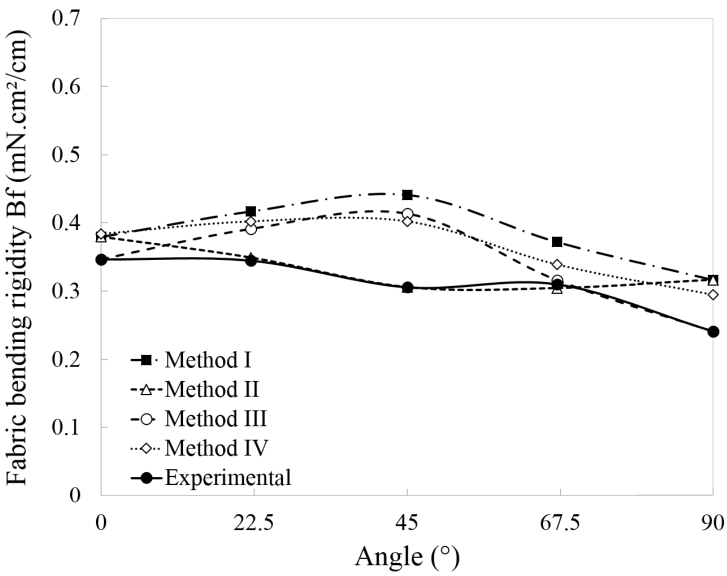


Figure 3.15: Comparison of experimental and calculated bending rigidities for Sample A2

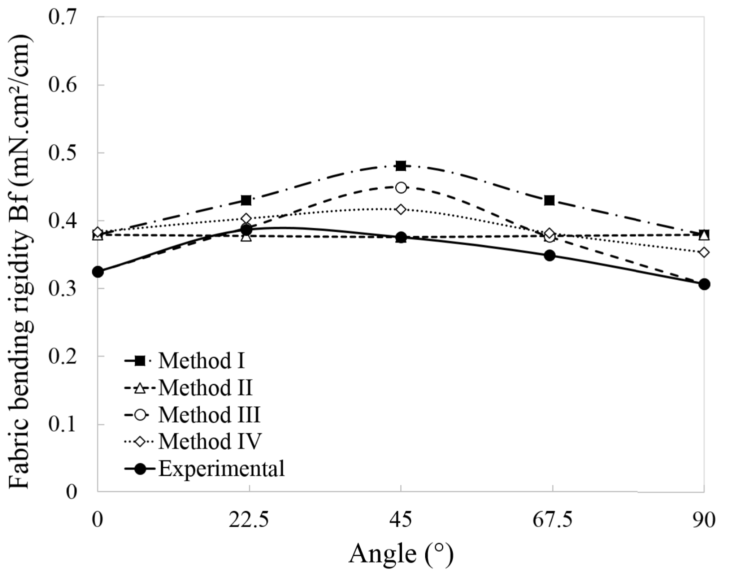


Figure 3.16: Comparison of experimental and calculated bending rigidities for Sample B2

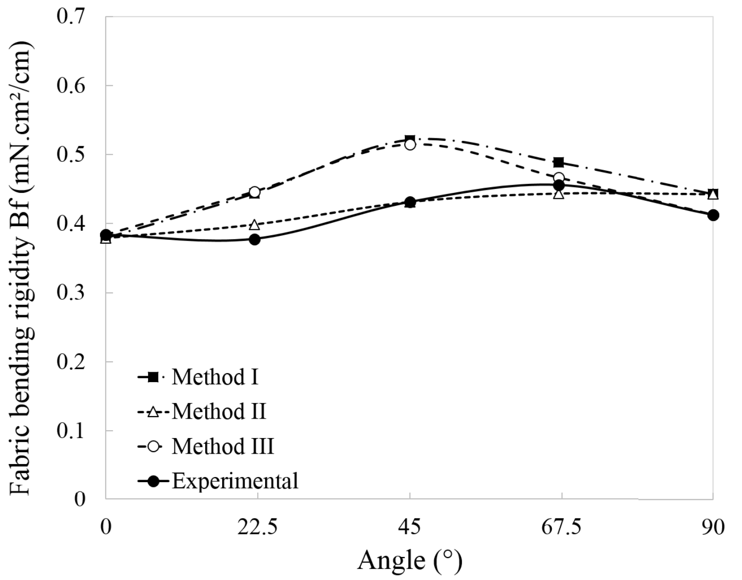


Figure 3.17: Comparison of experimental and calculated bending rigidities for Sample C2

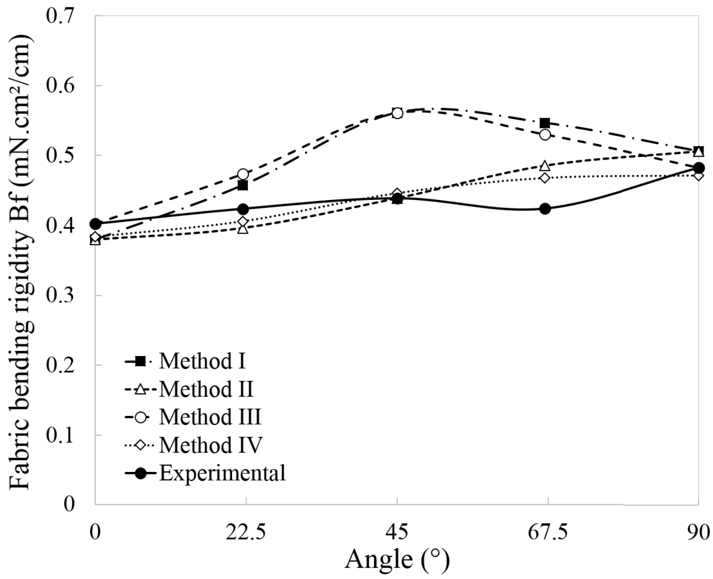


Figure 3.18: Comparison of experimental and calculated bending rigidities for Sample D2

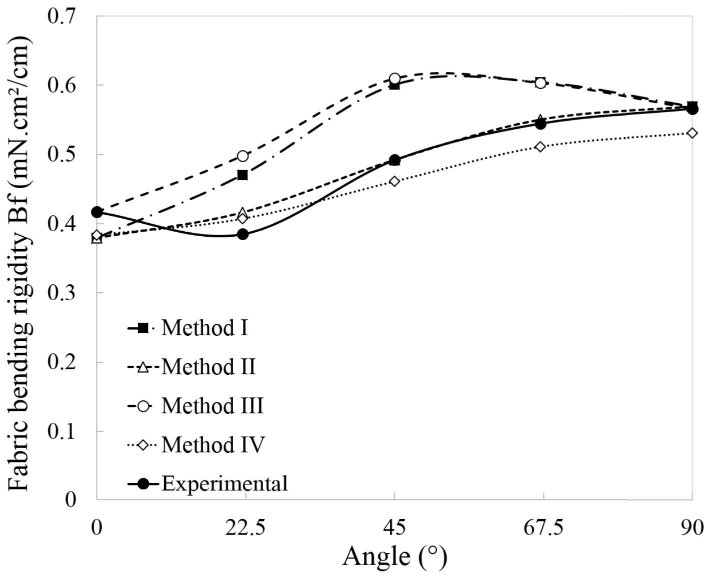


Figure 3.19: Comparison of experimental and calculated bending rigidities for Sample E2

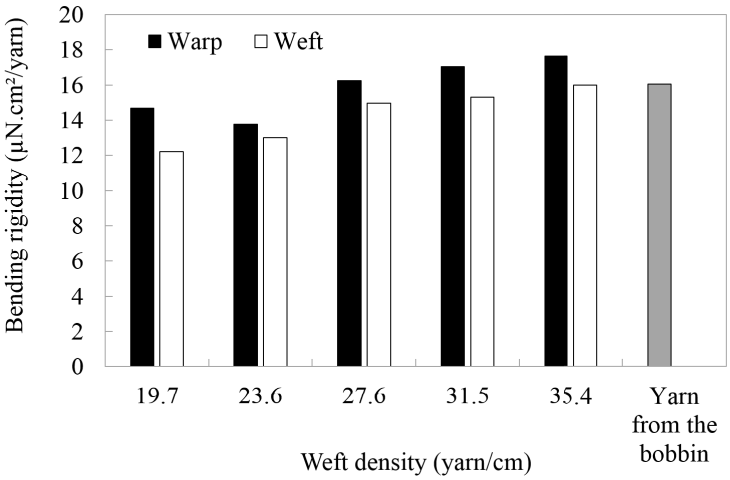


Figure 3.20: Bending rigidity per yarn calculated from fabric bending rigidity and measured yarn bending rigidity from the bobbin for Samples A2 to E2

3.5 Conclusion

The effect of yarn torsional rigidity on the Cooper model for fabric bending rigidities in any direction was verified. Five commercial fabrics were first used as experimental samples. Then, an additional five cotton fabrics with different weft densities were woven. The torsional rigidities of yarn from the bobbin and yarn directly extracted from the fabric were measured with a yarn torsional tester. The bending rigidity of yarn from the bobbin was measured using the same pure bending tester used for fabric bending testing. The fabric bending rigidity calculated using torsional rigidities of yarns extracted from the fabric showed better agreement with the experimental values than that calculated using the torsional rigidity of yarn from the bobbin. Measurements showed that the torsional rigidity of yarn from the bobbin was appreciably higher than torsional rigidities of yarns from fabric. This could be due to the crimp of yarn. The results show that the torsional rigidity of yarn is affected by the weaving process and does not remain the same as that of yarn on the bobbin. It was thus found that, in predicting the bending rigidity of fabric using the Cooper model, measured torsional rigidities of yarns extracted from fabric should be used instead of yarn straight from the bobbin. The same results were obtained for the commercial fabrics. These results will be useful for fabric simulation.

3.6 References

[1] F. Peirce, “26—the “handle” of cloth as a measurable quantity,” *Journal of the Textile Institute Transactions*, vol. 21, no. 9, pp. T377–T416, 1930.

