Doctoral Dissertation (Shinshu University)

Study on prediction for bending rigidity of laminated fabrics

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Introduction

Chapter 1 Introduction

1.1 Use of adhesive interlining

Fabrics for garments need appropriate mechanical properties for a suitable appearance and stability. However, a face fabric does not always have such a property alone because it is selected by other properties such as the appearance, texture and hand etc. An interlining is used to make up the necessary mechanical properties. In the traditional garment manufacturing process, an interlining is an important subsidiary material for stabile and aesthetic shaping of a garment. Interlining is a layer of fabric inserted between the face fabric and the lining in the part of a garment in which rigidity is needed. An interlining can be put on the reverse side of a face fabric and special and practiced skills are necessary. As developing polymer chemistry technique, adhesive interlinings come onto the market. Adhesive interlinings are made by imparting thermoplastic synthetic resin as shown in Figure 1.1. They adhere to a face fabric before sewing each garment parts. Press machine and iron are usually used. They can be adhered to the face fabric by heating under the conditions of temperature, pressure and time according to the property of adhesives used [1, 2].

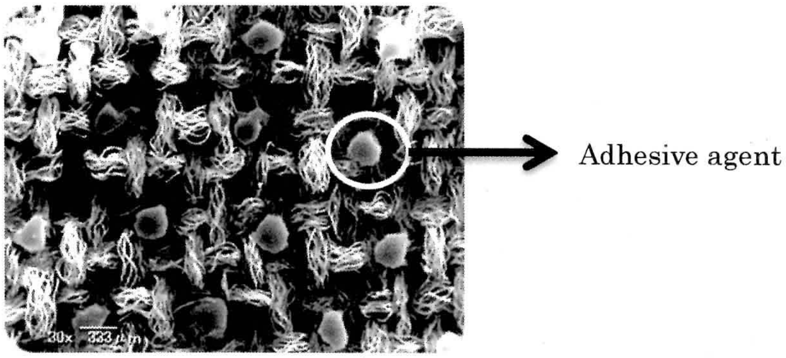


Figure 1.1 SEM picture of surface of adhesive interlining.

Formerly, in the garment manufacturing process, an interlining setting was an important work requiring skill and experience but the adhesive interlinings has enabled us to obtain uniform fused interlinings in a short time, without the necessity of skill. The main purposes of using interlinings are roughly classified as shape stability and aesthetic shaping. Adhesive interlinings play an important role for beautiful silhouette and excellent shape-retentivity to clothing. In manufacturing a garment, interlinings are used for several important parts of a garment. General parts for adhesive interlining in patterns of a tailored jacket are shown in Figure 1.2. The effect of adhesive interlining on a garment, especially in the case of a jacket, was clearly shown in Figure 1.3.

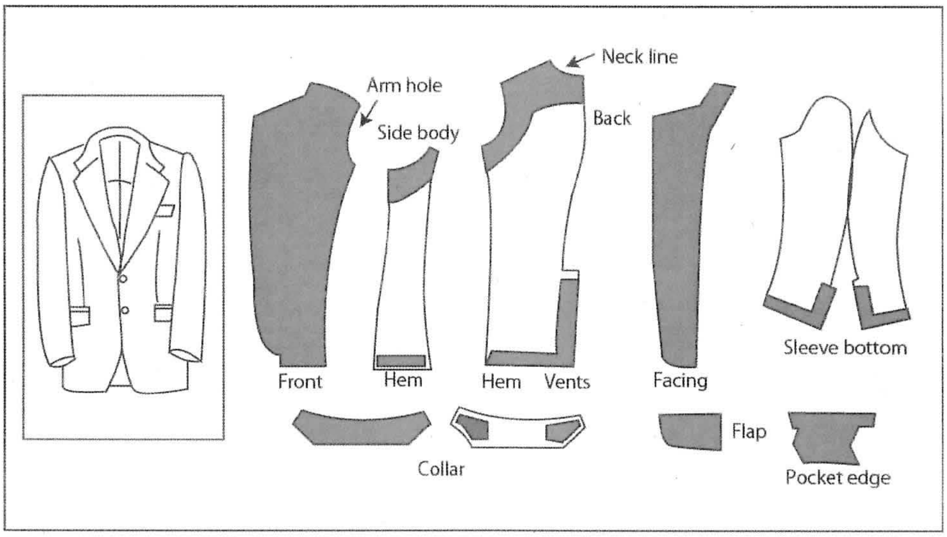


Figure 1.2 Parts adhesive interlinings used in a jacket. [1]

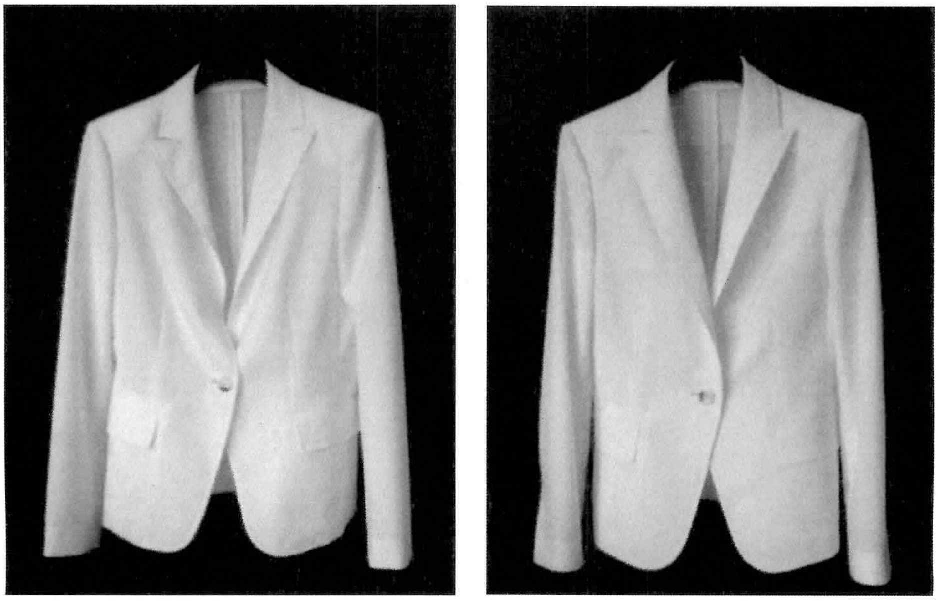

(a) (b)

Figure 1.3 Changes of jacket appearance depending on use of adhesive interlining: (a) Jacket without adhesive interlining, (b) Jacket with adhesive interlining.

1.2 Kinds and classifications of adhesive interlinings

An adhesive interlining made up of two parts, a base cloth and adhesive agent. The material and characteristic are different depending on the garment kinds and those properties.

1.2.1 Base cloths of adhesive interlining [1, 2]

Table 1.1 shows base cloths mainly used for adhesive interlinings. Count of yarn and weave density are selected according to thickness, toughness and hand required for adhesive interlinings. The base cloths of adhesive interlinings are mostly plain weave but according to use, warp count, weft count, density and design are changed so as to obtain the required hand. Wool and hair, and linen have long been used as material of interlining but their importance has diminished with the spread of fusing and synthetic fiber and now they are used only little as material of adhesive interlinings. Knitted interlinings began to display its characteristic as material of interlinings. Non-woven interlinings are available but adhesive type was developed for exclusive use of clothing.

Table 1.1 Kinds of base cloths for adhesive interlining [1]

	Fiber content	Construction
Woven fabrics	Cotton, polyester, poly-nosic, rayon and blended yarn thereof	Plain weave (including basket weave), satin weave, twill weave and fancy weave thereof
Knitted fabrics	Cotton, polyester, nylon, acrylic, acetate, rayon (including blended yarn)	Tricot, weft inserted warp knitting (tricot, raschel)
Non-woven fabrics	Polyester, rayon, nylon	Random, parallel, cross punched

1.2.2 Kinds of adhesives [1, 2]

Various kinds of adhesives are in use. Adhesives now in use for adhesive interlinings are as given below, from which an appropriate one should be selected that has the adhesive characteristic for the intended use of interlinings.

1) Polyamides

Polyamides are made by copolymerization of three or more kinds of monomers. According to their composition, adhesives have different properties, for example, different adhesive temperature. After fusing, this adhesive provides "soft" hand, strong bond strength and high dry cleaning-resistance. It is character of polyamides resin that it increases its adhesion force when steam is used for fusing. In the case of face cloth to which adhesion force is difficult to reach enough strength, use of steam is effective.

2)Polyvinyl chlorides (P.V.C.)

Different from other resins which have adhesiveness in themselves, PVC is imparted with adhesion force only when it is added by a plasticizer (softening agent). This adhesive displays many features owing to the function of the plasticizer. Resins themselves are soft. They can be colored easily. Striking through of adhesives rarely takes place at after-treatments stage, such as finishing press, etc. They have high durability with dry cleaning and washing in water.

3) Polyethylene

This group consists of two kinds, namely, low density polyethylene and high density polyethylene. Low density polyethylene is durable to washing in water, but in dry cleaning it dissolves away. High density polyethylene is highly durable to both washings in water and dry cleaning. It is free from striking through at after treatment but requires a high temperature and a high pressure for fusing and therefore is limited in use.

4) Ethylene vinyl acetate co-polymers (EVA)

This adhesive is made by copolymerization of ethylene and vinyl acetate and is abbreviated as EVA is durable washing in water but is weak to dry cleaning and therefore has been used for temporary fusing. However, modified EVA, having durability to solvent has been developed. This chemically modified type is fusible at a comparatively low temperature and is durable for both washings in water and dry cleaning.

5) Polyesters

This is newly developed adhesive and has high durability to washings in water. It is especially used for clothing made of polyester fiber.

1.2.3 Forms of adhesives [1, 2]

Forms of adhesives imparted to adhesive interlinings are as shown below and in Figure 1.4.

1) Dot type is the dot arrangement of adhesives in a fixed size and is mainly used for adhesive interlinings for main parts. This type is roughly classified into the dry dot (powder point type) and the wet dot. While the dry dot is processed with adhesive only, the wet dot is processed with addition of an auxiliary agent such as plasticizer and therefore denaturing, such as lowering of a fusible temperature, change of fusing hand, improvement of washing- resistance, etc. is practicable. The size and the number of dots are selected properly according to the use, ranging from the big size and few numbers to the small size and many numbers.

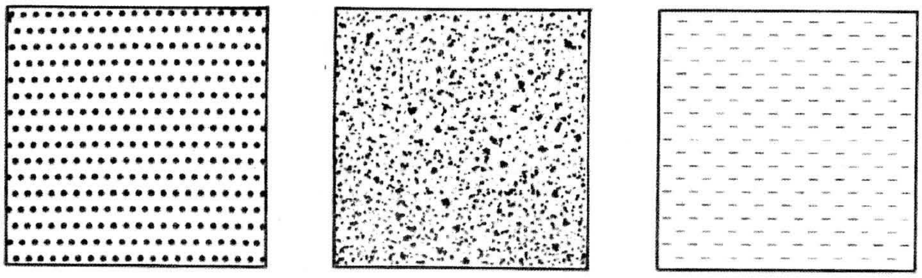
2) Sinter type is also called the random powder type. It is made by spraying powdered adhesives and fixing them. Similarly to the dots type, the size of particles and the quantity of adhesives are selected to suit the use. As compared with the dots type, this type is inferior in the distribution of size of particles and uniformity of sprayed condition but is easy to process. This type is mainly used for interlinings for temporary fusing.

3) The dash type and the net type are variations of the dot type

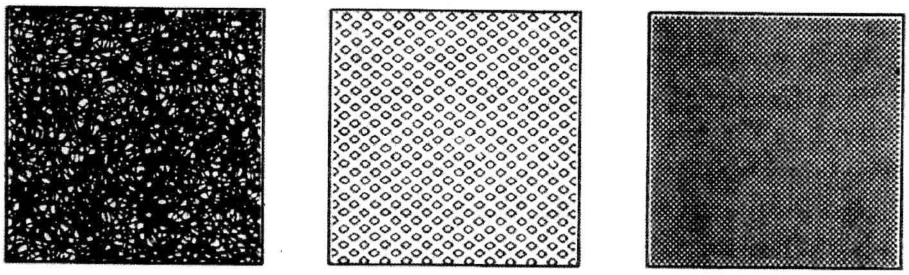
4) The web type is made by melting the adhesives into a fibrous state. It is available in two kinds, one is adhesive itself in a sheet state and the other is stuck to the base cloth.

5) The laminate type is made by making adhesives into laminate and sticking it. It provides strong adhesion force but when compared with the dot fusing, it hinders the fabric performance, with resultant hardness of fusing hand. It is limited in use.

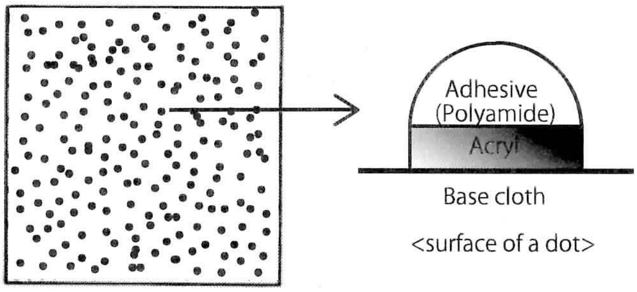
6) Double dot type is made of two layers, acryl base and adhesive on its base.



(a)Dot (b) Sinter/Random powder (c) Dash



(d) Web (e) Net (f) Laminate



(g) Double dot

Figure 1.4 Adhesive forms. [1]

1.2.4 Pressing machine [2]

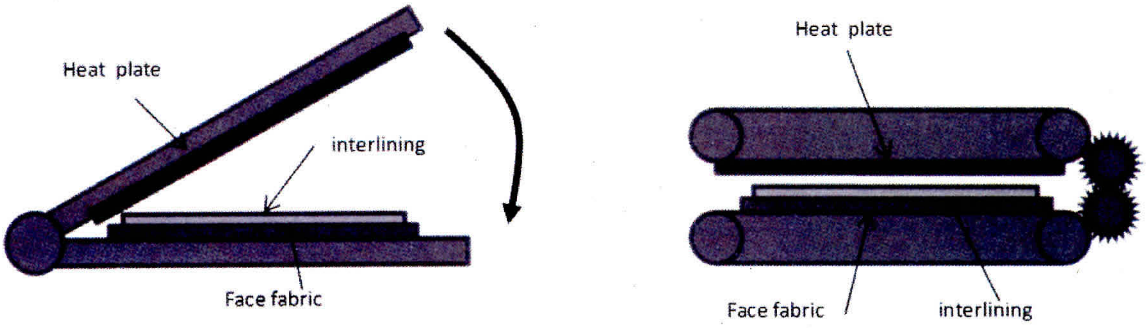
There are two types of pressing machine for bonding adhesive interlining as shown in Figure 1.5. Those properties are as follows.

1) Flat Press Type

It pressurizes a cloth while heating the adhesive. Interlining side gets heat. There is low surface pressure. It is adjusted to various fabrics needed appropriate conditions. Small dimensional change of adhesion is occurred. It is easy to maintain and to control temperature.

2) Roller Press Type

It pressurizes a cloth after heating the glue. Both interlining and fabric side gets heat. There is high pressure by pressure roller. Productivity is better when the same fabric is bonded continuously. Generally, it is easy to show dimensional changes of adhesive agent and cloth. It is easy to miss the interlining. However it is easily obtained adhesive property in general. It is difficult to maintain.



<Flat press>

<Roller press>

Figure 1.5 Flat press and roller press.[2]

1.2.5 The effect of adhesive interlining on textile and garments

The properties of fabric can be significantly altered by laminating on an adhesive interlining. The differences have effect on the garments properties so that the effect of adhesive interlining on fabric and garments are necessary to be investigated. Mechanical properties, handle, drape behavior, shape stability, delamination, buckling compression behavior etc. are the research themes. Some researchers have been tried to make clear the effect of adhesive interlining on such properties of laminated fabrics and to understand the relationship between the mechanical properties of each component and laminated fabrics. Okamoto et al. [3] investigated the physical properties and fabric hand of wool blended fabrics interlined with adhesive interlinings and compared them to blended fabrics without interlinings. Kim et al. [4] investigated the suitability of nonwoven adhesive interlinings to thin worsted fabrics with various fabric structural parameters. Jevsˇnik et al. [5], [6] analyzed some mechanical properties and parameters of drapability using the finite element method. Namiranian et al. [7] investigated the plate buckling compression behavior of laminated fabric using a specially designed clamp according to Dahlberg's test method. Strazdiene et al. [8] investigated the method of punch deformation for the simulation of textile systems behavior and on the basis of that created an original method and found new criteria for shape stability evaluation. Sharma et al. [9] investigated the effect of sewing and fusing of interlining on drape behavior of men's suiting fabrics. Fan et al. [10] also examined the causes of rippling, localized delamination or surface distortion in fused garments, both theoretically and experimentally.

Studies on the selection of optimal adhesive interlinings were also investigated. Nagano [11] suggested a range of mechanical properties for desirable adhesive interlining for tailored jackets. Fan et al. [12] also suggested an optimal range of mechanical properties for optimal adhesive interlining. Jeong et al. [13] reported on the construction of an integrated tool consisting of a neural network to predict mechanical properties. Lai et al. [14] found the ideal laminated fabrics condition range for interlining and face fabrics through discriminate analysis and scatter plot.

1.3 The effect of adhesive interlining on mechanical properties of laminated fabrics

Mechanical properties of laminated fabrics are of great interest in garment manufacturing. Shishoo et al. [20] investigated the mechanical properties of laminated fabric with adhesive interlining and analyzed the relationships between the mechanical properties of face fabric and adhesive interlining. Fan et al. ([11], [21], [22]) investigated the relationship between the low-stress mechanical properties of laminated fabrics and those of component fabrics. In their studies, they showed that the extensibility, bending rigidity and shear stiffness of laminated fabrics are considerably changed after laminating face fabric and adhesive interlining.

Among the mechanical properties of laminated fabrics, it is well-known that the bending rigidity and shear stiffness of laminated fabric is much greater than the sum of each component. In particular, bending rigidity is an important mechanical property for the garment appearance. Bending curves of a face fabric, an adhesive interlining, and a laminated fabric are shown in Figure 1.6.

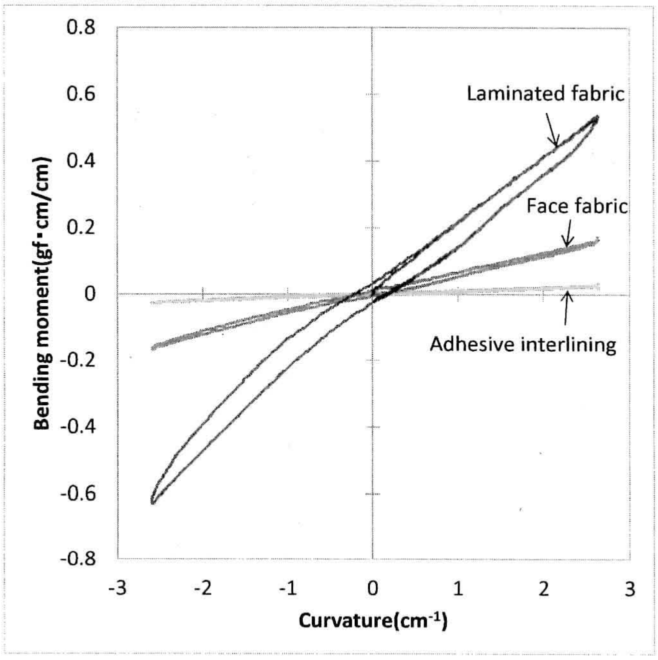


Figure 1.6 General bending curves of laminated fabric, face fabric and adhesive interlining.

The prediction of mechanical properties for laminated fabric bonded with adhesive interlining is of great interest. However, the changes were taken into account for manufacturing system by manufacturer's discretion and assessment. The relationship between the mechanical properties of adhesive interlining and laminated fabric is still unclear. Quantifying the effects of adhesive interlining properties is desirable for more efficient garment manufacturing.

1.4 Previous study on prediction for mechanical properties of laminated fabric

There are some studies about prediction for mechanical properties of laminated fabric made of face fabric and adhesive interlining from the properties of components. Uruma et al. [15] investigated the relationships, both experimentally and statistically, between the physical properties of laminated fabrics and those constituting face fabric and adhesive interlinings. Cassidy et al. [16] studied the anisotropic mechanical behavior of woven fabrics, adhesive interlinings and their laminated fabrics in order to investigate the accuracy of equations used to predict the anisotropic linear elastic behavior of fabric for in-plane and bending deformation. Matsunashi et al. [17] and [18] studied the behavior of needle penetration in blind stitch sewing and examined the case where interlining is seamed together with other fabric. Jing et al. [19] suggested predicting bond qualities of laminated fabrics after wash and dry wash, based on a principal neural network model. Shishoo et al. [20] investigated the mechanical properties of laminated fabric with adhesive interlining and analyzed the relationships between the mechanical properties of face fabric and adhesive interlining statistically. According to the analyzed relationship, they derived simple regression equations for mechanical properties of laminated fabric. Fan et al. [21], [22] and [11] investigated the relationship between the low-stress mechanical properties of laminated fabrics and those of component fabrics. Based on these relationships, they suggested a set of equations to predict the low-stress mechanical properties of laminated fabrics composed of fabric and adhesive interlining fabrics. These studies proposed equations of prediction for the mechanical properties of laminated fabric based on statistical analysis. Although the prediction method by statistical analysis is a way of selecting adhesive interlining, a more precise prediction method is necessary to achieve greater accuracy. The theoretical approach for the precise prediction method for the bending rigidity of laminated fabric with adhesive interlining was insufficient in those studies.

On the other hand, Kanayama et al. [23], [24] and Dawes et al. [25] suggested a prediction method of bending rigidity of the laminated fabrics with adhesive interlining based on laminate theory. Kanayama et al. [23], [24] proposed laminated model taken into account for the rigidity of adhesive agent. Dawes et al. [25] proposed a prediction method for the bending rigidity of a laminated fabric, which is considered tensile and bending properties. Even though they investigated the prediction of bending rigidity theoretically, the accuracy of those predicted results were also not so high. Furthermore, the studies were conducted in the 1970s–80s and the making of the adhesive interlining technique has since improved following progress of technical skill. It is necessary to verify the efficiency of these methods for current adhesive interlining. The changes of mechanical properties for face fabric and adhesive interlining after pressing also need to be investigated further. Therefore, it is necessary to investigate the prediction method for bending rigidity with high accuracy from a theoretical point of view.

1.5 The purpose of this study

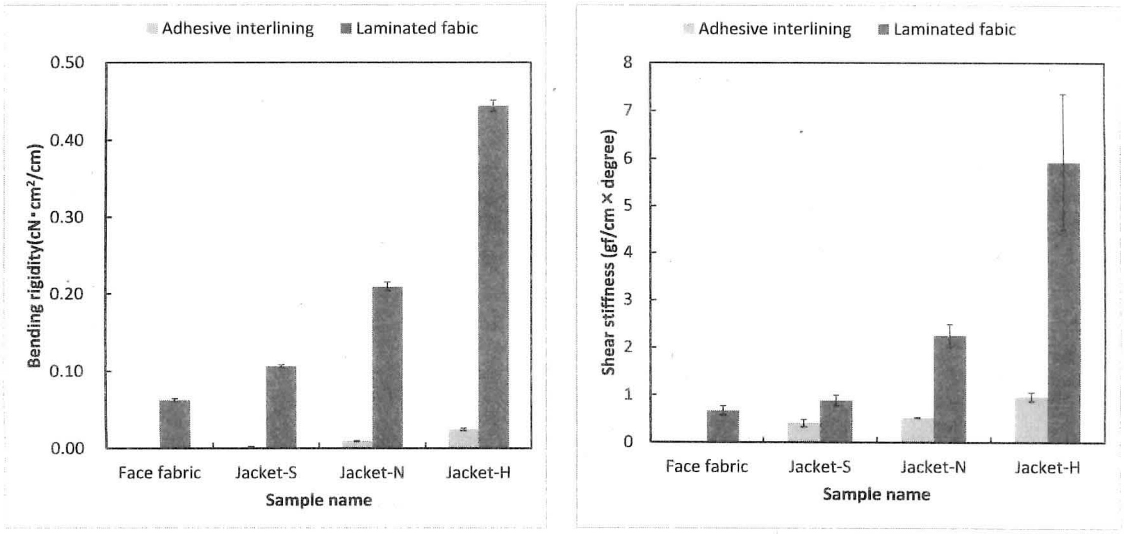
As described previously, it is well-known that the mechanical properties of laminated fabrics are different from the ones of both face fabric and adhesive interlining. Figure 1.7 shows jackets made with three laminated fabrics composed of the same face fabric and three adhesive interlinings of different rigidities [26]. The appearances of all jackets were different as shown in the figure. Therefore, it is clear that the adhesive interlining affects the appearance of garments. This is due to the differences of the mechanical properties of the laminated fabrics.

Among the mechanical properties of the laminated fabrics, the bending rigidity and the shear stiffness of the face fabrics changed significantly by laminating adhesive interlinings as shown in Figure 1.8 [26]. Although the face fabric was the same, the bending rigidity and shear stiffness of the laminated fabrics were different and it must affect the garment appearance. Except for bending rigidity and shear stiffness, tensile and compressive properties of face fabric also changed by laminating adhesive interlining. However, these changes are not so large and they do not affect the garment appearances too much. Thus, on the garment appearance, bending rigidity and shear stiffness are the most important mechanical properties. The selecting an adhesive interlining with suitable rigidities is essential for manufacturing garments. This process currently carried out by making trial samples. It takes extra cost and time. Therefore, it is necessary to investigate the theoretical prediction method for bending rigidity and shear stiffness of laminated fabrics with ones of components for selecting a suitable adhesive interlining for garments.