[2] P. Grosberg, “The mechanical properties of woven fabrics part ii: the bending of woven fabrics,” *Textile Research Journal*, vol. 36, no. 3, pp. 205–211, 1966.

[3] Y. Go, A. Shinohara, and F. Matsuhashi, “Viscoelastic studies of textile fabric (v) on the relationship between the bending behaviours of fabrics and fabric structures,” *Sen’i Gakkaishi*, vol. 14, no. 2, pp. 78–83, 1958.

[4] D. Cooper, “24—the stiffness of woven textiles,” *Journal of the Textile Institute Transactions*, vol. 51, no. 8, pp. T317–T335, 1960.

[5] B. Chapman and J. Hearle, “The bending and creasing of multicomponent viscoelastic fibre assemblies,” *J Text Ins*, vol. 63, no. 7, pp. T385–T412, 1971.

[6] F. Shinohara, A. Shinohara, and K. Sakaebara, “A theoretical study on the anisotropy of the bending rigidity of woven fabrics,” *J Textil Mach Soc Jpn*, vol. 32, no. 8, pp. T66–T71, 1979.

[7] I. Saxl, “The quantitative determination of stiffness in individual yarns,” *Textile Research Journal*, vol. 6, no. 3, pp. 152–156, 1936.

[8] M. Horio and S. Onogi, “Forced vibration of reed as a method of determining viscoelasticity,” *Journal of Applied Physics*, vol. 22, no. 7, pp. 977–981, 1951.

[9] T. Isshi, “Bending tester for fibers, yarns and fabrics,” *Journal of the Textile Machinery Society of Japan*, vol. 3, no. 2, pp. 48–52, 1957.

[10] S. Kawabata, *The Standardization and Analysis of Hand Evaluation*, 2nd ed. Textile Machinery Society of Japan, 1980.

[11] R. Postle, P. Burton, and M. Chaikin, “41—the torque in twisted singles yarns,” *Journal of the Textile Institute Transactions*, vol. 55, no. 9, pp. T448–T461, 1964.

[12] W. D. Freeston, M. M. Platt, and G. Butterworth, “Mechanics of elastic performance of textile materials part xvii: Torsional recovery of filaments and singles yarns, and plied-yarn balance,” *Textile Research Journal*, vol. 36, no. 1, pp. 12–30, 1966.

[13] H. Kimura, M. Matsumoto, Y.-I. Matsumoto, and K. Fukushima, “Structure of novel composite single yarn from polypropylene staple fibers,” *Journal of Textile Engineering*, vol. 58, no. 3, pp. 27–34, 2012.

[14] W.-S. Lo, K.-F. Choi, and T. Lo, “Measurement of yarn bending and torsion rigidities of naturally curved yarns part 1: Monofilament yarn in helical shape,” *Textile Research Journal*, vol. 80, no. 18, pp. 1875–1886, 2010.

[15] H. WY, “A study of yarn torsional property and its effects on knitted fabric,” Ph.D. dissertation, Institute of Textile and Clothing, The Hong Kong Polytechnic University, Hong Kong, 2011, phD Thesis.

[16] S. Inui, H. Okabe, M. Takatera, M. Hashimoto, and Y. Horiba, “A fabric simulation based on a model constructed from a lower level,” in *Computational Engineering in Systems Applications, IMACS Multiconference on*, vol. 1. IEEE, 2006, pp. 178–180.

[17] X. Dai, Y. Li, and X. Zhang, “Simulating anisotropic woven fabric deformation with a new particle model,” *Textile research journal*, vol. 73, no. 12, pp. 1091–1099, 2003.

[18] M. Xiao and Z. Geng, “A model of rigid bodies for plain-weave fabrics based on the dynamics of multibody systems,” *Textile Research Journal*, 2010.

[19] S. Inui, Y. Mesuda, Y. Horiba, and M. Kurihara, “Fabric weave form simulation based on the characteristics of yarn,” in *Biometrics and Kansei Engineering (ICBAKE), 2011 International Conference on*. IEEE, 2011, pp. 49–52.

[20] G. Zhou, X. Sun, and Y. Wang, “Multi-chain digital element analysis in textile mechanics,” *Composites science and Technology*, vol. 64, no. 2, pp. 239–244, 2004.

[21] J. S. Association, *JIS: Japanese Industrial Standards - Handbook 54 Sen’i*. Japanese Standards Association, 2010.

Chapter 4 : Measurement of torsional rigidity of yarns with different crimps

Chapter 4: Measurement of torsional rigidity of yarns with different crimps

4.1 Introduction

When simulating the draping and bending behavior of a fabric, the fabric material, its structure, and the properties of the yarn must be taken into account. The bending, torsional, and tensile properties of the yarn are important for predicting the mechanical properties of the fabric [1–3].

The torsional properties of yarns have been widely studied over the years. Yarn properties have been investigated because they influence fabric bending properties and therefore the hand of the fabric [4, 5].

Fiber crimp has been extensively studied for analyzing the geometrical structure and mechanical properties of fiber and yarn [6–8]. Meredith first developed a method to measure fiber crimp [9]. Subsequently, models of the geometry of fiber crimp were investigated [10]. Starting with Pierce's model, many studies have been carried out on yarn crimp geometry and its effect within the fabric [11, 12]. However, only a few studies have been conducted on the mechanical properties of crimped yarn.

In 1958, Platt et al. [5] developed a model for the yarn torque of single yarns, taking into account fiber bending, fiber torsion, and a combination of the two. This study was continued by Postle et al. [13, 14] who developed a model to estimate the torque for newly twisted as well as for continuous filament yarns.

To predict fabric bending properties it is necessary to estimate the effect of crimp on the torsional rigidity of the yarn. Cooper demonstrated the influence of yarn torsional rigidity on fabric torsional rigidity by establishing a model that included both the torsional and bending rigidity of the yarn [4]. Shinohara later pursued this research on the yarn torsional rigidity term of

Cooper's model [15]. Peiffer et al. [16] showed that fabric bending properties could be predicted using Cooper's [4] and Shinohara et al.'s [15] models taking into account the torsional rigidity of the yarn to predict fabric bending rigidity. The study also showed an important difference between yarn torsional rigidity measured from the bobbin, and that measured when extracted from the fabric. The difference in properties between straight and crimped yarns could explain this discrepancy.

Regarding the effect of crimp on yarn properties, Skelton [17] published an extensive study on the tensile, flexural, and torsional properties of crimped filaments. He made theoretical models of saw tooth, rectangular, and circular-arc crimps, and verified his theory by measuring the torsional rigidity of circular-arc piano wire and nylon monofilament yarn extracted from a fabric using a torsional pendulum. However, the torque-twist curve was not obtained due to the measuring method used. Furthermore, this study was not conducted for common spun yarn with undulating crimp. Ordinarily, experimental yarn with crimp extracted from a fabric is used for experiments. However, this does not allow much freedom in the choice of parameters, such as the wavelength or amplitude of the crimp. Furthermore, it would be more convenient for simulation purposes if it were possible to estimate the torsional rigidity of the yarn without weaving. The design of a torsional test for crimped spun yarn is problematic because of the difficulty in creating and maintaining crimp experimentally.

In Chapter 3, it was observed that the crimp could have an impact on the torsional rigidity of yarn. In this study, crimped monofilaments and spun yarns with various amplitudes and wavelengths were made using original crimp setting equipment. The torque-twist curves of straight and crimped yarns were obtained using a torsional tester and determined their torsional rigidities. The effect of crimp on yarn torsional rigidity was investigated by comparing the torsional rigidities of crimped and straight yarns.

4.2 Theoretical

The theory of the torsional properties of crimped fibers has been discussed by Skelton [17]. If the bending rigidity of the straight filament is B, the torsional rigidity of the straight filament is W, and the torsional rigidity of the crimped filament is W_2, the relationship between W and

W_2 in the initial state is given by Equation 4.1.

$$\frac{L}{W_2} = \frac{L}{W} + \left(\frac{1}{B} - \frac{1}{W}\right) \int_0^l f(s)\mathrm{d}s \tag{4.1}$$

where L is the projected length of the filament on the torsional axis, l is the length of the filament along the crimp, and $\phi = f(s)$ is the configuration of the filament in a plane, given by s, the distance along the filament between the origin and ϕ the tangent angle at s. Skelton solved Equation 4.1 for circular crimp and produced Equation 4.2.

$$\frac{1}{W_2} = (1+c)\left[\frac{1}{W} + \left(\frac{1}{B} - \frac{1}{W}\right)\left(\frac{1}{2} - \frac{\sin 2\phi_0}{4\phi_0}\right)\right] \tag{4.2}$$

where c is the crimp ratio and ϕ_0 is the value of ϕ at $s = 0$. In this Equation, c and ϕ_0 are linked by Equation 4.3.

$$\frac{\phi_0}{\sin\phi_0} = 1 + c \tag{4.3}$$

Therefore,

$$\frac{W}{W_2} = (1+c)\left[\frac{1}{2} + \frac{\sin 2\phi_0}{4\phi_0} + \frac{W}{B}\left(\frac{1}{2} - \frac{\sin 2\phi_0}{4\phi_0}\right)\right] \tag{4.4}$$

These equations describe the important relationship between crimp ratio and filament rigidity in the initial state. For the same crimp configuration yarn, the ratio $\frac{W}{W_2}$ is affected mainly by the bending rigidity B. However, the torque-twist relationship during twisting is not given because ϕ can no longer be considered a constant, and the configuration is no longer in a plane but rather in three dimensions.

4.3 Experimental

To investigate the effect of crimp on yarn torsional properties, different crimps were applied to monofilaments and cotton spun yarns. The torsional rigidity of the yarn was then measured and the results were compared.

4.3.1 Crimp condition setting

To investigate the effect of crimp on yarn torsional rigidity, yarns with crimps of various amplitudes and wavelengths were generated. Four types of crimp setting equipment were created using a box with many parallel metal rods with circular cross sections, as shown in Figure 1. The diameters Øof the rods were Ø1.2 mm, Ø2 mm, Ø3 mm, and Ø4 mm, and the interval l between the rods was d_r+ 1.5 mm. Each yarn interlaced the rod as shown in Figure 4.1. Figure 4.2 shows the yarn geometry set-in for the equipment, with d_f the diameter of the yarn, λ the wavelength of the crimp, A the amplitude of the crimp, and s the yarn length for a wavelength λ and an amplitude A. Figure 4.3 shows a full set of crimp setting equipment, with all 4 diameters.

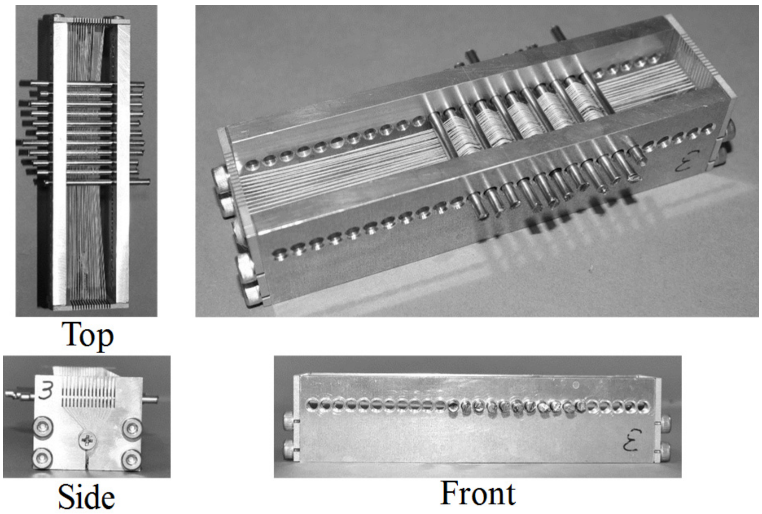


Figure 4.1: Example of crimp setting equipment with yarn interlaced

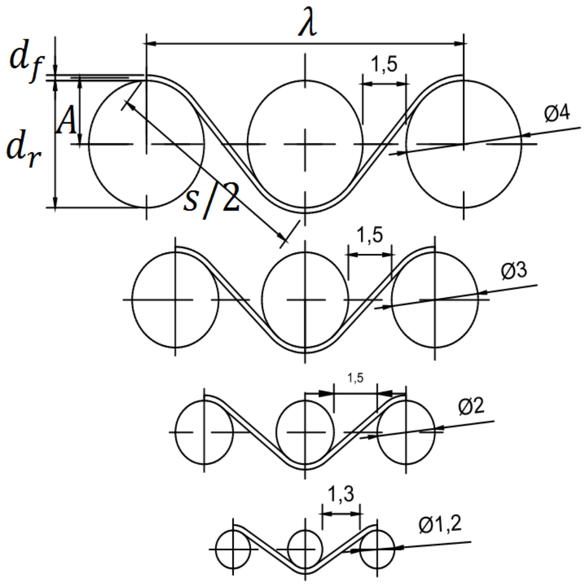


Figure 4.2: Yarn geometry on the setting equipment

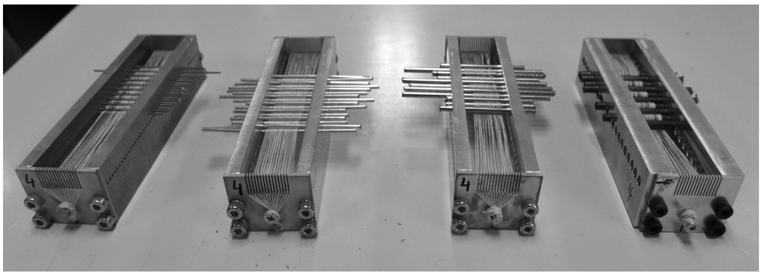


Figure 4.3: Full set of crimp setting equipment

Setting of crimp for monofilament yarns

First, the monofilaments were set in position in the crimp setting equipment. To fix the crimp, the equipment was put in an oven at 160°C for 15 min. Once the equipment had cooled to room temperature, the metal rods were removed leaving the crimped samples.

Setting of crimp for cotton spun yarns

To fix the crimp in the cotton spun yarns, the yarns were set in the equipment and subjected to steam treatment for 30 min using a common steam cooker as shown in Figure 4.4. The samples were then left to dry in a thermo-hygrostat set to standard conditions (20 ± 1°C and relative humidity of 65 ± 5%) for 24 h. After this process, the crimp stayed set, as shown in Figure 4.5.

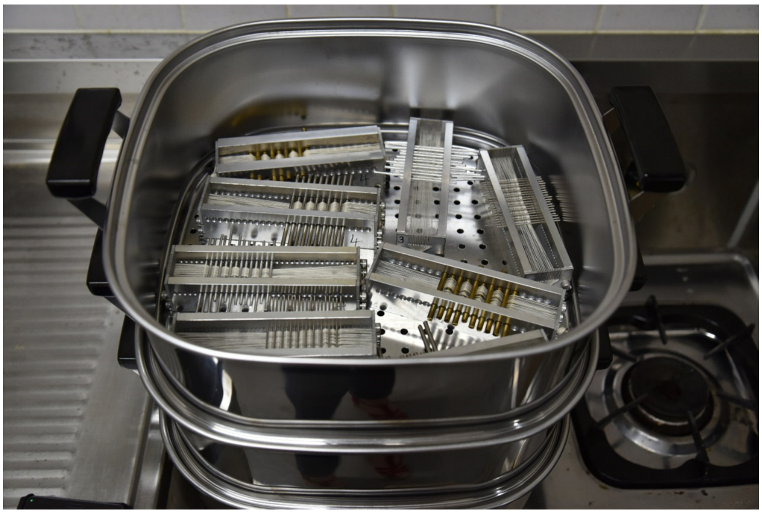


Figure 4.4: Steam processing of cotton samples

Table 4.1: Yarn specifications

Sample	Material	Structure	Yarn count (tex)	Twist (tpm)	Diameter d_f
FC	Fluorocarbon	Monofilament	45	-	0.165
Nylon	Polyamide 6.6		26		0.170
A	Combed cotton	Spun yarn	15	1234	0.156
B			20	1069	0.191
C			30	874	0.228
D			40	755	0.265

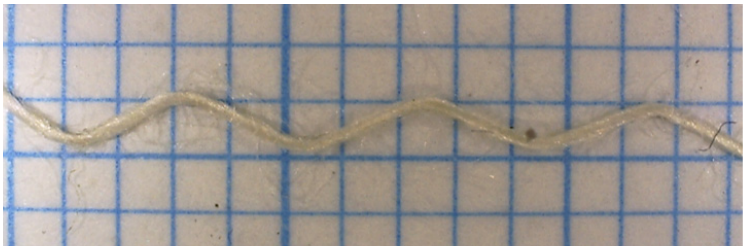


Figure 4.5: Crimp formation for sample D Ø1.2

4.3.2 Samples

Six types of yarn were used, as shown in Table 4.1. Nylon yarn (no.1, Toho Co., Ltd., Hiroshima, Japan) and fluorocarbon yarn (Basic FC, no. 1, Sunline Co., Ltd., Iwakuni, Japan) were used as monofilament yarns. The cotton yarn samples were made by ring spinning using the same combed cotton roving. The average diameter of cotton spun yarn was obtained using a digital micrometer (Keyence Corporation, LS7000, measurement accuracy $\pm$ 0.5µm) at an angle from 0° to 180° [18].

The yarn setting conditions are shown in Table 4.2. The suffix refers to the diameter of the rods. The crimp c was calculated using Equation 4.5, as defined by Pierce [11].

$$c = \frac{s}{\lambda} - 1 \tag{4.5}$$

4.3.3 Measurement of yarn torsional rigidity

To obtain the torsional rigidity, a Kawabata Evaluation System yarn torsional tester (KES)-YN1 (Kato Tech Co. Ltd., Kyoto, Japan) [16] was used. This device gives a measurement of the torque and the twist angle by measuring the resistance of the sample when rotating one extremity while the other is fixed. The movable part of the apparatus then makes a 6π rotation in one

Table 4.2: Crimped yarn geometry at setting (mm)

d_r	Samples	FC	Nylon	A	B	C	D
Ø1.2	$A_{1.2}$	1.28	1.29	1.3	1.31	1.31	1.33
	$\lambda_{1.2}$	5	5	5	5	5	5
	$s_{1.2}$	7.55	7.58	7.5	7.68	7.88	8.09
	$c_{1.2}$	0.51	0.52	0.5	0.54	0.58	0.62
Ø2	A_2	2.08	2.09	2.08	2.1	2.11	2.13
	λ_2	7	7	7	7	7	7
	s_2	11.53	11.56	11.48	11.69	11.92	12.16
	c_2	0.65	0.65	0.64	0.67	0.7	0.74
Ø3	A_3	3.08	3.09	3.08	3.1	3.11	3.13
	λ_3	9	9	9	9	9	9
	s_3	16.6	16.64	16.53	16.79	17.07	17.36
	c_3	0.84	0.85	0.84	0.87	0.9	0.93
Ø4	A_4	4.08	4.09	4.08	4.1	4.11	4.13
	λ_4	11	11	11	11	11	11
	s_4	21.88	21.92	21.81	22.1	22.42	22.75
	c_4	0.99	0.99	0.98	1.01	1.04	1.07

direction followed by a 12π rotation in the other, and returns to the original position while the device registers the torque and twist angle. Torsional rigidity is obtained from the mean of the two slopes between 2π and 4π in the forward rotation, and -2π and -4π in the backward rotation. The torsional rigidity W_{mes} is then calculated using sample length L (in this case, the distance between the clamps), as shown in Figures 4.6 and 4.7. The rotating speed was set at 12 degree/s. The forward torsional rigidity was used for this study. The torsional rigidity W_{mes} during forward rotation is given by Equation 4.6.

$$W_{\text{mes}} = \frac{T_{4\pi} - T_{2\pi}}{\frac{2\pi}{L}} \tag{4.6}$$

where, $T_{4\pi}$ and $T_{2\pi}$ are the torques at 2π and 4π, respectively.