About shear stiffness of laminated fabrics, it was found that adhesive agent on adhesive interlining has great effects on the shear stiffness of laminated fabrics [27]. The effect of yarn interlacing point fixed by adhesive on shear stiffness of laminated fabric was investigated and the prediction method for shear stiffness of laminated fabric was proposed taking into account those effects [27]. However, the prediction method for bending rigidity of laminated fabric is not established.

(a) Jacket-S (b) Jacket-N (c) Jacket-H

Figure 1.7 Jacket pictures made of laminated fabrics with the same face fabric and different three adhesive interlinings. [26]



(a) Bending rigidity in warp direction (b) Shear stiffness in warp direction

Figure 1.8 Bending rigidity and shear stiffness of face fabric and laminated fabrics for jackets. [26]

The purpose of this study is to establish the prediction method for bending rigidity of laminated fabrics with face fabric and adhesive interlining using the mechanical properties of the components to promote effective selection of adhesive interlining in garments manufacturing. At first, the previous prediction methods for bending rigidity of laminated fabric are verified theoretically and experimentally. Based on the verification, more precise prediction methods taken into account mechanical parameters, such as the tensile and in-plane compressive moduli of each component, are proposed theoretically. Through the theoretical investigation and experimental verification of the proposed methods, more precise prediction theory and method will be established.

1.6 Composition of this study

In this study, the prediction of bending rigidity for laminated fabric was investigated. To predict bending rigidity of laminated fabric more precisely, first present prediction methods were verified theoretically and experimentally. Then, new prediction methods were proposed and verified for more precise prediction.

In Chapter 2, general bending theory of fabric is described. Measurements of bending rigidity of fabric also explained.

In Chapter 3, the prediction methods of bending rigidity for laminated fabric with adhesive interlining, laminate theory and Kanayama's model were investigated and verified. The parameters in the models were also investigated taken into account the changes of mechanical properties after pressing.

In order to achieve an accurate prediction, the reason of errors from laminate theory was investigated in the difference of moduli in tension and bending. In Chapter4, prediction of bending rigidity for laminated fabric with adhesive interlining was investigated taking into account tensile and in-plane compressive moduli of components.

In Chapter 5, the reason for errors in the prediction method taken into account the tensile and in-plane compressive moduli was investigated. The assumption of placement for neutral axis was considered to be the reason for the errors. The effect of the placement of neutral axis for components was investigated both theoretically and experimentally. Prediction of bending rigidity for laminated fabric with adhesive interlining taken into account the neutral axes of components was investigated.

Finally, in Chapter6, the conclusion of this study is described.

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Chapter 2

General bending theory of a fabric

Chapter 2 General bending theory of a fabric

2.1 Bending property of a fabric

Bending rigidity of a fabric is used as a scale to show a resistance to bending deformation in the elastic region. The bending rigidity of materials such as metal which show small curvature in practical use is measured by three-point bending and four-point bending test based on small deformation theory. It is usually considered that bending deformation of continuum body is continuous tensile and in-plane compressive deformation on the cross section. Thus, a multiplication of the tensile modulus and the moment of inertia of area can be used as a bending rigidity. However, textile is not continuum body and the moment of inertia is unable to obtain. Moreover, the relationship between bending, and tensile and in-plane compression is complicated. The curvature of textile is very large even in practical use and hysteresis phenomena are shown. Thus, pure bending test which can measure large deformation of curvature is used. In the range of small curvature, cantilever method is used to measure the average of bending rigidity. Using the bending deformation affected by gravity, Clark and loop methods are also used to obtain relative resistance in bending as bending rigidity.

Peirce [1] investigated the handle of cloth as a measurable quantity and first proposed a measurement of flexural rigidity objectively from bending length and weight of a material using cantilever. After Peirce, many researchers investigated and developed the measurement of bending rigidity for fabrics. Takatera et al [2] analyzed the interrelation among the conventional tests of the bending rigidity of textile fabrics, such as the cantilever, Clark and heart loop methods, etc. They compared and estimated the errors and applicable ranges of these methods.

Since the bending rigidity of fabrics could now be measured, researchers investigated the relationship between bending rigidity of yarns and the fabric. Grosberg [3] investigated the friction effect on bending rigidity. It was shown that the frictional restraint to bending of most cloths arises from frictional rubbing between the fibers during bending. Cooper [4] investigated the factors affecting the resistance to bending such as fibers, yarns and woven fabrics. The relationship among fibers, yarns and woven fabrics were discussed and also directional dependence of bending was also identified. Ghosh et al. [5] and [6] investigated an elastic based computational model of plain-woven fabrics in pure bending. Thy also verified their model and described the reason of errors as yarn cross sectional deformation [7].

Bending hysteresis is also of great interest in considering bending properties of fabric. Owen [8] found that bending behavior is determined by the mechanical properties of the fibers and the frictional and geometrical restraints within yarns in the fabric. Levesey et al. [9] investigated the relationship between cloth bending rigidity and single fiber bending rigidity. They proposed a mathematical formula derived for the minimum cloth bending rigidity, which takes account of the twist and crimp in the yarns.

2.1.1 Measurement of bending properties of a fabric in pure bending

In a fabric bending, the engineering theory for bending of linear elastic material is generally used. If the assumption of Euler-Bernoulli shall be established, curvature of a material point is proportional to a bending moment. When moment acts on the surface, a proportional constant will be a bending rigidity. To measure bending rigidity of a fabric, Equation (2.1) has been usually used.

$$\frac{1}{r} = -\frac{M}{EI} \tag{2.1}$$

where r is radius of curvature, M is bending moment and EI is bending rigidity. E is the longitudinal elastic modulus in the continuum and I is the moment of inertia.

Tensile and compressive modulus is generally considered to be equal. When dealing with the bending of the fabric, E is considered as the independent value and the moment of inertia cannot be calculated as well-known. Thus, a measured EI is equivalent to bending rigidity so it is common to express as bending rigidity. EI can be measured by obtaining r and M experimentally by pure bending test.

In Equation (2.1), a fabric sample can be bent in a circular arc of constant r under constant moment. Conversely, if the bending moment is known when a fabric is bent in a circular arc, EI can be also measured. In other words, bending rigidity of a fabric can be measured from the bending moments of a sample bent in a semicircular.

Among the measurement methods for bending rigidity of a fabric, method using pure bending is broadly considered as an effective way to measure it because of the inelastic characteristic of fabric. The principle of a pure bending in constant curvature is shown in Figure 2.1. Both edges of a sample can be clamped on both the center of curvature, O and moving clamp, A_0. l is the length of the sample.

When A_0 can be moved along ρ, $\overline{OA_\Theta}=\rho$, race for moving clamp until the clamp angle, $\angle A_0OA_\Theta=\Theta$ is 2Θ, the sample can be bent arc-like. The shape of ρ can be made when the length of ρ is

$$\rho = l \sin\Theta/\Theta. \tag{2.2}$$

Then, the curvature, R is $1/R=2\Theta/l$. When the moment at B can be measured, the relationship between the curvature and the moment can be measured.

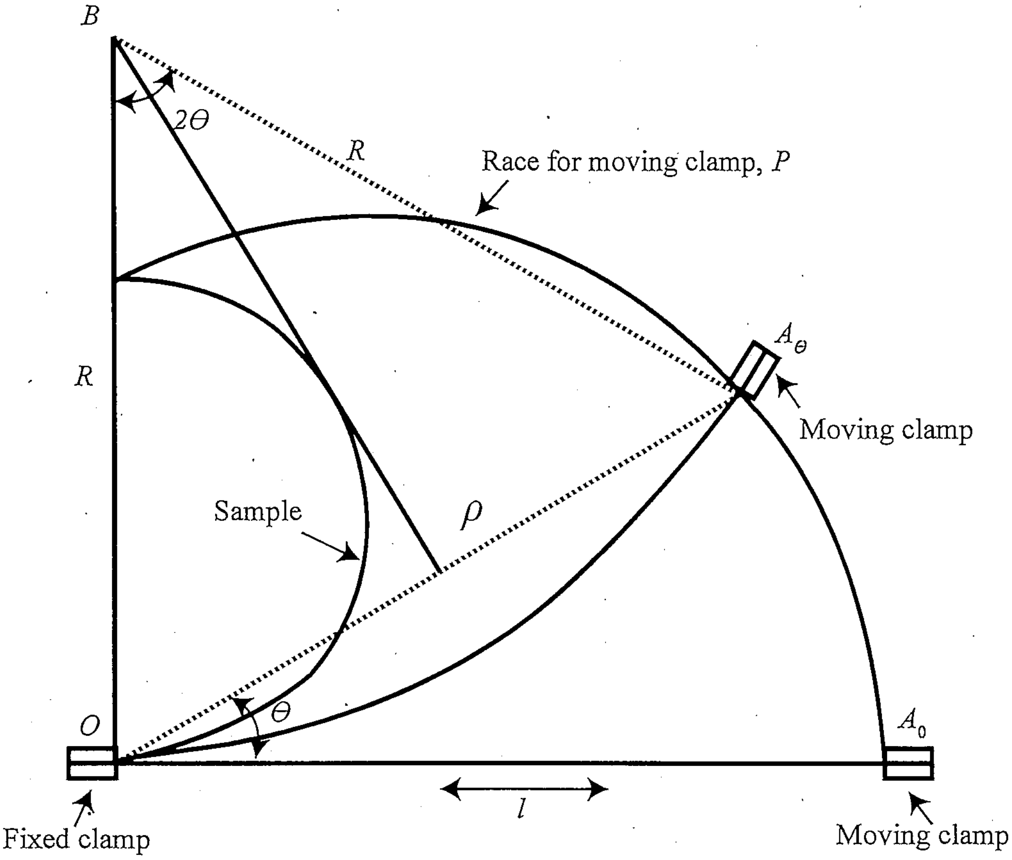

Figure 2.1 Principle of a pure bending tester in constant curvature [10]

Using the pure bending method offers three advantages; firstly curvature dependency on bending behavior can be measured. Secondly, bending hysteresis can be directly measured. Finally, repeatable bending test and easing bending test can be carried out. Specially, the inelasticity of a fabric which cause the distinct fabric handle can be measured.

2.1.2 Measurement of bending properties using KES-FB2

In bending a fabric, bending moment does not perfectly follow the Equation (2.1) and tend to vary depending on the curvature. Thus, using a machine which can record the relationship between bending moment and curvature under continuously changing curvature, bending rigidity of a fabric can be measured. As a representative tester, a pure bending test, KES-FB2 [11] is widely used nowadays.

Bending rigidity under constant moment can be obtained using pure bending tester, KES-FB2. In KES-FB2 system, pure bending between the curvature K= -2.5 and 2.5(cm^{-1}) was obtained as shown in Figure 2.2. In this case, bending rigidity (B) defined by the slope between K= 0.5 and 1.5 (cm^{-1}) for B_f, for the face side, and K= -0.5and -1.5 (cm^{-1}) for B_p, for the back side, respectively. And the mean of both B_f and B_p (B) was also obtained (Figure 2.3). This can show the different properties of face and back side. Usually the bending rigidity of textile shows anisotropy properties, so each test needs to be conducted in the warp and weft direction separately. When the B value is high, it means that the sample is difficult to bend.

In bending properties, hysteresis is also taken into account for the handle of clothes. In KES-FB system, the distances between K= 0.5 and 1.5 (cm^{-1}) for B_f, for the face side, and K= -0.5 and -1.5 (cm^{-1}) for B_p, for the back side, respectively, were defined as bending hysteresis. When the 2*HB* value is high, it means that the sample is easy to recovers easily.