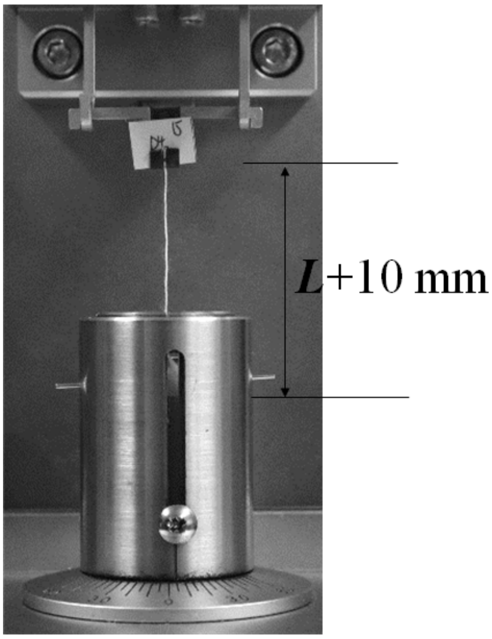


Figure 4.6: Sample D, crimp setting Ø2, testing method (a)

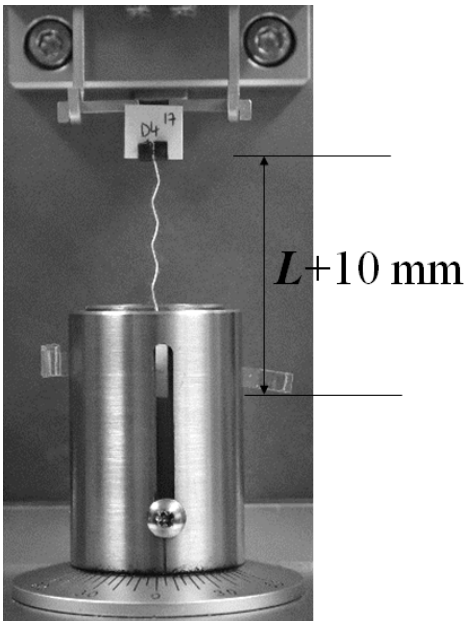


Figure 4.7: Sample D, crimp setting Ø2, testing method (b)

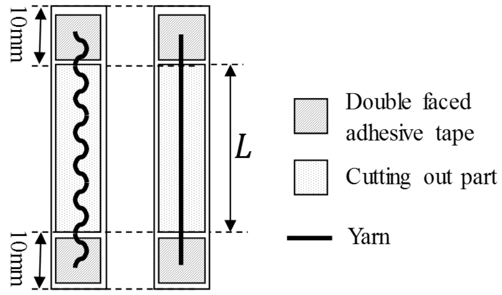


Figure 4.8: Sample layout with and without crimp, with L=30 mm

4.3.4 Sample preparation and testing conditions

Monofilament

The sample length was adapted for every crimp setting so that the test samples had a yarn length of 3 cm. Ten samples of each kind of yarn and each value of crimp, including no-crimp samples, were prepared and tested. The sample layout is shown in Figure 4.8. Figure 4.9 shows a set of finished samples.

During testing, the monofilament yarn was subjected to a weight of 5.342 g (clamp + 5-g weight) in addition to its own weight. Due to the weight, the sample length and the distance between the clamps changed. Therefore, the new length was measured for the calculation of rigidity. Samples without the 5-g weight were also tested, but the results were inconclusive due to uneven deformation as shown on Figure 4.10.

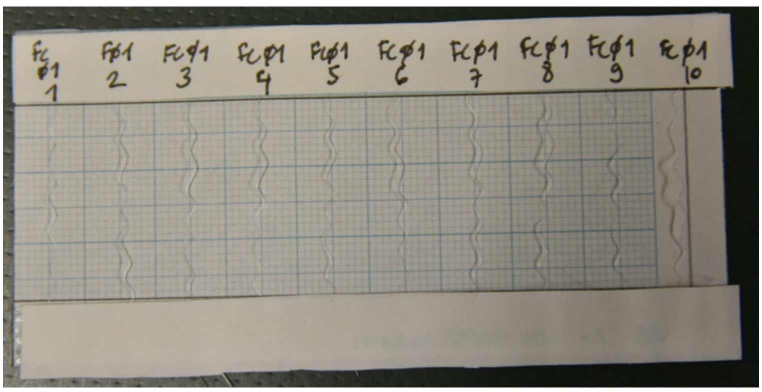
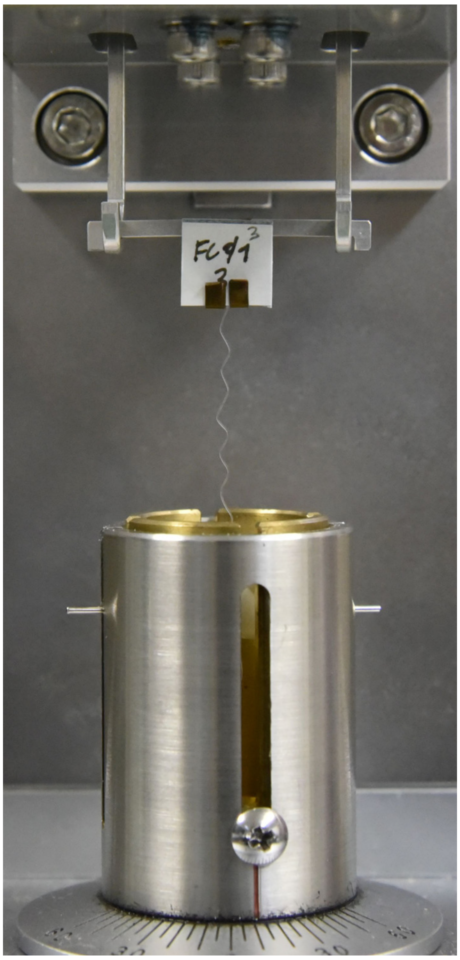


Figure 4.9: Set of finished samples (FC monofilament, Ø1.2)



(a) Before testing

(b) After testing

Figure 4.10: FC sample with crimp set at Ø1.2 tested without an additional 5-g weight

Cotton spun yarn

Cotton spun yarn samples were prepared and tested by the following two methods.

(a) As an initial load, a weight equivalent to 200 m of yarn was applied when making the sample according to the Japanese Industrial Standard (JIS) for testing fabrics (JIS L1096:2010) [19]. Then, after 24 h under standard conditions (at 20 ± 1°C and a relative humidity of 65 ± 5%), the yarn torsional rigidity was measured. Fifteen samples of each kind of yarn and each crimp setting (including the no-crimp setting) were prepared and tested. During testing, the cotton spun yarn samples were subjected to the weight of the clamp (0.342 g) in addition to their own weight. An example of a yarn being tested is shown in Figure 4.6.

(b) No weight was applied during sample production to maintain the crimp. For each crimp setting (including the no-crimp setting), 15 samples were produced. During testing, almost no weight was applied to the samples to preserve the crimp. To reduce the load and maintain the rotation of one end of the sample, a double-sided strip of adhesive tape was used instead of the clamp, as shown in Figure 4.7. The tape weight was approximately 0.07 g. When put in place, the sample hung down freely under its own weight and that of the tape. When rotating, the adhesive part of the tape maintained the sample in position.

During measurement, a picture was taken of each sample to measure the wavelength λ and the length L from the clamp to the end. L was used to calculate the torsional rigidity of the crimped yarns. S was measured after testing by applying a weight to straighten the sample. L, λ, and S were used to calculate the amplitude A, the length s of the yarn for one period λ, and the crimp ratio c.

4.4 Results and Discussions

4.4.1 Geometrical parameters in testing

Table 4.3 shows the geometrical parameters of the samples during measurement using testing methods (a) and (b), measured from the pictures. The crimp ratio during testing was smaller than that at setting because λ increased.
For testing method (a), as the yarn was straightened, λ reached a maximum equal to s, and consequently A and c were equal to zero. For testing method (b), A,λ, s, and c decreased due to the weight, but the crimp shapes were still apparent.

4.4.2 Typical torque curves for monofilament yarn and cotton spun yarn

Figure 4.11 shows an example of a typical torque curve for monofilament yarn. Because FC and Nylon monofilaments are homogeneous materials, the samples produced the same response in both the forward and backward direction, giving a symmetrical curve. For the FC monofilaments, the crimp setting decreased the torsional rigidity of the samples compared with the straight samples. For the Nylon monofilaments, the opposite was true: the torsional rigidity of the straight yarn was lower than that of the crimped yarn.

Table 4.3: Crimped yarn geometry during measurements (in mm)

d_r	Samples	FC	Nylon	A-a	B-a	C-a	D-a	A-b	B-b	C-b	D-b
Ø1.2	$A_{1.2}$	1.24	1.26	0	0	0	0	1.24	1.26	1.25	1.26
	$\lambda_{1.2}$	5.55	5.49	7.5	7.68	7.88	8.09	5.29	5.38	5.31	5.23
	$s_{1.2}$	7.41	7.44	7.5	7.68	7.88	8.09	7.26	7.39	7.37	7.38
	$c_{1.2}$	0.33	0.35	0	0	0	0	0.37	0.37	0.39	0.41
Ø2	A_2	2.01	2.08	0	0	0	0	2	2.06	2.07	2.02
	λ_2	8.02	7.46	11.48	11.69	11.92	12.16	7.51	7.52	7.54	7.46
	s_2	11.36	11.34	11.48	11.69	11.92	12.16	11.04	11.33	11.39	11.24
	c_2	0.42	0.52	0	0	0	0	0.47	0.51	0.51	0.51
Ø3	A_3	3.01	3.04	0	0	0	0	2.96	3.03	3.13	2.9
	λ_3	11.13	11.07	16.53	16.79	17.07	17.36	10.53	10.2	10.34	10.13
	s_3	16.45	16.54	16.53	16.79	17.07	17.36	16	16.17	16.72	15.74
	c_3	0.48	0.49	0	0	0	0	0.52	0.59	0.62	0.55
Ø4	A_4	3.98	3.95	0	0	0	0	3.99	4.1	3.93	3.98
	λ_4	14.1	14.23	21.81	22.1	22.42	22.75	13.78	12.89	12.15	12.79
	s_4	21.4	21.36	21.81	22.1	22.42	22.75	21.33	21.55	20.71	21.13
	c_4	0.52	0.5	0	0	0	0	0.55	0.67	0.7	0.65

Figure 4.12 shows an example of a typical torque curve for the cotton spun yarn. The torsional rigidity and hysteresis in the forward direction were larger than in the backward direction. This was due to the twisted structure of the cotton spun yarn. For the cotton spun yarn, the torsional rigidity of the yarn without crimp was larger than that of the crimped yarn. Furthermore, the results of applying a weight during testing (method a) showed a similar torsional rigidity for the yarns preserving crimp (method b).

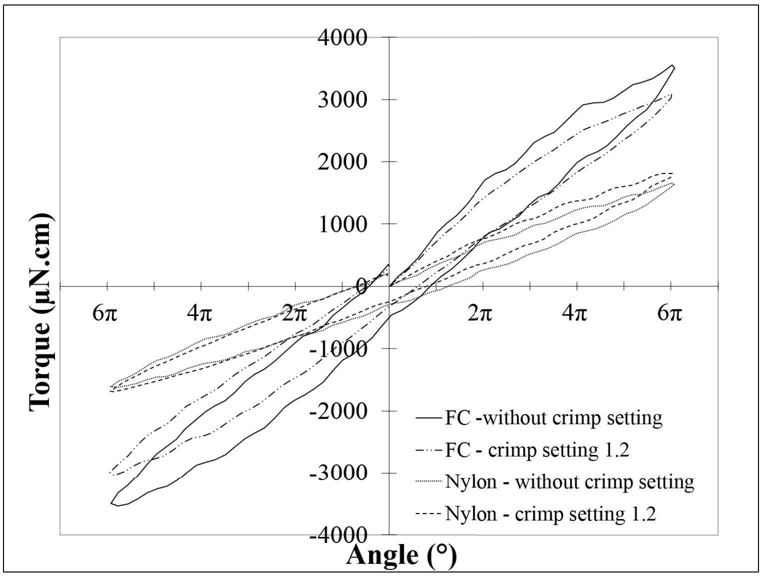


Figure 4.11: Example of a torque curve for monofilament yarn (FC and Nylon) with and without crimp setting

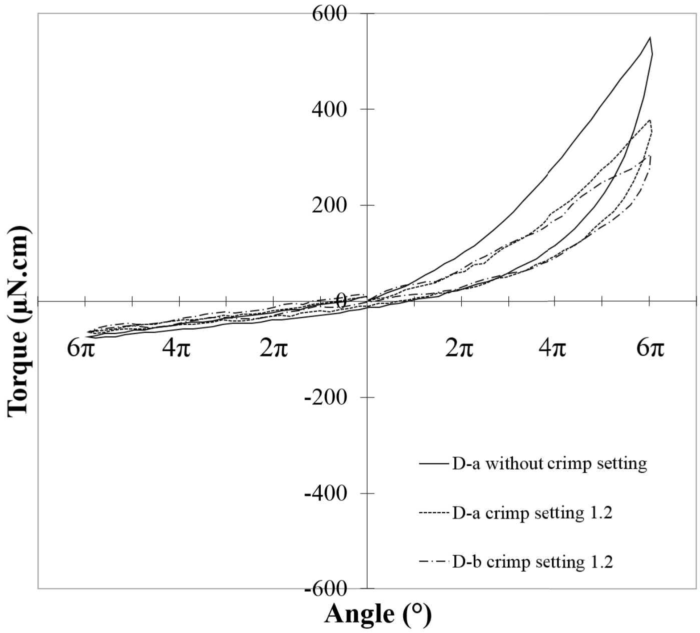


Figure 4.12: Example of a torque curve for cotton spun yarn (D) without crimp setting, and with crimp setting using testing methods (a) and (b)

4.4.3 Relationship between torsional rigidity and crimp setting of monofilament yarns

Figure 4.13 shows the torsional rigidities of FC and Nylon monofilament yarns for each crimp setting. The torsional rigidity of the FC monofilaments decreased as the crimp setting increased. The Nylon monofilament torsional rigidity, in contrast, did not show any variation with the different crimp settings. According to Equation 4.4, the torsional rigidity ratio $\frac{W}{W_2}$ increase or decrease with crimp depend on $\frac{W}{B}$[17]. $\frac{W}{B}$ depends on Poisson ratio in the case of isotropic materials. The difference is caused by their different Poisson's ratio. For the monofilament yarns, few tests were necessary because the results were very consistent and had a very low standard deviation.

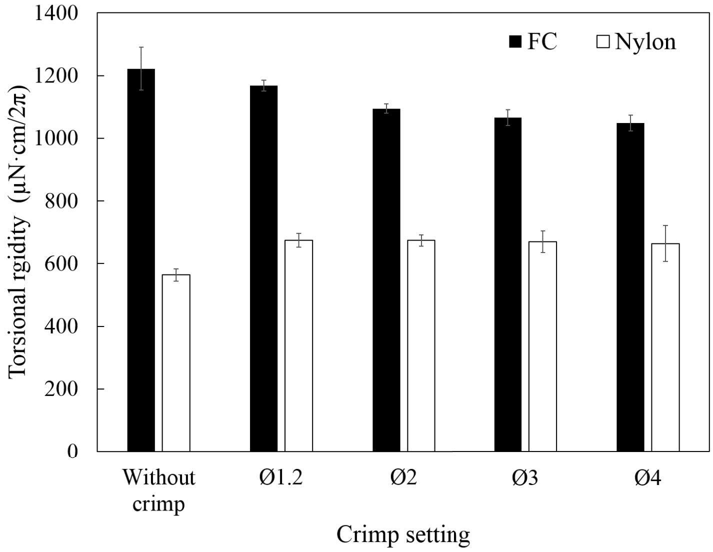


Figure 4.13: Torsional rigidity of FC and Nylon monofilament yarns for each yarn setting

4.4.4 Relationship between torsional rigidity and crimp setting of cotton yarn

Effect of the crimp setting Figures 4.14 to 4.17 show the torsional rigidity of the cotton spun yarn samples (A to D) for each crimp setting. For all samples, the torsional rigidities of the yarns without crimp were greater than those with crimp. For the samples with crimp settings, the smaller the crimp, the lower the crimp rigidity. There was generally a small difference between samples with (a) and without (b) the application of a weight during crimp setting, and both testing methods showed almost similar torsional rigidities.

This means that the torsional rigidity of the crimped yarn was the same whether or not it had been straightened at the time of the test. This could have been due to the fibers being bent when the crimp was set on the yarn, and staying bent even when the yarn was straightened.