The characteristic values from KES-FB2 are as follows:

- B: Bending rigidity per unit length (unit: gf·cm^2/cm)
- 2*HB*: Moment of hysteresis per unit length (unit: gf·cm/cm)

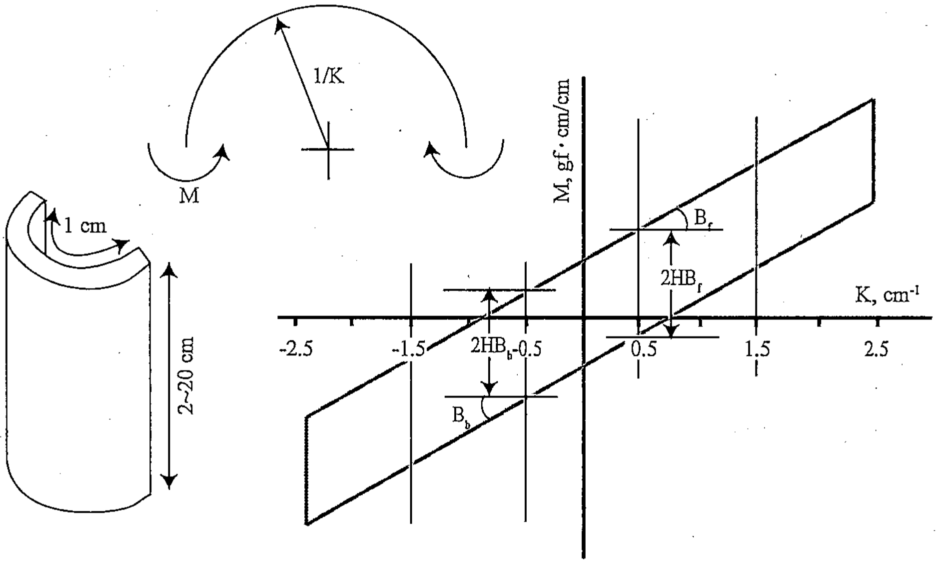

Figure 2.2 Bending property

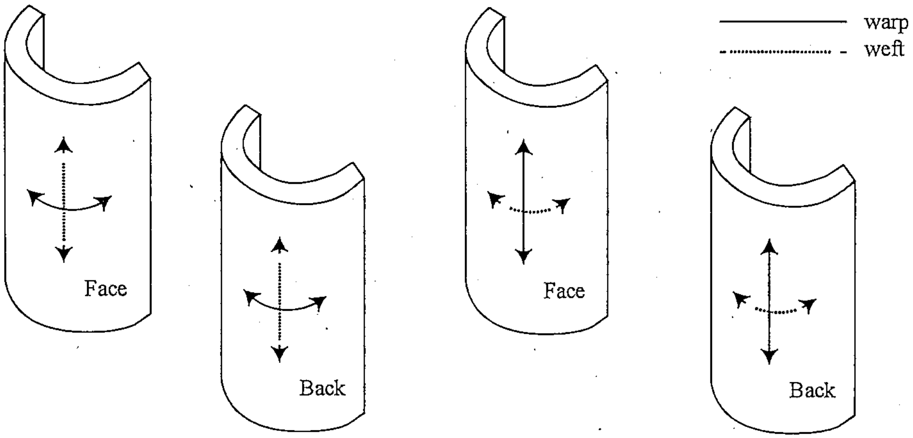

Figure 2.3 bending mode depending on face and back, warp and weft

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Chapter 3

Prediction for bending rigidity of laminated fabric with adhesive interlining based on the laminate theory

Chapter 3 Prediction for bending rigidity of laminated fabric with adhesive interlining based on the laminate theory

3.1 Introduction

Interlining is a layer of fabric inserted between the face and the lining of a garment to give the clothing a suitable appearance and stability as described in Chapter 1. An adhesive interlining is usually used nowadays because of convenience. Adhesive interlining generally gives a higher level of quality in a garment. Because of these property changes, adhesive interlining is considered an important material for clothing and the effects of an adhesive interlining were investigated by several researchers [1-7].

Bending rigidity is considered an important property for garment appearance when considering mechanical properties of interlinings. It is well known that the bending rigidity of laminated fabric is much larger than the sum of ones for components. Therefore, it is necessary to predict the bending rigidity of the laminated fabrics after laminating interlining and there have been some studies about this subject [8-11].

However, except for the methods and equations focused on experimental results [8, 9], theoretical approaches are still needed for more precise predictions. Kanayama et al. [10, 11] proposed prediction methods about bending rigidity of a laminated fabrics based on laminate theory for composite structure. Even though, these equations were considered useful to predict bending rigidity, there were still some differences between the theoretical values and the predicted ones. Therefore it is necessary to examine the calculation and measurement method of the parameters for the prediction equations.

From the view point of parameters for the prediction, changes of mechanical properties of components by pressing were taken into account in this chapter. Adhesive interlining is bonded to face fabric by a pressing machine with high heat and pressure.

Accordingly, the face fabric and adhesive interlining are pressed at the same time. Thus heat and pressure affect both adhesive interlining and face fabric. Therefore, it is necessary to study changes in mechanical properties of face fabric and adhesive interlining after pressing to understand the properties and effectiveness of adhesive interlining. The changes of mechanical properties on those, by pressing, were investigated in this study.

Since these studies were conducted in the 70s–80s and the making of the adhesive interlining technique was improved following progress of technical skill. It is necessary to verify the efficiency of these methods with current adhesive interlinings. Thus, laminate theory and Kanayama et al.'s prediction method were verified and the parameters of the method were supplemented with the measured results in this chapter.

3.2 Theoretical discussion for laminate theory and Kanayama's model

3.2.1 Laminate theory

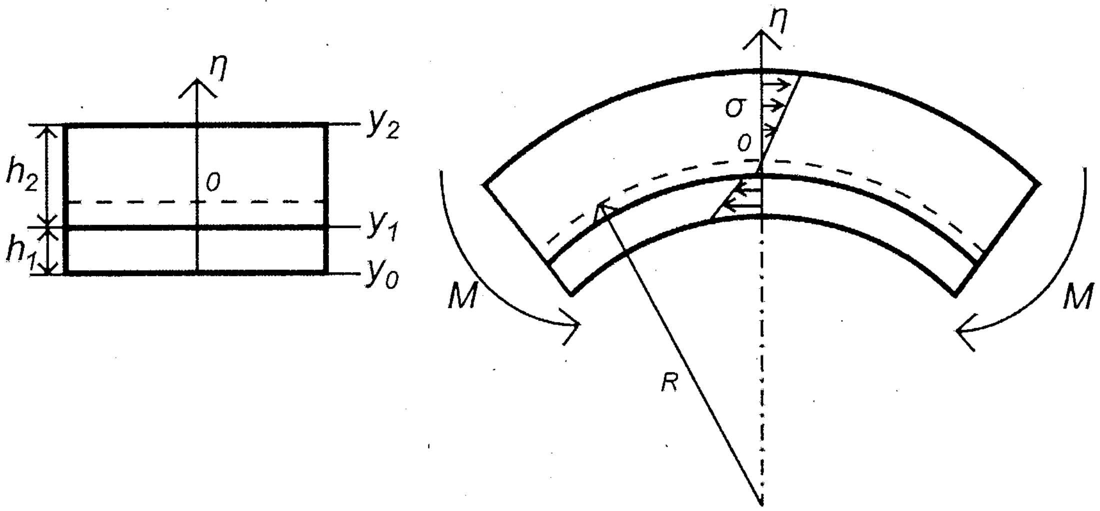


Figure 3.1 Structure of laminated fabric and its bending.

The bending laminated fabric of two plates, of which each modulus is different, was considered in this study. The structure of laminated fabric is shown in Figure 3.1. The elastic modulus of each plate is E_1 and E_2, and the thickness of each plate is h_1 and h_2.

When the laminated fabric is bent, the strain distribution in the cross section is continuous. However the stress distribution is discontinuous at boundary. The neutral surface is not consistent to the symmetry axis of the cross-section.

In considering bending deformation, strain, ε, is given by

$$\varepsilon = \frac{\eta}{R} \tag{3.1}$$

where R is the radius of curvature for the neutral surface of the laminated fabric after bending and η is the distance from the neutral surface in a laminated fabric. Assuming Bernoulli-Euler law, the bending moment, M, is given by

$$M = \frac{\overline{EI}}{R} \tag{3.2}$$

where $\overline{EI}$ is the equivalent bending rigidity of the laminated fabric. From the laminated composite theory of elastic plates, $\overline{EI}$ is given by

$$\overline{EI} = \frac{b}{3}\left(E_1\left[y_1^3 - y_0^3\right] + E_2\left[y_2^3 - y_1^3\right]\right) \tag{3.3}$$

where y_0, y_1 and y_2, are the coordinates of surface and boundaries from the neutral surface in the cross-section of the laminated plate as shown in Figure 3.1 and b is the breadth of plates.

In this case, the neutral surface of the laminated fabric can be determined by the following relationship.

$$N = \int_A \sigma dA = 0 \tag{3.4}$$

in which N is the resultant force in axial direction of the laminated fabric and σ is stress.

From Equation (2.4), we obtain

$$y_1 = \frac{h_1^2 E_1 - h_2^2 E_2}{2(E_1 h_1 + E_2 h_2)} \tag{3.5}$$

By substituting $y_0 = y_1 - h_1$ and $y_2 = h_2 + y_1$ into the Equation (3.3), we obtain

$$\overline{EI} = \frac{b}{3}\left(E_1\left[h_1^3 + 3y_1 h_1 (y_1 - h_1)\right] + E_2\left[h_2^3 + 3y_1 h_2 (y_1 + h_2)\right]\right) \tag{3.6}$$

Introducing the moment of inertias, I, of each plate,

$$I_1 = \frac{bh_1^3}{12}, \quad I_2 = \frac{bh_2^3}{12} \tag{3.7}$$

then

$$\overline{EI} = E_1\left[I_1 + bh_1\left(\frac{h_1}{2} - y_1\right)^2\right] + E_2\left[I_2 + bh_2\left(\frac{h_2}{2} + y_1\right)^2\right] \tag{3.8}$$

Then substituting Equation (3.5) into Equation (3.8), after some reductions

$$\overline{EI} = E_1I_1 + E_2I_2 + 3E_1I_1E_2I_2\frac{(h_1 + h_2)^2}{\left(E_1I_1h_2^2 + E_2I_2h_1^2\right)} \tag{3.9}$$

where E_1I_1 and E_2I_2 are the bending rigidity of each plate. They can be measured by a pure bending test. This can be expressed as follows.

$$B_{12} = \frac{\overline{EI}}{b} = B_1 + B_2 + 3B_1B_2\frac{(h_1 + h_2)^2}{\left(B_1h_2^2 + B_2h_1^2\right)} \tag{3.10}$$

where B_1 and B_2 are the bending rigidity of face fabric and adhesive interlining per unit width. The bending rigidity per unit width of the laminated fabric calculated from Equation (3.9) is denoted by B_{12}.

The bending rigidity of the laminated fabric can be calculated from the bending rigidities and thicknesses for the each plate by Equation (3.10). The theory of bending rigidity for a laminated fabric as previously described was suggested by Kanayama et al. [10].

3.2.2 Kanayama's model

Kanayama et al. [11] also suggested an equation taken into account the effect of adhesive agent with B_{12} as follows.

$$B_{12}' = \left(1 + \frac{l_h}{l_s}\right) B_{12} \tag{3.11}$$

where l_h and l_s are each width of adhesive agent area and no adhesive resin area of interlining (See Figure 3.2). They assumed that the shape of adhesive agent area was a rectangle and the adhesive agents were put on regularly following a pattern.

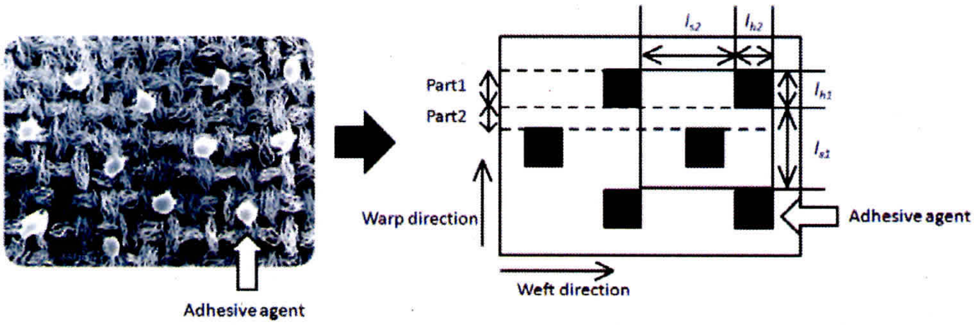


Figure 3.2 SEM pictures of adhesive interlining (left) and structure model of adhesive interlining from Kanayama et al. (right).

3.3 Experimental

The prediction of the bending rigidity of laminated fabric with adhesive interlining with equations (3.10) and (3.11) was carried out. Face fabrics, adhesive interlinings and the laminated fabrics were prepared as samples and their bending rigidities and thicknesses were measured and used to verify the equations. The mechanical properties of the face fabric and adhesive interlining may change after the pressing process. Therefore, it was also considered necessary to use the mechanical properties changed by pressing to verify the equations. To measure the mechanical properties changed by pressing, face fabric and adhesive interlining were pressed and the bending rigidity and thickness of each sample was measured and used to verify the equations as well. Bending properties of each sample were measured by KES-FB2 pure bending tester and the *B* values of cases where the face fabrics are outside were used as shown in Figure 3.3.