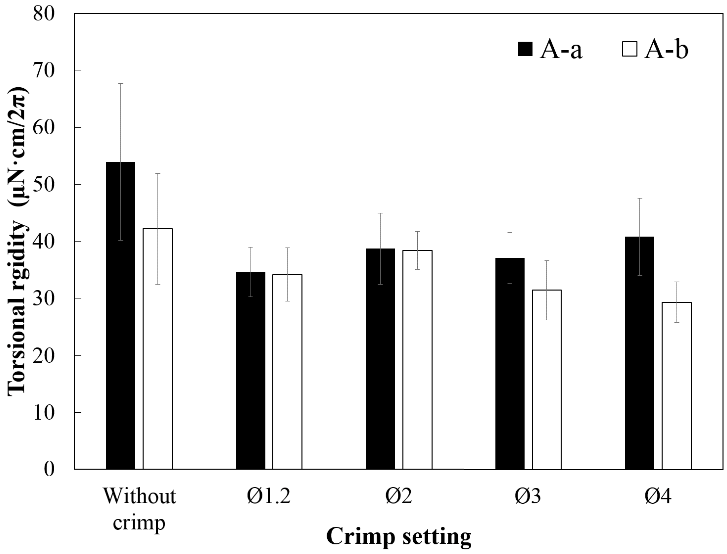


Figure 4.14: Torsional rigidities of A with (A-a) and without (A-b) weight

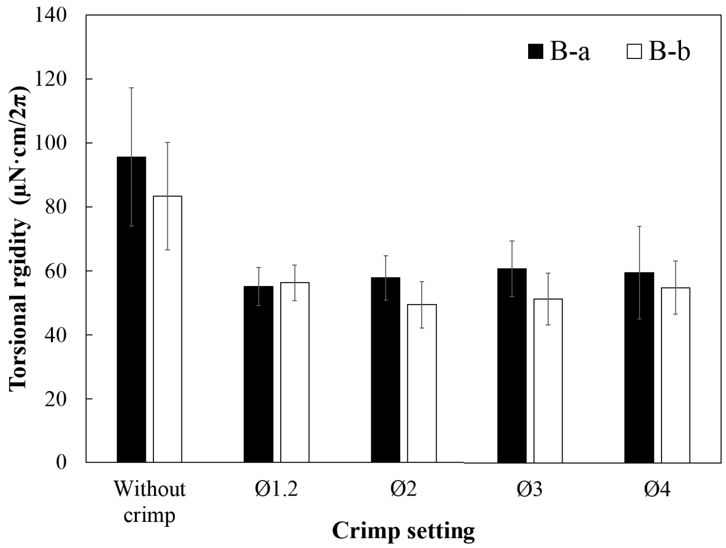


Figure 4.15: Torsional rigidities of B with (B-a) and without (B-b) weight

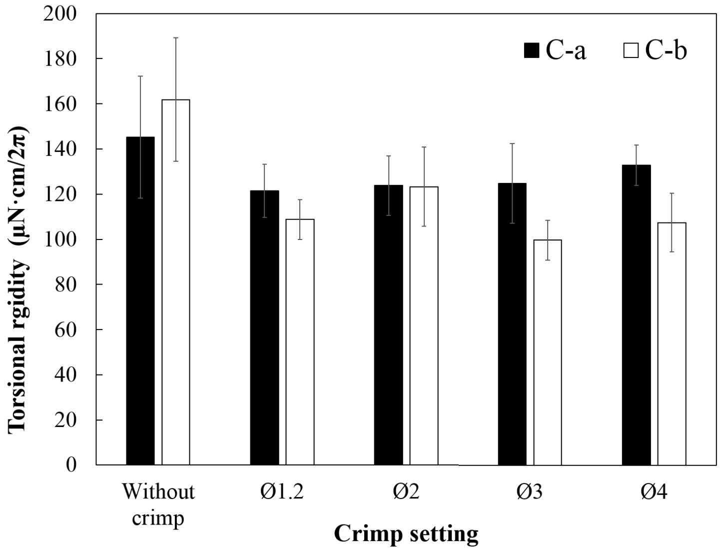


Figure 4.16: Torsional rigidities of C with (C-a) and without (C-b) weight

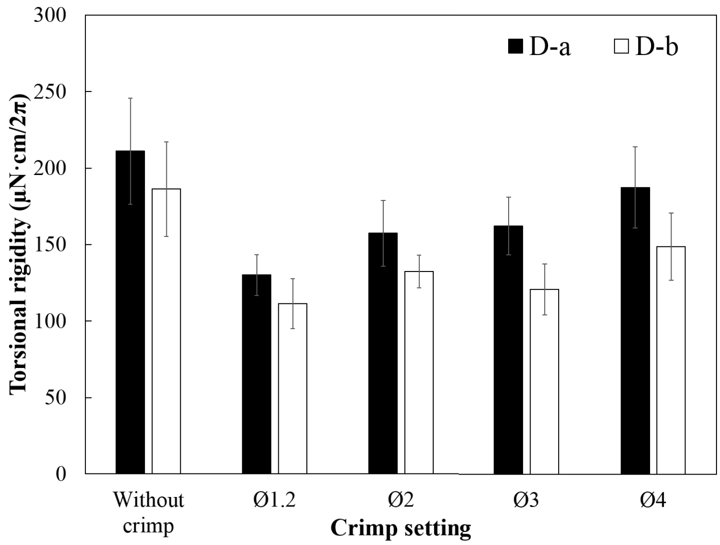


Figure 4.17: Torsional rigidities of D with (D-a) and without (D-b) weight

Effect of the yarn count Figures 4.18 and 4.19 show the results for all samples (A to D) for testing methods (a) and (b). As expected, the smaller the yarn count, the smaller the yarn torsional rigidity. Therefore, it was found that the effect of crimp on torsional rigidity differed according to the yarn count.

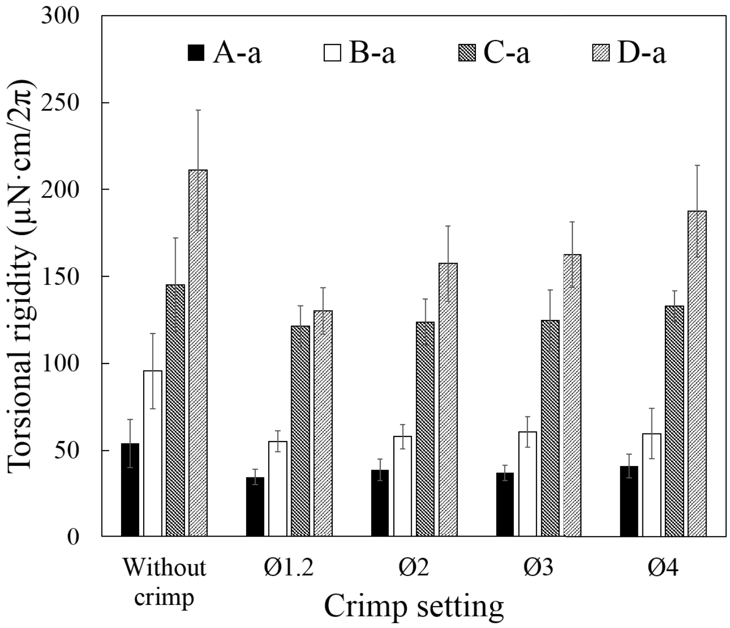


Figure 4.18: Torsional rigidity for samples A to D for testing method (a) (with weight)

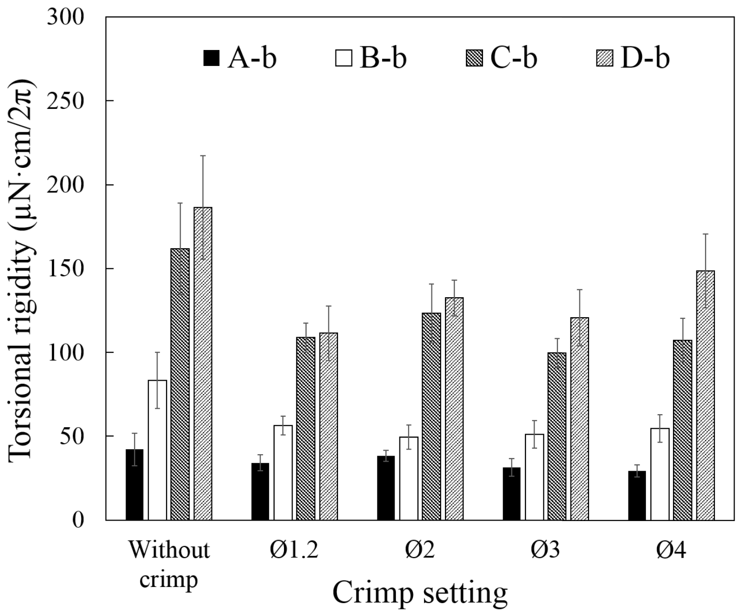


Figure 4.19: Torsional rigidity for samples A to D for testing method (b) (without weight)

4.4.5 Relationship between the torsional rigidity ratio and the crimp ratio

Figure 4.20 shows the relationship between the torsional rigidity ratio $\frac{W}{W_2}$ (where W is the torsional rigidity of the yarn without crimp and W_2 is the torsional rigidity of the crimped yarn) and the crimp ratio c (Equation 4.5). The torsional rigidity ratio $\frac{W}{W_2}$ was defined by Skelton [17] for circular crimp as:

$$\frac{W}{W_2} = (1+c)\left[\frac{1}{2} + \frac{\sin 2\phi_0}{4\phi_0} + \frac{W}{B}\left(\frac{1}{2} - \frac{\sin 2\phi_0}{4\phi_0}\right)\right] \tag{4.7}$$

For the monofilament yarns, $\frac{W}{W_2}$ had an almost linear relationship with the crimp ratio. The W_2 of the FC monofilament was smaller than W, and $\frac{W}{W_2}$ increased with the crimp ratio. Conversely, the W_2 of the Nylon monofilament was larger than the W, and $\frac{W}{W_2}$ decreased slightly in the tested crimp range. This could have been due to the bending rigidity B, as shown in Equation 4.7. Figure 4.21 shows the bending rigidities of FC and nylon monofilament measured without crimp. The FC monofilament yarns bending rigidity is higher than its torsional rigidity. The results for the cotton spun yarns showed the large effect of the crimp. The W_2 values for the cotton spun yarns were smaller than the W values. According to Equation 4.7, the torsional rigidity ratio and the crimp ratio didn't present a monotonic increase for smaller $\frac{W}{B}$ [17]. The results in Figure 4.20 include this phenomenon. However, no linear clear relationship was observed due to the high variance in the torsional rigidity results, as shown in Figures 4.14 to 4.17. However, it can be noted that the torsional rigidity ratio of cotton spun yarn samples were higher than the ones of monofilaments.

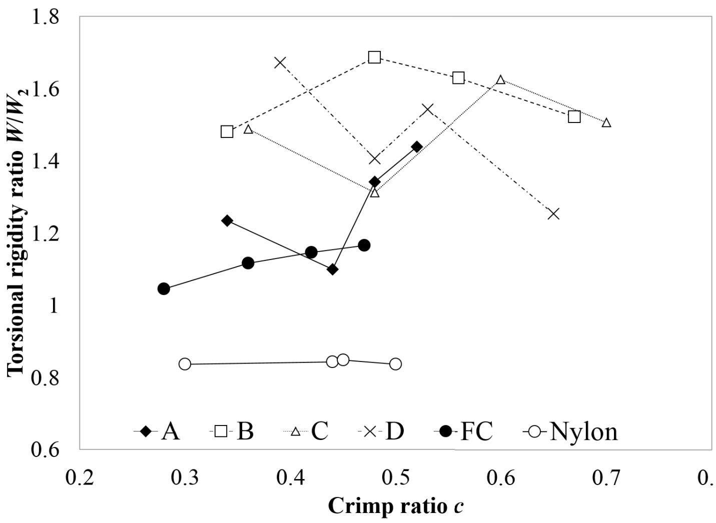


Figure 4.20: Relationship between torsional rigidity ratio and crimp ratio

Table 4.4: Crimp ratio for samples A2 to E2

	A2	B2	C2	D2	E2
Warp crimp ratio	0.218	0.156	0.169	0.124	0.117
Weft crimp ratio	0.127	0.147	0.165	0.167	0.185