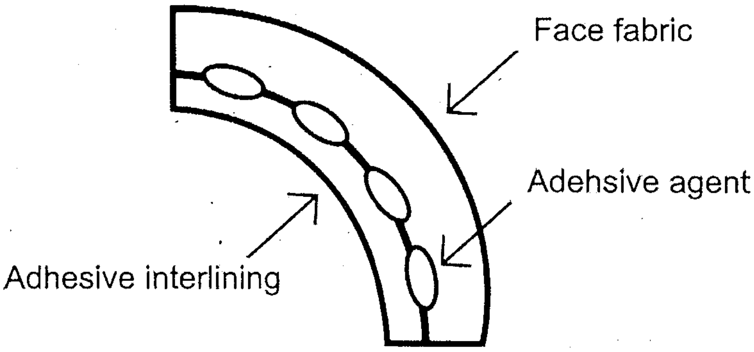


Figure 3.3 Laminated fabric with adhesive interlining.

The thickness of each sample was measured by a KES-FB3 compression tester at 49 Pa load. Bonding interlining to face fabric was treated by a press machine (KOBE DENKI KOGYOSYO, BP-V4812D) and the bonding conditions were at 150°C, under 29.4 kPa and for 10s pressing time. Every test was carried out under standard conditions (a temperature of 20±1°C and a relative humidity of 65±5%). All samples were treated under standard conditions for 24 hours. Every test was conducted for five samples and the average was used for the result. Changes in cross-section for adhesive interlinings before and after pressing were observed by taking a SEM picture.

Four types of woven fabric made with different yarn count and weave for women's jackets were prepared as face fabrics. Specification of face fabrics and their weave are shown in Table 3.1. Ten kinds of adhesive interlinings were prepared as samples. Specifications of adhesive interlinings are shown in Table 3.2. They were polyester plain fabrics and the adhesive agent was polyamide. The adhesive was double dot which means a structure of the superimposed adhesive dots. Five were controlling density of cloth on weft direction and another five types had a different adhesive agent pattern by controlling the number of adhesive agent dots per area. When the adhesive agent was put on cloth, a screen, which has a thin plate and holes for the adhesive agent, was used.

Table 3.1 Specification of face fabrics

Sample name	Yarn Count(tex)	Weave	Width (cm)	Density(/cm) (Warp × Weft)	Material	Pressed face fabric
A	16.5 tex×2; R33tex	Twill	148	28×22	Wool 100%	P-A
B	14tex×2; R28tex	Twill	148	29×24	Wool 100%	P-B
C	14tex×2; R28tex	Satin	148	43×29	Wool 85%, Angora15%	P-C
D	8.5tex×2; R17tex	Satin	148	52×35	Polyester 80%, Wool 15%, Cashmere 5%	P-D

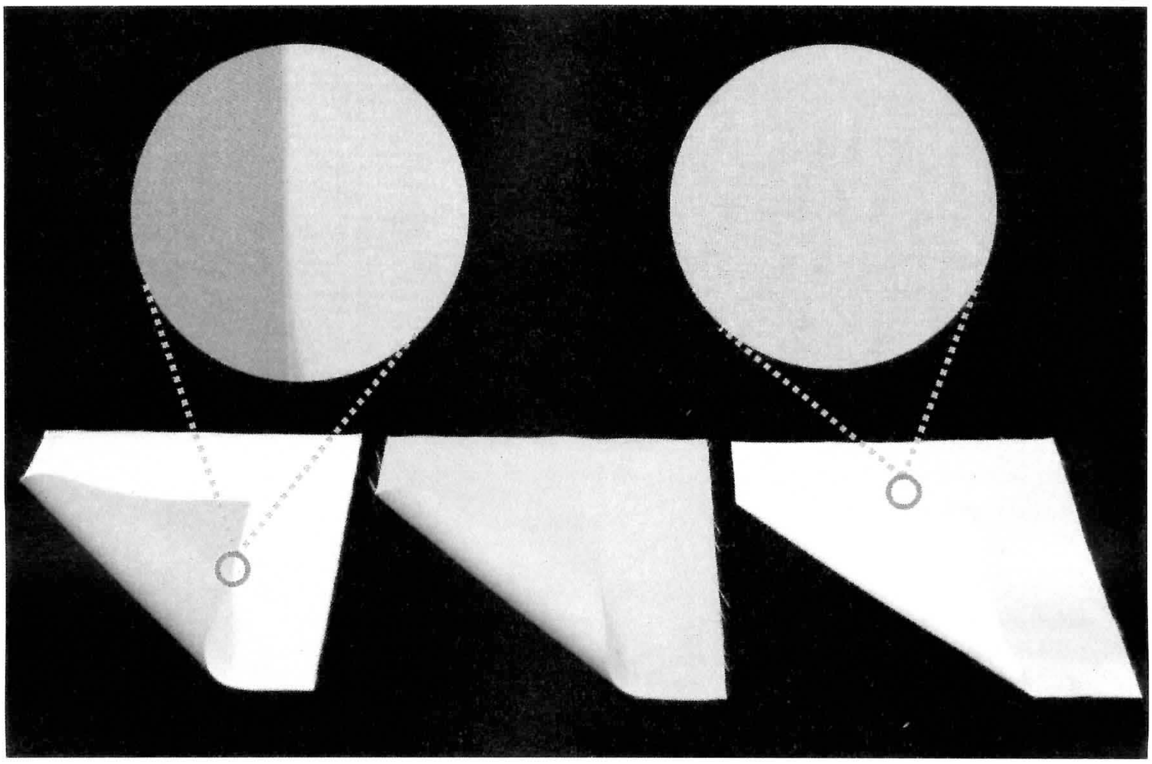
Table 3.2 Specification of interlinings

Sample name	Width (cm)	Density (/cm)	Adhesive dot number(/cm) (warp×weft)	Adhesive dot size (mm)	Mass per unit area (g/m^2)	Adhesive Mass without Interlining (g/m^2)	Pressed adhesive interlining
CE-1	96.5	38×22	10×10	0.17	36.2	8.6	P-CE-1
CE-2	96.7	38×23	10×10	0.17	35.6	8.0	P-CE-2
CE-3	97.0	38×25	10×10	0.17	36.5	8.3	P-CE-3
CE-4	97.5	37×26	10×10	0.17	36.5	8.1	P-CE-4
CE-5	97.2	37×26	10×10	0.17	35.7	7.7	P-CE-5
DP-1	93.5	39×24	9×9	0.25	38.5	8.7	P-DP-1
DP-2	93.5	39×24	10×10	0.23	39.9	10.0	P-DP-2
DP-3	93.5	39×24	10×10	0.30	41.8	11.6	P-DP-3
DP-4	93.5	39×24	11×11	0.20	37.5	8.7	P-DP-4
DP-5	93.5	39×24	12×12	0.10	39.3	10.1	P-DP-5

Composites of face fabrics and adhesive interlinings were also prepared as shown in Table 3.3. The pictures of a laminated fabric, a face fabric and an adhesive interlining are shown in Figure 3.4.

Table 3.3 Combinations of laminated fabrics

Adhesive interlining / Face fabric	CE-1	CE-2	CE-3	CE-4	CE-5	DP-1	DP-2	DP-3	DP-4	DP-5
A	A-CE -1	A-CE -2	A-CE -3	A-CE -4	A-CE -5	A-DP -1	A-DP -2	A-DP -3	A-DP -4	A-DP -5
B	B-CE -1	B-CE -2	B-CE -3	B-CE -4	B-CE -5	B-DP -1	B-DP -2	B-DP -3	B-DP -4	B-DP -5
C	C-CE -1	C-CE -2	C-CE -3	C-CE -4	C-CE -5	C-DP -1	C-DP -2	C-DP -3	C-DP -4	C-DP -5
D	D-CE -1	D-CE -2	D-CE -3	D-CE -4	D-CE -5	D-DP -1	D-DP -2	D-DP -3	D-DP -4	D-DP -5



(a) B-DP-1 (b) B (c) DP-1

Figure 3.4 Picture of laminated fabric (B-DP-1), face fabric(B) and adhesive interlining(DP-1).

Furthermore, to investigate the pressing effects on the mechanical properties of each sample, bending rigidities and thicknesses of the adhesive interlinings, face fabrics and interlining cloth without adhesive were measured after being pressed individually. Face fabric samples were pressed with the same conditions of bonding interlining and those samples were named as 'pressed face fabric'. The pressing process of adhesive interlining sample was difficult to carry out because the adhesive on adhesive interlining melted when pressed and the adhesive interlining was adhered to the base after pressing. Therefore, polytetrafluoroethylene (PTFE) film (NITTO, No. 900, 0.05 mm) was used as a base for pressing the adhesive interlining. Adhesive interlining was bonded to PTFE film by pressing then the PTFE film was removed from the laminated fabric as shown in Figure 3.5. By this process, the adhesive agent was fixed on the cloth for interlining by pressing to a fabric because the PTFE film is infusible and has a flat surface.

Consequently, it was possible to investigate the behavior of the adhesive after pressing. These samples were labeled as 'pressed interlining'. The properties of the cloth for adhesive interlining and the changes of these by pressing were important to understand mechanical properties of adhesive interlining. Therefore, CE-3-NA, which was interlining cloth of CE-3, was prepared as a sample. These were also pressed and called P-CE-3-NA and P-CE-3 respectively.

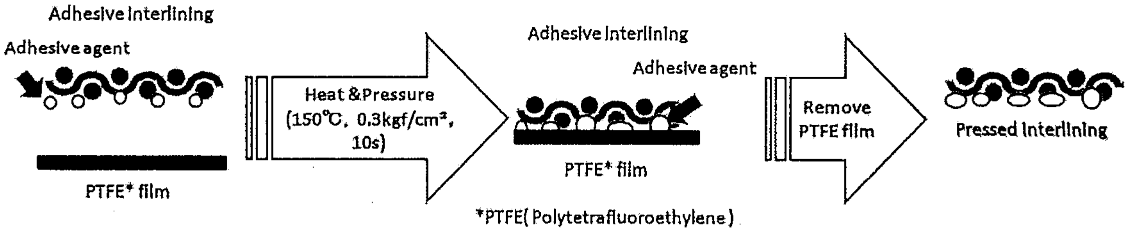


Figure 3.5 The process of making pressed interlining.

3.3.1 Results and discussion

3.3.2 Changes of the bending property and thickness for woven fabric and adhesive interlining by pressing

The pressing effects were investigated by comparing the properties of each sample before and after pressing. The thicknesses of face fabrics changed after pressing are as shown in Figure 3.6. However the effects were different for the different samples. The thicknesses of B, C and D fabric increased and that of A fabric decreased. It was conceivably due to the effects from heat and pressure during pressing. Therefore, it was found that thicknesses of the face fabrics were affected by pressing while bonding adhesive interlining. However, it is necessary to study more about the pressing effects on woven fabric of different weaving.

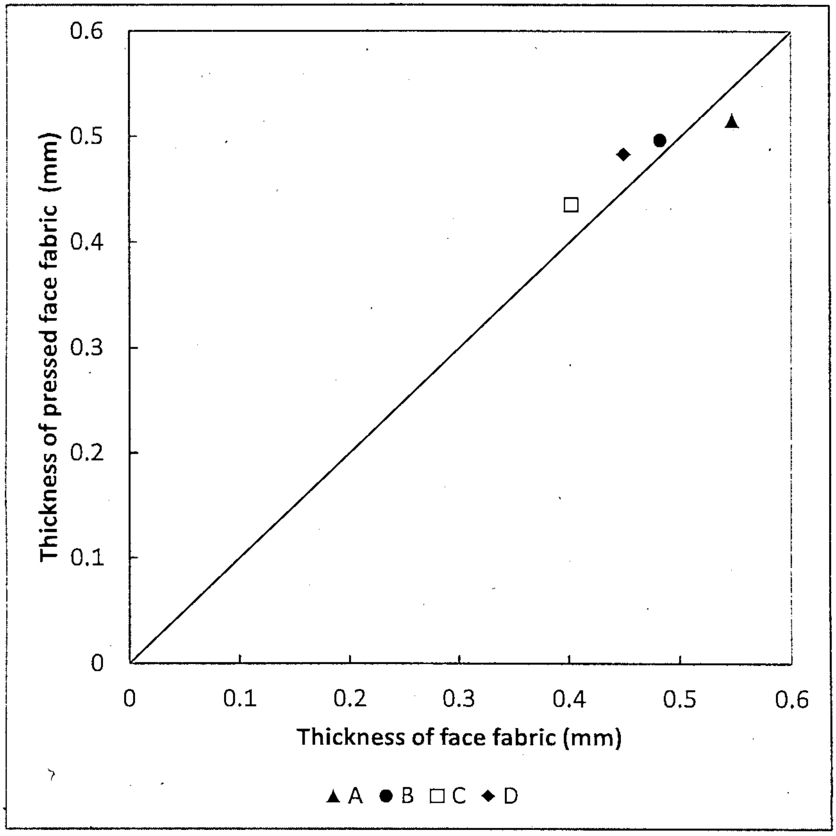


Figure 3.6 Relationship between thicknesses of pressed face fabrics and thicknesses of face fabrics.

Even though, the thicknesses of face fabrics were changed by pressing, bending rigidities of pressed face fabric were almost the same as before pressing as shown in Figure 3.7. Therefore, it was determined that bending rigidities of face fabrics were not affected by pressing.

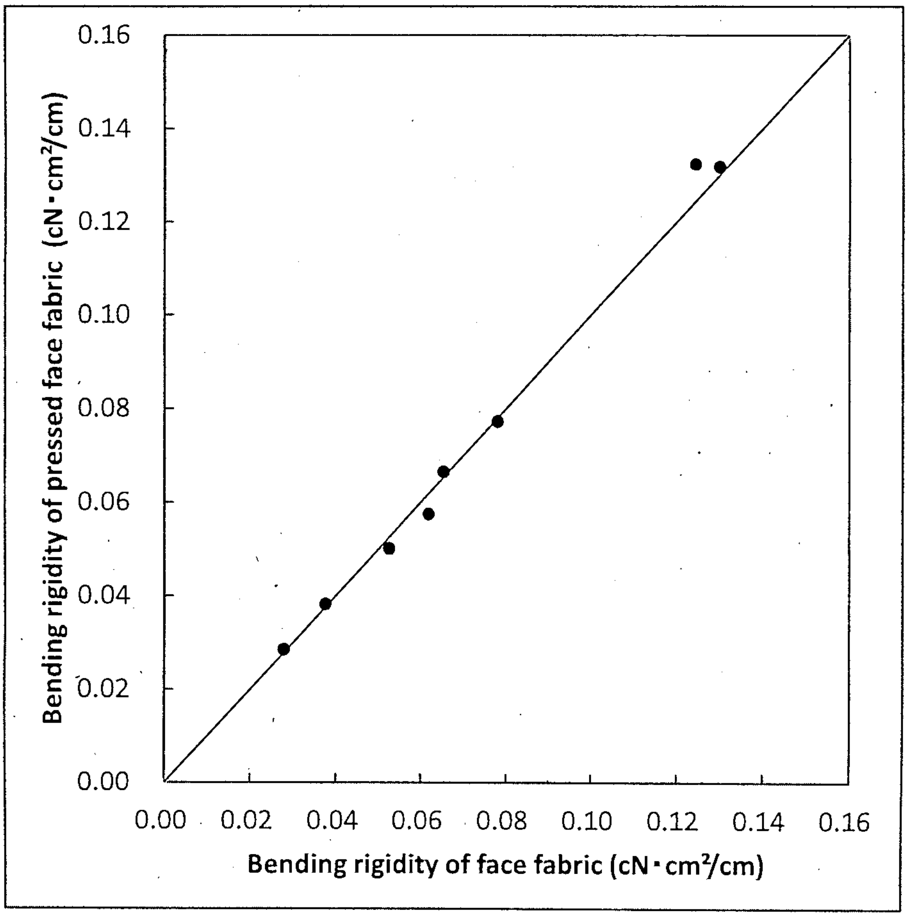


Figure 3.7 Relationship between bending rigidities of pressed face fabrics and bending rigidities of face fabrics.

The thicknesses of pressed interlining were lower than that before pressing as shown in Figure 3.8. In addition, some changes in the adhesive agent shape were observed after taking SEM pictures as shown in Figure 3.9. The round shape of the adhesive was flattened and the shape changed. Adhesive agent permeation into the space between warp and weft yarns was also observed, as shown in Figure 3.10. These changes were also found in all laminated fabrics.

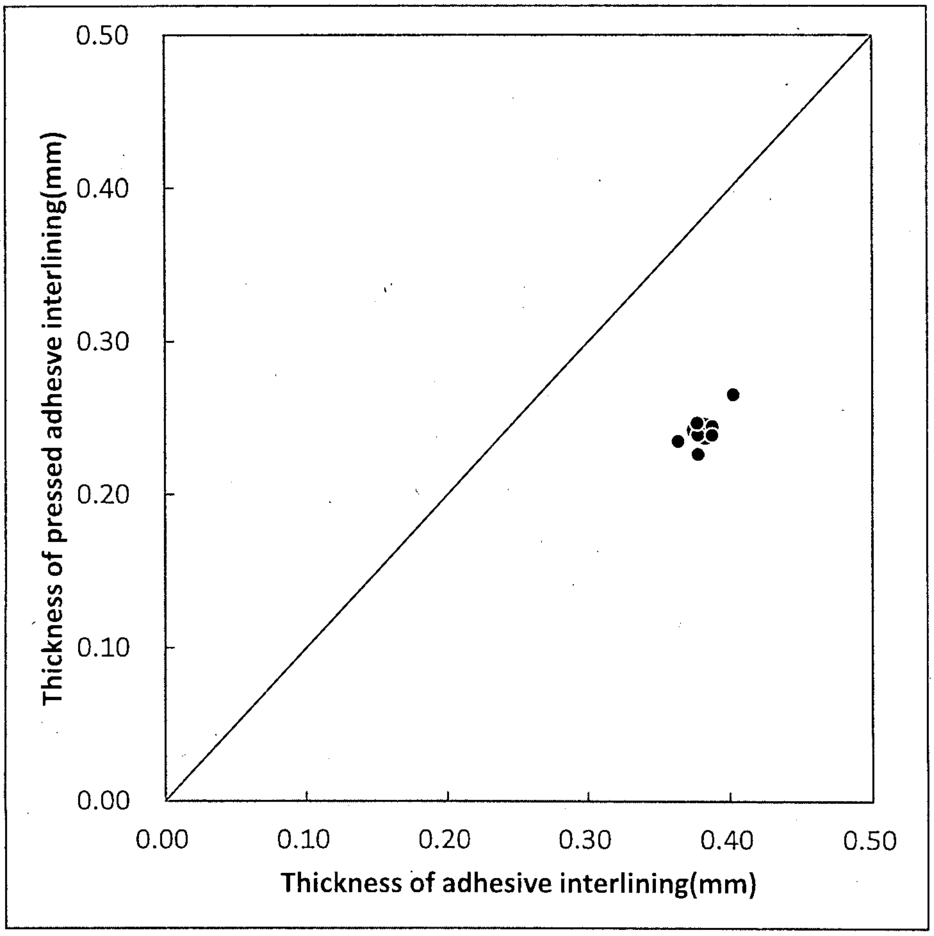
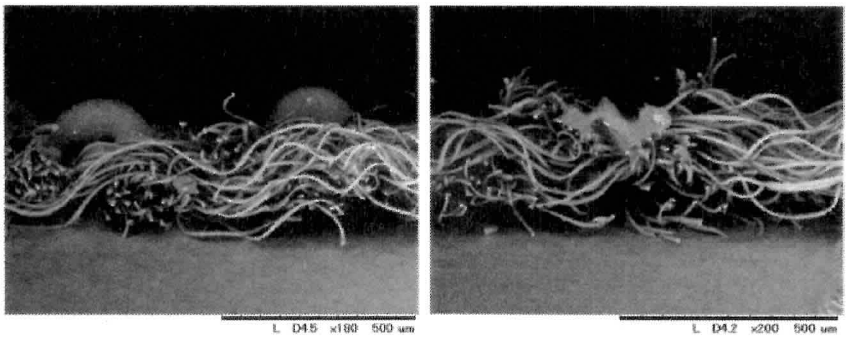
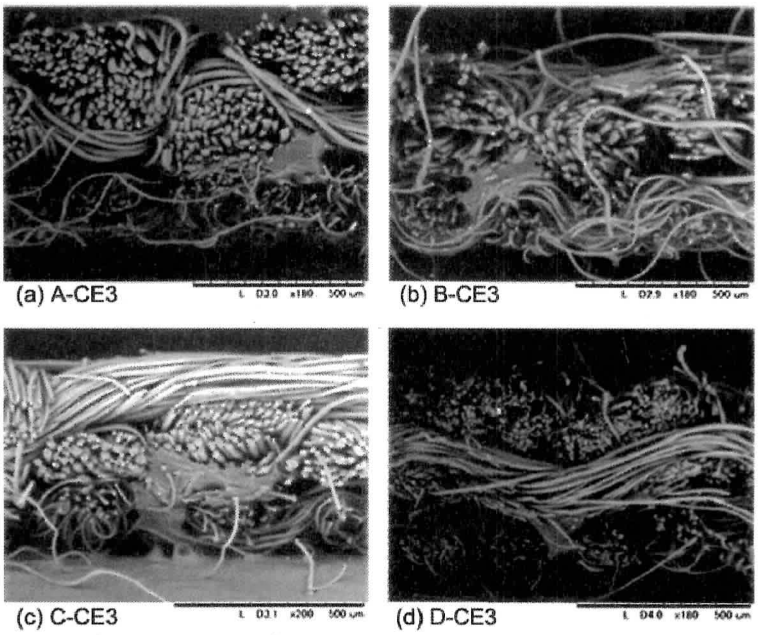


Figure 3.8 Relationship between thicknesses of pressed interlining and thicknesses of adhesive interlining before pressing.



(a)Before pressing(CE3) (b) After pressing(CE3)

Figure 3.9 SEM pictures of cross-section for adhesive interlining: (a) before pressing (CE3) and (b) after pressing (CE3).



(a) A-CE3 (b) B-CE3

(c) C-CE3 (d) D-CE3

Figure 3.10 SEM pictures of cross-section for laminated fabrics: (a) A-CE-3, (b) B-CE-3, (c) C-CE-3, (d) D-CE-3.

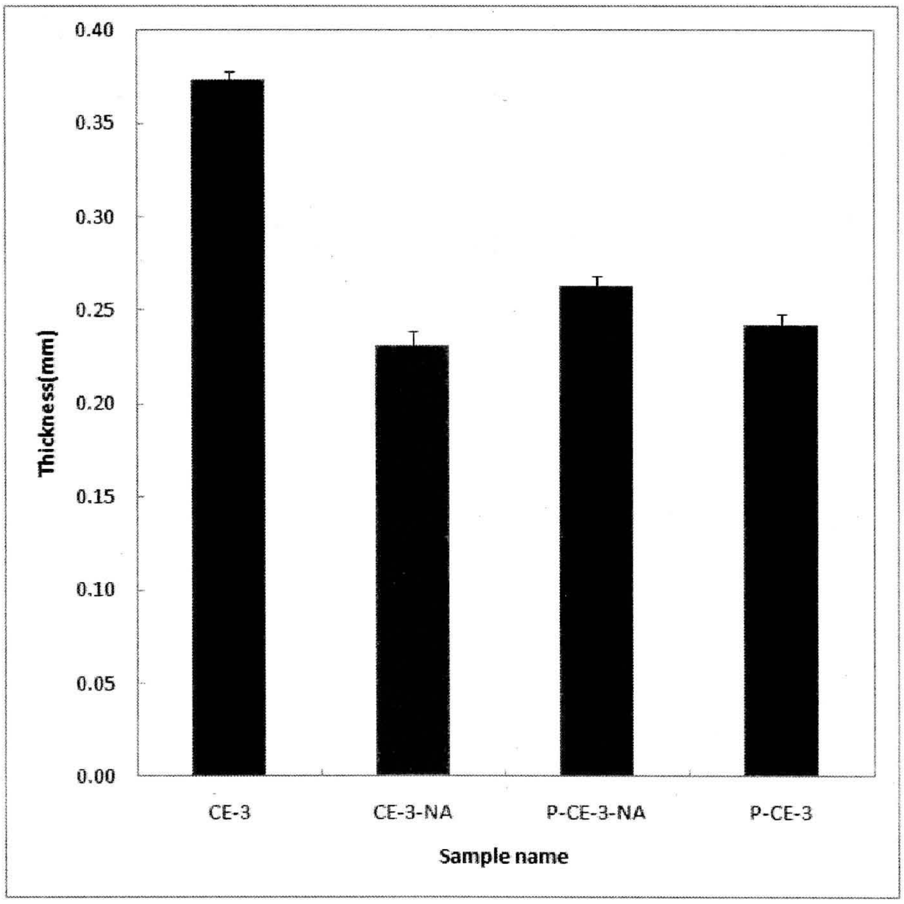


Figure 3.11 Thickness of adhesive interlining and its cloth without adhesive, before and after pressing.

Furthermore, the thickness changes of adhesive interlinings and interlining cloth by pressing are shown in Figure 3.11. When comparing CE-3 to P-CE-3, the thickness of P-CE-3 was lower than that of CE-3. The thicknesses of the adhesive interlinings became clearly thinner due to pressing. The thickness of CE-3 was lower than the sum of thickness for CE-3-NA and adhesive screen, 200 mm. The reason was that the adhesive agent was permeated into the cloth surface during the manufacturing process. Comparing P-CE-3-NA to CE-3-NA, the thickness of P-CE-3-NA was higher than that of CE-3-NA. With these results, it was conceivable that shrinkage and extension of cloth for adhesive interlining occurred on adhesive interlining cloth by pressing so the thickness of adhesive interlining changed. Therefore, it is clear that pressing is affected not only by adhesive agent but also cloth respectably.

Bending rigidity of the pressed interlining increased compared with that before pressing as shown in Figure 3.12.