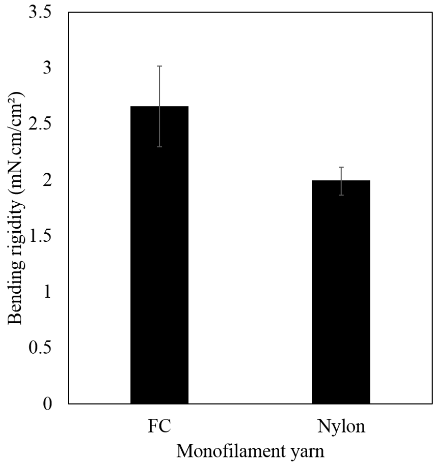


Figure 4.21: Bending rigidity of FC and nylon straight yarns

4.5 Estimation of fabric bending rigidity using torsional rigidity from crimped yarn

As shown in Chapter 3, using torsional rigidity of yarn from the bobbin can give a large error when estimating the fabric bending rigidity, and crimped yarn torsional rigidity should be used. Considering the torsional rigidity of a yarn with a crimp c_1 noted Γ_{c_1}, and the torsional rigidity of the same yarn but with a crimp c_2 noted Γ_{c_2}, Γ_{c_1} and Γ_{c_2} should be proportional.
Therefore, the torsional rigidity for the crimp ratio in warp and weft direction was calculated for fabric A2 to E2. The yarn used to weave samples A2 to E2 was the same than the one used in this Chapter for samples B-a and B-b. Therefore, the torsional rigidity from the crimped yarn torsional rigidity for sample B with crimp set as Ø1.2. Then, using a simple cross-multiplication between the crimp ratio (table 4.4) and the torsional rigidity, the torsional rigidity was calculated for each samples A2 to E2. The results are shown in table 4.5. Then using Cooper and Shinohara et al equation, the fabric bending rigidity of samples A2 to E2 was estimated.

Figures 4.22 to 4.26 shows the obtained results. Those results were also compared with yarn torsional rigidity extracted from the fabric in warp and weft direction.

Table 4.5: Estimated yarn torsional rigidity for samples A2 to E2 (μN.cm/cm^2)

	A2	B2	C2	D2	E2
Warp crimp	0.218	0.156	0.169	0.124	0.117
Weft crimp ratio	0.127	0.147	0.165	0.167	0.185

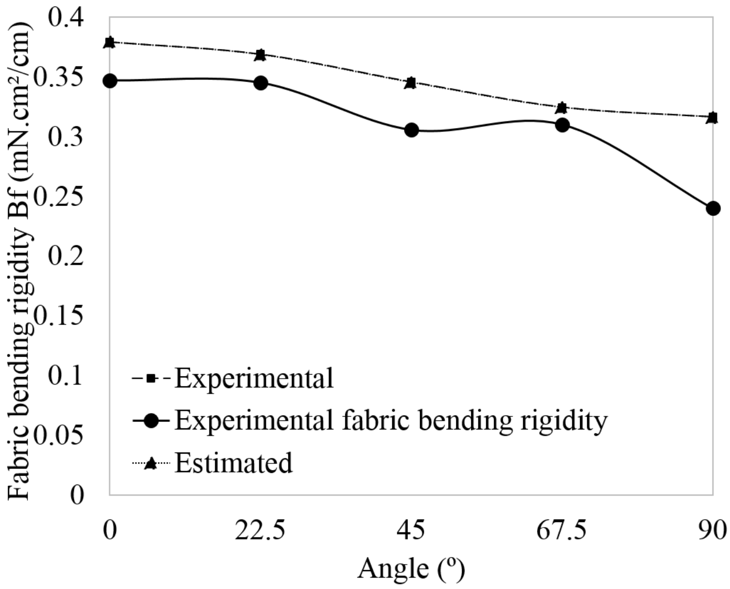


Figure 4.22: Bending rigidity of sample A2

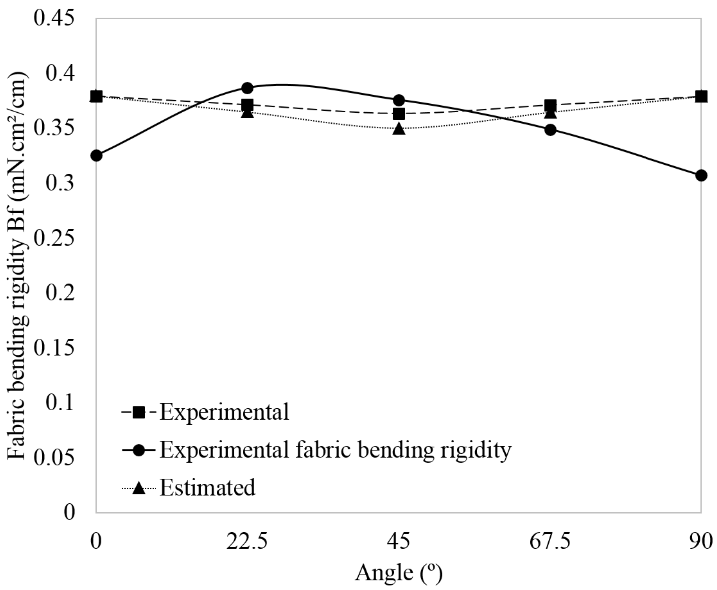


Figure 4.23: Bending rigidity of sample B2

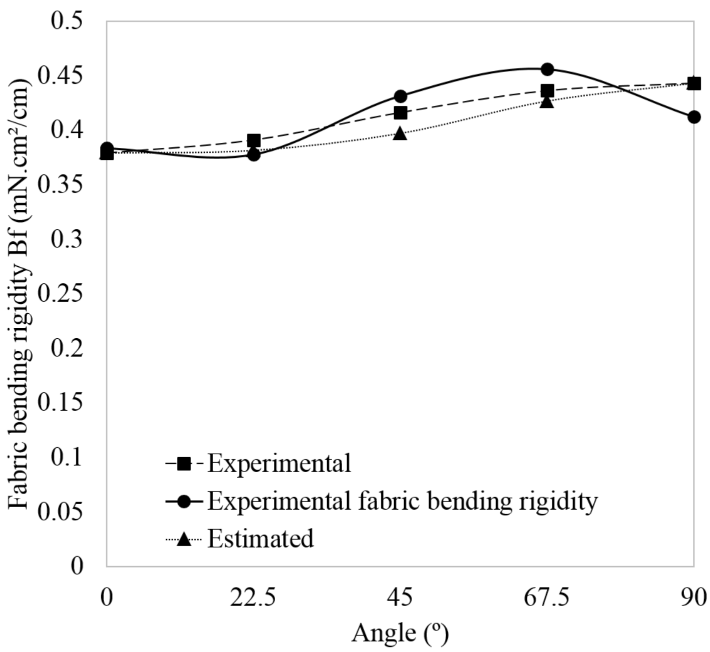


Figure 4.24: Bending rigidity of sample C2

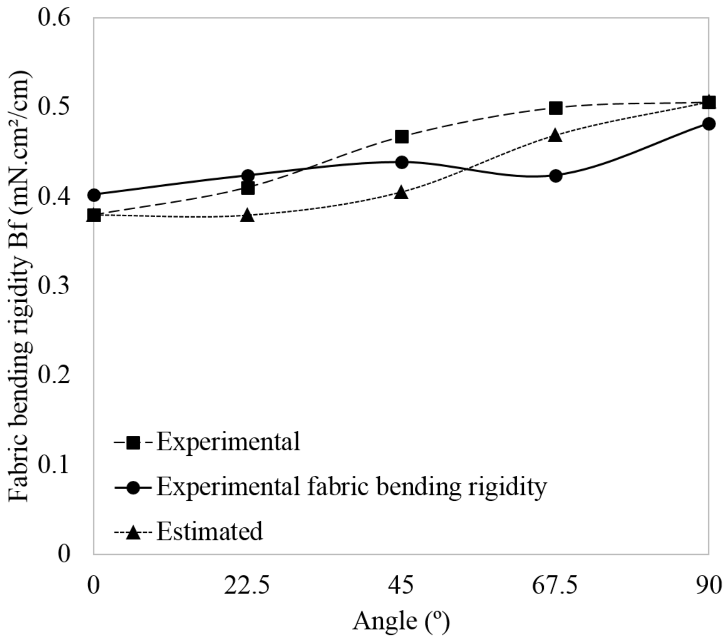


Figure 4.25: Bending rigidity of sample D2

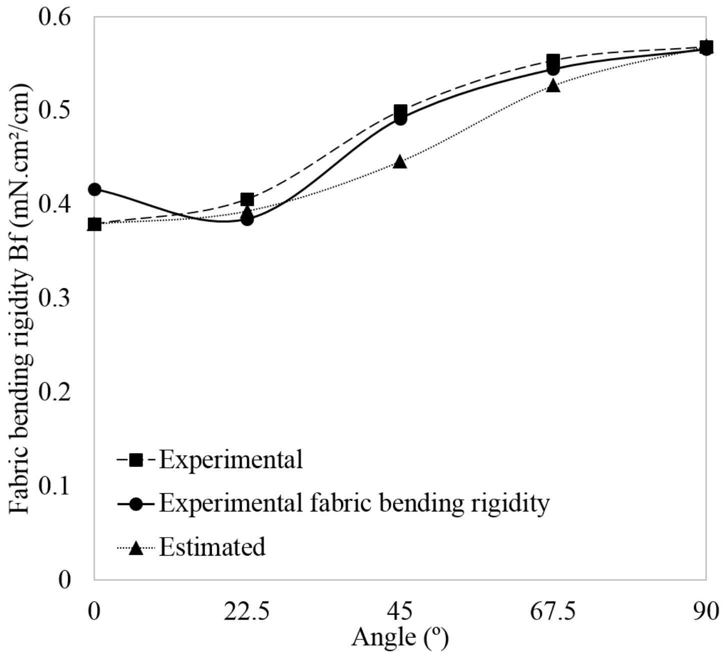


Figure 4.26: Bending rigidity of sample E2

As expected, the calculated values from the experimental yarn bending rigidities extracted from the fabric were close to the experimental values. When using the estimated fabric bending rigidity from the artificially crimped yarn, the results showed agreement as good as the experimental values, Therefore the mechanism were understood and the crimp is intrinsically included in Cooper and Shinohara et al. model.