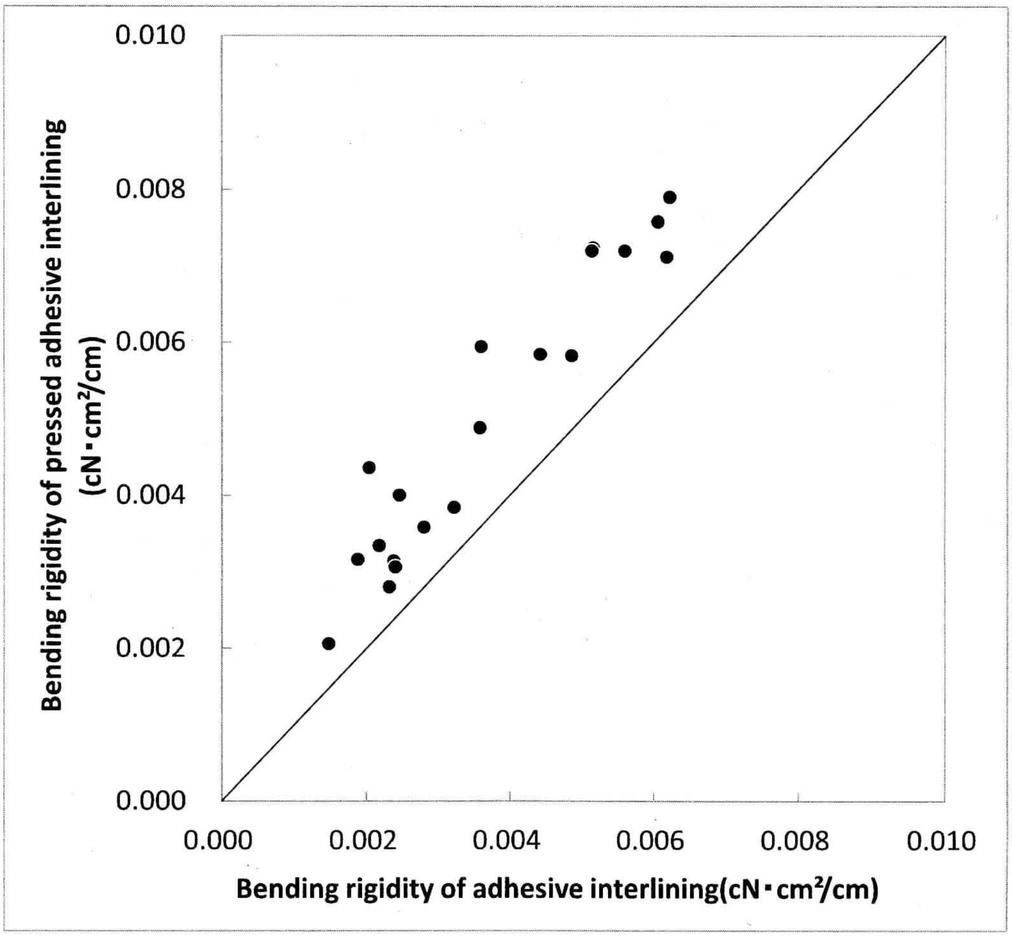


Figure 3.12 Relationship between bending rigidities of pressed interlining and bending rigidities of adhesive interlining before pressing.

In addition, bending rigidity of P-CE-3-NA was slightly smaller than that of CE-3-NA whereas bending rigidity of P-CE-3 increased in comparison with that of CE-3 as shown in Figure 3.13. Therefore, it is conceivable that most of the pressing process did not affect the bending rigidity of cloth for adhesive interlining and similar results were obtained with pressed face fabric. With these results, it was concluded that the adhesive agent permeation made adhesive interlining stiffer than before. As shown in Figure 3.13, the standard deviation of CE-3 is larger than the others. The reason would be the uneven distribution of adhesive dot on thin cloth of interlining.

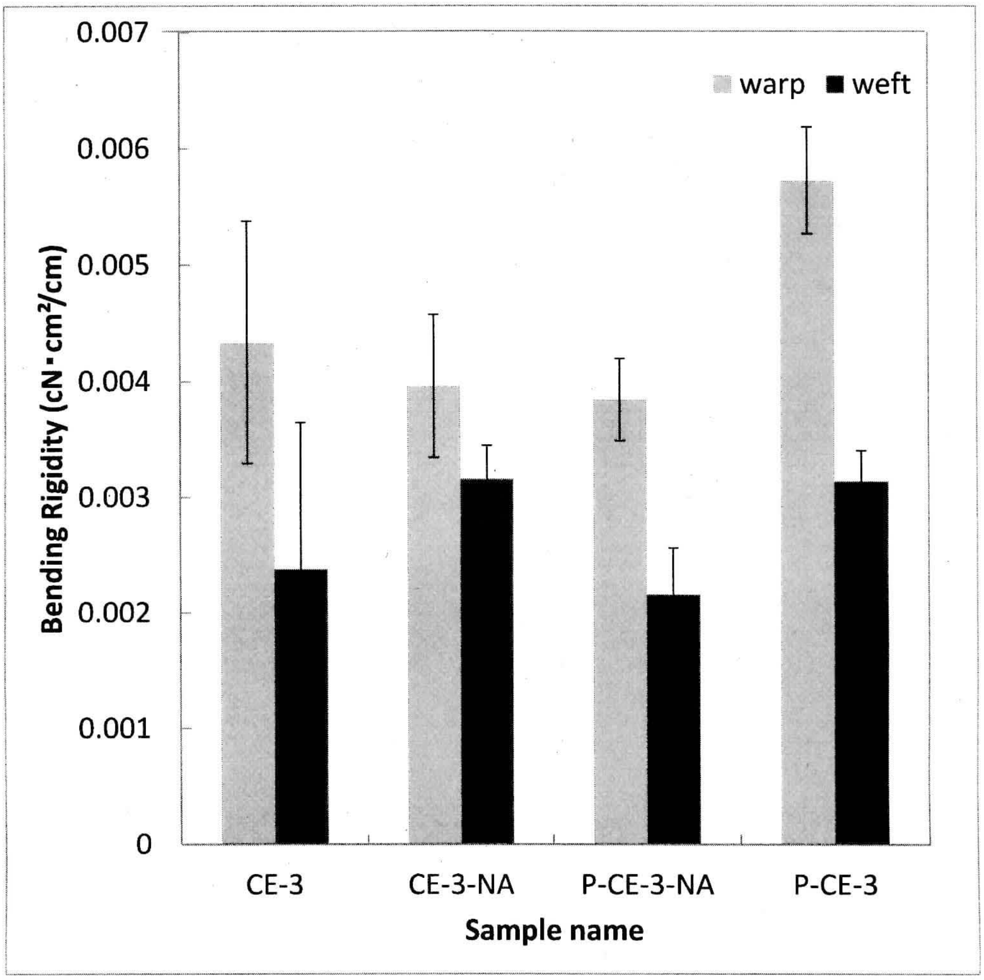


Figure 3.13 Bending rigidities of adhesive interlining and its cloth without adhesive, before and after pressing.

3.3.3 Prediction of bending rigidity for laminated fabrics with adhesive interlining

The Equation (3.10) and (3.11) were used to verify the measured mechanical properties. Bending rigidity and thickness of adhesive interlining before pressing was used to verify Equation (3.10) and (3.11) and this case was named as *A.I.* As previously mentioned, it was found that the pressing process affected the mechanical properties of each sample. Therefore, it was necessary to consider the mechanical property changes due to pressing. Bending rigidity and thickness of pressed interlining used to verify those equations and that was named as *P.I.* Furthermore, it was also found that the pressing process affected the mechanical properties of face fabric. Therefore, bending rigidity and thickness of pressed interlining and thickness of pressed fabric were used to verify these equations and the condition was named as *F.P.I.* The list of parameters used for the calculation and nomenclature of the result is shown in Table 3.4.

Table 3.4 Parameters used for calculation and nomenclature

Symbol	Condition
A.I.	Used bending rigidity and thickness of adhesive interlining before pressing
P.I.	Used bending rigidity and thickness of *pressed interlining*
F.P.I.	Used bending rigidity and thickness of *pressed interlining* and thickness of *pressed fabric*

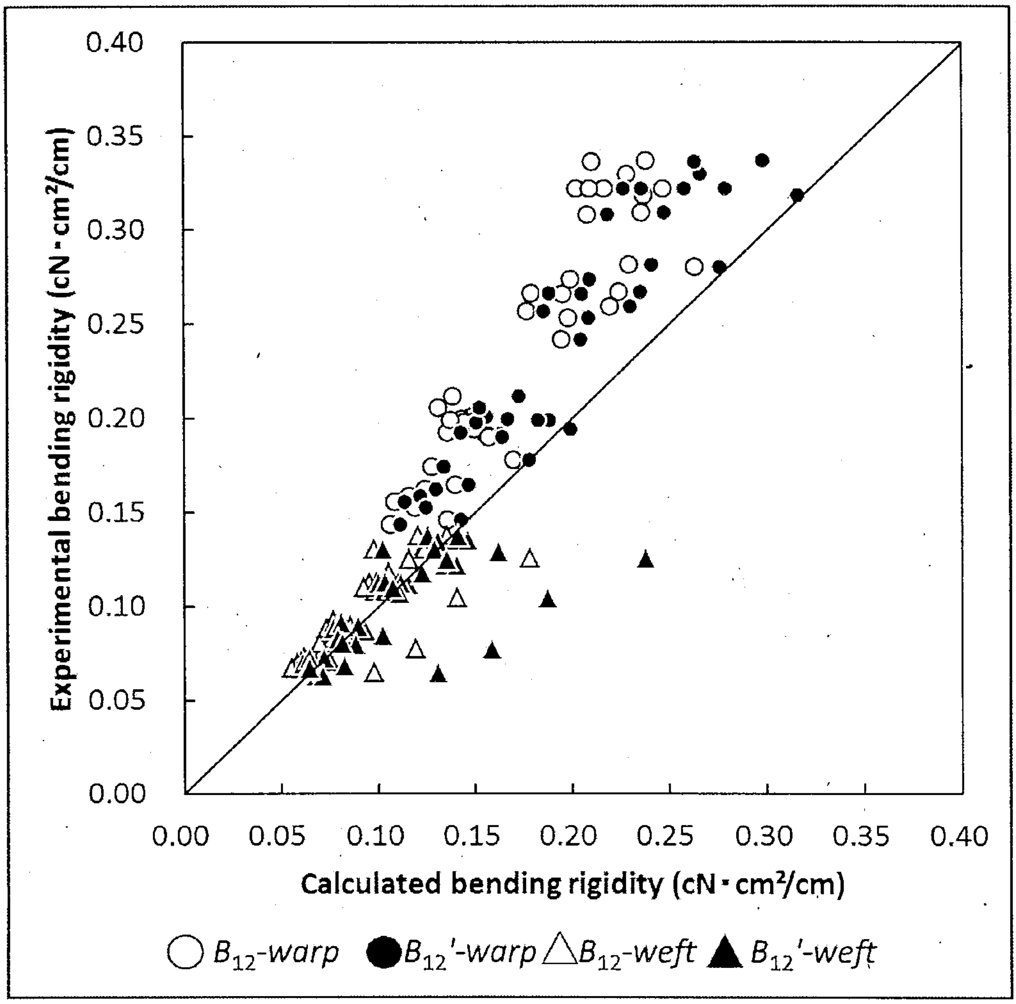


Figure 3.14 Comparison between experimental bending rigidities and theoretical bending rigidities using B_{12} (*A.I.*) and B_{12}' (*A.I.*).

A comparison of the experimental and calculated bending rigidities with B_{12} (*A.I.*) and B_{12}' (*A.I.*) equations is shown in Figure 3.14. Comparing the results of equation B_{12} (*A.I.*) to B_{12}' (*A.I.*), B_{12}' (*A.I.*) was slightly closer to the experimental results. It was because equation B_{12}' considered the adhesive agent effects on B_{12}. Comparing the bending rigidities of warp and of weft direction, the lower values of weft direction agreed with the experimental values more than those in the warp direction. This tendency was also shown in Kanayama's results [10, 11]. The reason why the results from equation B_{12} were not close to experimental ones may be explained as follows. One reason may be due to the thickness changes of face fabric and adhesive interlining after pressing. Changes of bending rigidity for adhesive interlining after pressing may be additional one. In equation B_{12} and B_{12}', thicknesses and bending rigidities of samples after bonding were assumed to be the same as that before bonding. However after bonding an adhesive interlining to face fabric, the thickness of the laminated fabric, after bonding interlinings, became lower than the sum of thickness for face fabric and interlining before bonding. This occurred due to the change of adhesive agent shape and changes in mechanical properties of the cloth by pressing, as mentioned previously.