4.6 Conclusion

In this study, the effect of crimp on the torsional rigidity of monofilament yarns and cotton spun yarns was investigated. Crimped monofilaments and spun yarns with various amplitudes and wavelengths were produced using original crimp setting equipment. The torque–twist curves of the straight and crimped yarns were measured using a torsional tester, and their torsional rigidities were obtained.

The results showed that the torsional rigidities of all the straight yarns except the nylon monofilament were higher than those of the crimped yarns. For the cotton spun yarn, the torsional rigidity of crimped yarn was smaller than the one of the straight yarn. The variation of torsional rigidity in between samples with the same yarn count for different crimp setting wasn't however significant. As expected, the smaller the yarn count, the smaller the torsional rigidity. It was also noted that straightening after crimp setting made almost no difference to the torsional rigidity of the crimped yarn. Therefore, there is a possibility that the property changes in the yarn were due to the fiber being bent during crimp setting, and were not due to the shape of the crimp afterwards.

After calculating the ratio between torsional rigidity of straight and crimped yarn, the relationship between the torsional rigidity ratio and the crimp ratio was studied. The monofilament results showed nearly linear relationships between the torsional rigidity ratio and the crimp ratio. On the other hand, the torsional rigidity ratio for cotton spun yarn did not show a clear relationship with the crimp ratio due to a higher variance in the testing results. However, it can be noted that the torsional rigidity ratio of cotton spun yarn samples were higher than the ones of monofilaments. This study demonstrated the effect of crimp on the torsional rigidity of yarn, which had not been clarified experimentally until now.

It was also shown that the torsional rigidity of artificially crimped yarn could be used to estimate the fabric bending rigidity of a fabric in any direction.

4.7 References

[1] S. Inui, H. Okabe, M. Takatera, M. Hashimoto, and Y. Horiba, "A fabric simulation based on a model constructed from a lower level," in *Computational Engineering in Systems Applications, IMACS Multiconference on*, vol. 1. IEEE, 2006, pp. 178–180.

[2] S. Inui, Y. Mesuda, Y. Horiba, and M. Kurihara, "Fabric weave form simulation based on the characteristics of yarn," in *Biometrics and Kansei Engineering (ICBAKE), 2011 International Conference on*. IEEE, 2011, pp. 49–52.

[3] S. Kawabata, M. Niwa, and H. Kawai, "3—the finite-deformation theory of plain-weave fabrics part i: The biaxial-deformation theory," *Journal of the Textile Institute*, vol. 64, no. 1, pp. 21–46, 1973.

[4] D. Cooper, "24—the stiffness of woven textiles," *Journal of the Textile Institute Transactions*, vol. 51, no. 8, pp. T317–T335, 1960.

[5] M. M. Platt, W. G. Klein, and W. J. Hamburger, "Mechanics of elastic performance of textile materials part xiii: torque development in yarn systems: singles yarn," *Textile Research Journal*, vol. 28, no. 1, pp. 1–14, 1958.

[6] R. Brand and S. Backer, “Mechanical principles of natural crimp of fiber,” *Textile Research Journal*, vol. 32, no. 1, pp. 39–49, 1962.

[7] J. Menkart and J. C. Detenbeck, “The significance of wool fiber crimp part i: A study on the worsted system,” *Textile Research Journal*, vol. 27, no. 9, pp. 665–689, 1957.

[8] M. Horio and T. Kondo, “Crimping of wool fibers,” *Textile Research Journal*, vol. 23, no. 6, pp. 373–386, 1953.

[9] R. Meredith, “30—the torsional rigidity of textile fibres,” *Journal of the Textile Institute Transactions*, vol. 45, no. 7, pp. T489–T503, 1954.

[10] R. Brand and R. Scruby, “Three-dimensional geometry of crimp,” *Textile Research Journal*, vol. 43, no. 9, pp. 544–555, 1973.

[11] F. Peirce, “26—the “handle” of cloth as a measurable quantity,” *Journal of the Textile Institute Transactions*, vol. 21, no. 9, pp. T377–T416, 1930.

[12] B. Olofsson, “49—a general model of a fabric as a geometric mechanical structure,” *Journal of the Textile Institute Transactions*, vol. 55, no. 11, pp. T541–T557, 1964.

[13] R. Dhingra and R. Postle, “19—the measurement of torque in continuous-filament yarn. part ii: The effect of yarn tension,” *Journal of the Textile Institute*, vol. 65, no. 4, pp. 171–181, 1974.

[14] R. Postle, P. Burton, and M. Chaikin, “41—the torque in twisted singles yarns,” *Journal of the Textile Institute Transactions*, vol. 55, no. 9, pp. T448–T461, 1964.

[15] F. Shinohara, A. Shinohara, and K. Sakaebara, “A theoretical study on the anisotropy of the bending rigidity of woven fabrics,” *J Textil Mach Soc Jpn*, vol. 32, no. 8, pp. T66–T71, 1979.

[16] J. Peiffer, K. Kim, and M. Takatera, “Verification of the effect of yarn torsional rigidity on fabric bending rigidity in any direction,” *Textile Research Journal*, p. 0040517516631321, 2016.

[17] J. Skelton, “38—the effect of planar crimp in the measurement of the mechanical properties of fibres, filaments, and yarns,” *Journal of the Textile Institute*, vol. 58, no. 11, pp. 533–556, 1967.

[18] M. Takatera, T. Arichi, J. Peiffer, C. Zhu, and K. Kim, "Continuous measurement of apparent poisson's ratio for yarn based on omni-directional diameters," *Textile Research Journal*, p. 0040517516639817, 2016.

[19] J. S. Association, *JIS: Japanese Industrial Standards - Handbook 54 Sen'i*. Japanese Standards Association, 2010.

Chapter 5 : Conclusion

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Today, it has become more than necessary to be able to predict the characteristics of textile in order to optimize the design and production of textile and decrease the costs by classifying the textile and garment. Previous studies have shown links between the yarn properties and the fabric properties based on the fabric layout and the properties of yarns used for. Moreover, the yarn and fabrics mechanics are old subject of studies and are quite well known. In fabric simulation, the bending properties of fabric are important because they have an effect on the hand value and draping behavior. Therefore, the bending of fabric must be considered when designing products. The hand value has also been the subject of numerous studies to predict it, including studies about prediction of the hand from the weaving parameters. The hand and draping properties are directly linked to the bending properties of the fabric and yarn. If we could predict fabric's bending properties using only the yarn's bending properties, we could appropriately select yarn according to the fabric's intended use.

In the first part of this study, the effect of yarn torsional rigidity on the Cooper model for fabric bending rigidities in any direction was verified. Five commercial fabrics were first used as experimental samples. Then, an additional five cotton fabrics with different weft densities were woven. The torsional rigidities of yarn from the bobbin and yarn directly extracted from the fabric were measured with a yarn torsional tester. The bending rigidity of yarn from the bobbin was measured using the same pure bending tester used for fabric bending testing. The fabric bending rigidity calculated using torsional rigidities of yarns extracted from the fabric showed better agreement with the experimental values than that calculated using the torsional rigidity of yarn from the bobbin. Measurements showed that the torsional rigidity of yarn from the bobbin was appreciably higher than torsional rigidities of yarns from fabric. This could be due to the crimp of yarn. The results show that the torsional rigidity of yarn is affected by the weaving process and does not remain the same as that of yarn on the bobbin. It was thus found that, in predicting the bending rigidity of fabric using the Cooper model, measured torsional rigidities of yarns extracted from fabric should be used instead of yarn straight from the bobbin. The same results were obtained for the commercial fabrics. These results will be useful for fabric simulation.

In Chapter 4, the effect of crimp on the torsional rigidity of monofilament yarns and cotton spun yarns was investigated. Crimped monofilaments and spun yarns with various amplitudes and wavelengths were produced using original crimp setting equipment. The torque–twist curves of the straight and crimped yarns were measured using a torsional tester, and their torsional rigidities were obtained. The results showed that the torsional rigidities of all the straight yarns except the Nylon monofilament were higher than those of the crimped yarns. The monofilament results showed nearly linear relationships between the torsional rigidity ratio and the crimp ratio. For the cotton spun yarn, the crimped yarn torsional rigidity was smaller than that of the straight yarn. However, the torsional rigidity ratio did not show a linear relationship with the crimp ratio due to a higher variance in the testing results than for the monofilaments. Straightening after crimp setting made almost no difference to the torsional rigidity of the crimped yarn. Therefore, there is a possibility that the property changes in the yarn were due to the fiber being bent during crimp setting, and were not due to the shape of the crimp afterwards. This study demonstrated the effect of crimp on the torsional rigidity of yarn, which had not been clarified until now. It was also shown that the torsional rigidity of artificially crimped yarn could be used to estimate the fabric bending rigidity of a fabric in any direction. It was also shown that the torsional rigidity of artificially crimped yarn could be used to estimate the fabric bending rigidity of a fabric in any direction. Since all the tests and simulation have been made under small deformation, those results are suitable to apply to apparel simulation.

In future studies, it could be interesting to develop a model for crimp behavior not based on the circular crimp but rather on a sinusoidal behavior, closer to the actual crimp shape observed.

Published papers

This dissertation is based on the following papers:

1. Julie Peiffer, KyoungOk Kim, and Masayuki Takatera. Verification of the effect of yarn torsional rigidity on fabric bending rigidity in any direction, *Textile Research Journal*, 0040517516631321, first published on February 15, 2016.
2. Julie Peiffer, KyoungOk Kim, Hiroaki Yoshida, and Masayuki Takatera. Measurement of torsional rigidity of yarns with different crimps, *Textile Research Journal*, 0040517516685283, first published on December 23, 2016.

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