Furthermore, bending rigidity of the adhesive interlining became larger than that before pressing. Therefore it will be necessary to consider these changes in order to predict the bending rigidity of the laminated fabric. In equation B_{12}', the percentage of adhesive agent was incorporated to enable the effects of the adhesive agent on bending rigidity to be considered. However, the increasing tendency of bending rigidity with increasing percentage of adhesive agent did not show up in the results of B_{12}' (*A.I.*) in Figure 3.14. This was because the mass of adhesive agent was not considered in equation B_{12}'. Some adhesive interlinings had different masses of adhesive agent even though the percentages were similar. Therefore not only the percentage of diameter but also the mass will need to be considered when calculating the effects of adhesive agent on bending rigidity of laminated fabric.

To consider the changes of mechanical properties for adhesive interlining by pressing, *P.I.* was used to predict the bending rigidity of the laminated fabric. Results of B_{12} (*P.I.*) and results of B_{12}' (*P.I.*) are shown in Figure 3.15.

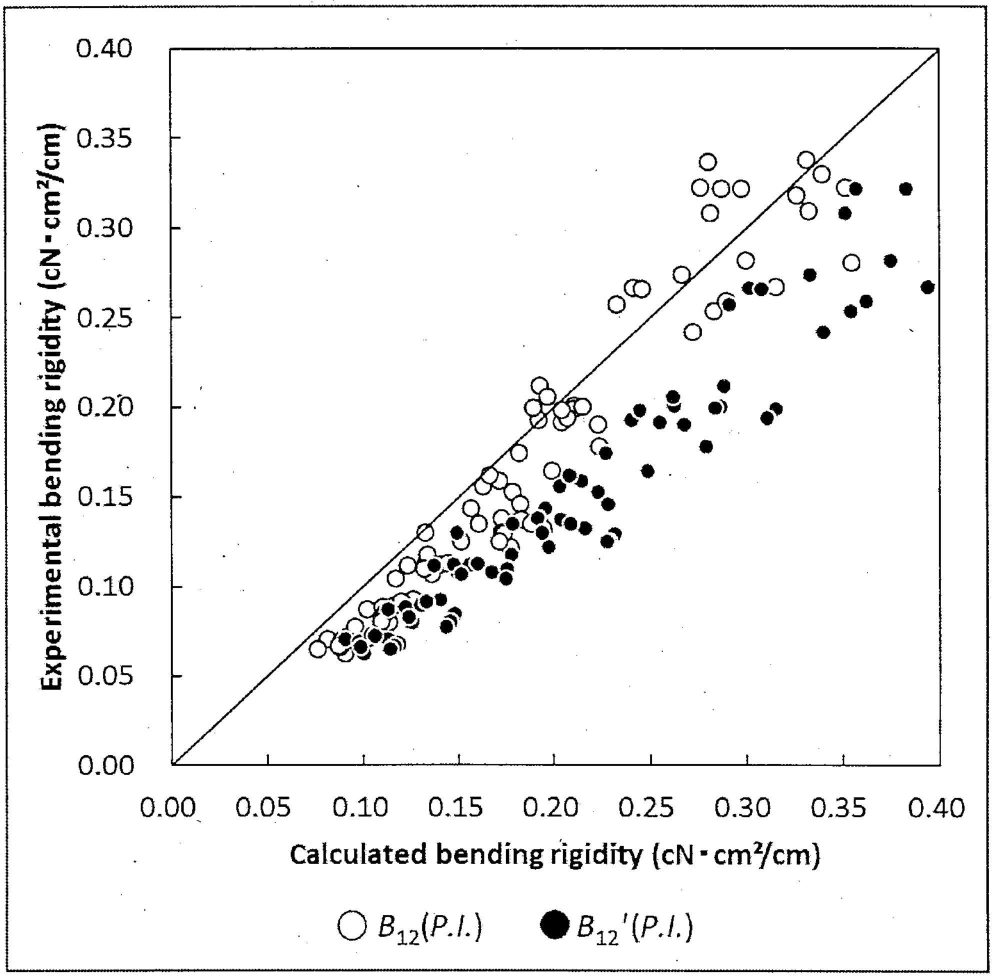


Figure 3.15 Comparison between experimental bending rigidities and theoretical bending rigidities using B_{12} (*P.I.*) and B_{12}' (*P.I.*).

Using bending rigidity values and the thickness of pressed interlining, B_{124} (*P.I.*) was introduced as a simple way to predict bending rigidity by Kanayama et al. However it was necessary to investigate the reason for using the method. In this study, it was found that the thickness and bending rigidity of adhesive interlining were changed by pressing. Therefore, using *P.I.* meant that the changes in adhesive interlining by pressing were already considered in the equation. Consequently the results of B_{12} (*P.I.*) were closer to experimental ones than B_{12} (*A.I.*) and B_{12}' (*A.I.*). The results of B_{12}' (*P.I.*) were higher than the experimental ones in the results from B_{12} (*P.I.*). It was not useful to use these properties in B_{12}' because the changes from pressing were already factored in the results of *P.I.* Therefore, equation B_{12} with *P.I.* should be better to predict a more accurate bending rigidity than B_{12}' (*P.I.*). However, the face fabric changes by pressing were not considered in the case of *P.I.* The equations were mainly affected by thickness and bending rigidity changes and also, in this study, it was found that the mechanical properties of face fabric were changed by pressing. Therefore, the thickness change on face fabric by pressing must be considered for predicting the bending rigidity of the laminated fabric. To consider the changes to the adhesive interlining and face fabric by pressing, *F.P.I.* was used to predict the bending rigidity of laminated fabric. The results of B_{12} (*F.P.I.*) and results of B_{12}' (*F.P.I.*) are shown in Figure 3.16. Root mean square of errors (RMSE) and coefficient of determination of experimental results and for each condition are shown in Table 3.5.

RMSE of B_{12} (*F.P.I.*) was lower than that of B_{12} (*P.I.*). Therefore, it was found that the results which considered thickness changes after pressing the face fabric gave a more exact prediction of the experimental ones. Consequently, it will be possible to predict the bending rigidity of the laminated fabrics with adhesive interlining with equation B_1 under *F.P.I.* conditions more precisely. Furthermore, Kanayama et al. [10, 11] calculated 3 types of face fabric (warp knit, plain woven and nonwoven). In their results, results of nonwoven agreed with those of the experimental ones. The results from the plain woven fabrics showed larger values than those of the experimental ones. However, the results of the woven fabric, which was used in this study, showed closer values to the experimental ones. This could be because of the technical improvement in manufacturing the adhesive interlining. The interlining cloth was getting thinner and adhesive agent mass was getting smaller than the samples from Kanayama et al. Efficiency improvement of the adhesive interlining reduced the space between face fabric and adhesive interlining after bonding. It made the decrease of the errors so that it was possible to predict the bending rigidity of laminated fabrics.

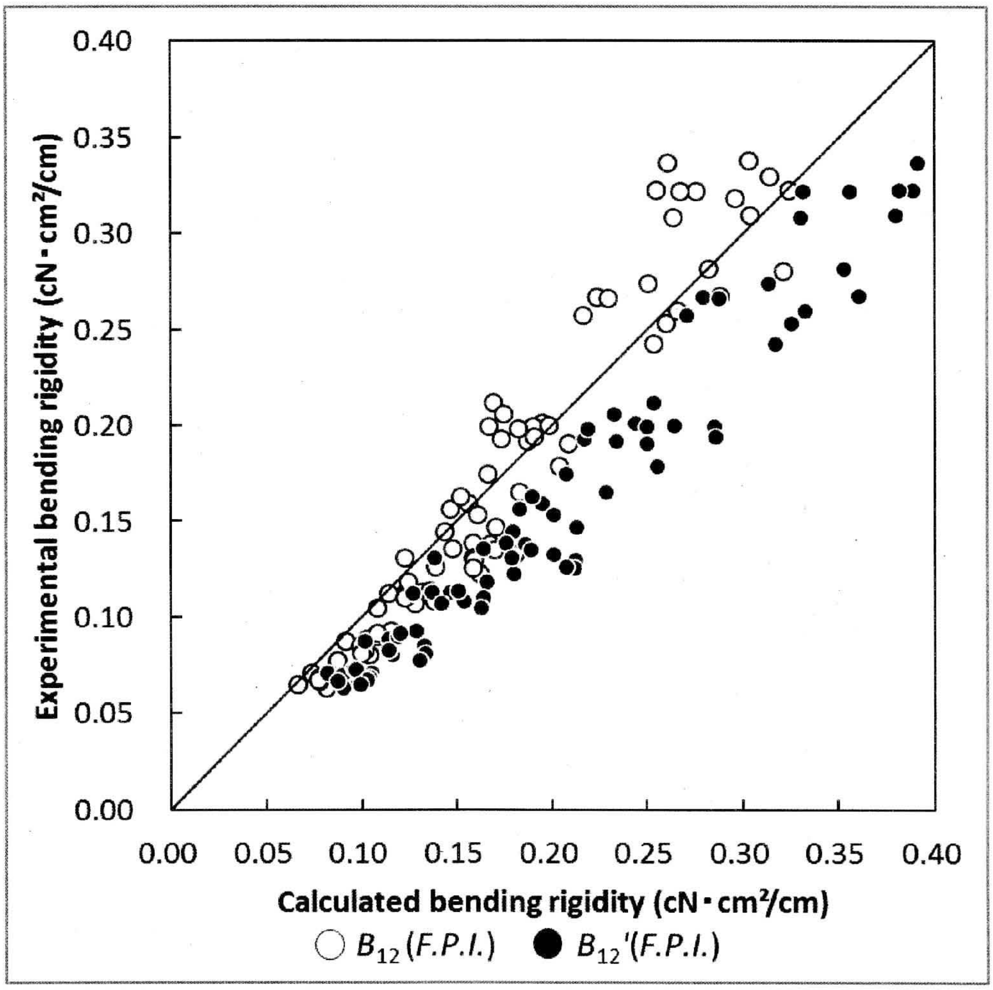


Figure 3.16 Comparison between experimental bending rigidities and theoretical bending rigidities using B_{12} (*F.P.I.*) and B_{12}' (*F.P.I.*).

Table 3.5 Root mean square of errors (RMSE) and coefficient of determination (R_2) between experimental results and those of each condition

Conditions	RMSE	R^2
B_{12} *(A.I.)* results and experimental results	0.0056	0.8817
B_{12}' *(A.I.)* results and experimental results	0.0046	0.8325
B_{12} *(P.I.)* results and experimental results	0.0039	0.9263
B_{12}' *(P.I.)* results and experimental results	0.0085	0.9355
B_{12} *(F.P.I.)* results and experimental results	0.0029	0.9264
B_{12}' *(F.P.I.)* results and experimental results	0.0062	0.9405

3.4 Conclusion

The changes of mechanical properties, for adhesive interlining, face fabric and laminated fabrics of these, by pressing were investigated and the predicting methods were verified with measured data. It was found that not only the properties of adhesive interlining but also the properties of face fabric changed in the pressing process. It was also found that the pressing process had also effects on cloth for adhesive interlining.

The predicting methods for bending rigidity of laminated fabric with adhesive interlining and face fabric suggested by Kanayama et al. based on laminate theory for the laminated fabric were verified. Comparing results of B_{12} and those of B_{12}', those of B_{12}', which considered the area of adhesive agent were closer to experimental results in the case of using mechanical properties of samples before pressing. However, B_{12} was closer to the experimental results in the case of results considering the pressing effects, which used bending rigidity and thickness of pressed interlining with B_{12}. Furthermore, the case of considering thickness of the pressed face fabric was more efficient at predicting bending rigidity of laminated fabric with B_{12}.

With these results, it was concluded that Equation (3.10) was useful to predict bending rigidity of laminated fabrics with adhesive interlining, with mechanical properties, the pressing effects on adhesive interlining and face fabric were considered. The entire predicted results for bending rigidities from this method agreed with experimental ones. For the prediction having higher accuracy, improvement of the further model will be necessary. Therefore, future studies will need to address this.

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Chapter 4

Prediction for bending rigidity of laminated fabric with adhesive interlining taken into account tensile and in-plane compressive moduli of components

Chapter 4 Prediction for bending rigidity of laminated fabric with adhesive interlining taken into account tensile and in-plane compressive moduli of components

4.1 Introduction

In Chapter 3, prediction methods, laminate theory and Kanayama's model [1, 2] of bending rigidity for laminated fabric with adhesive interlining were verified both theoretically and experimentally. According to the verification, the prediction method for bending rigidity was proposed, considering the pressing effects on adhesive interlining and face fabric as well. The entire predicted results for bending rigidities from that method showed a better agreement with experimental ones than those results from existing prediction methods. However, for highly accuracy of prediction, an improvement for the new model is necessary to consider. Therefore, in this chapter, we proposed a new prediction method taking into account the elastic modulus for bending rigidity given by *EI*, where *E* is elastic modulus and *I* is the moment of inertia of area, derived based on the laminate theory.

EI values from the bending test are commonly used as bending rigidity. It is known that *E* in *EI* disagrees with the elastic modulus for the tensile modulus of a fabric. There are some studies about differences between those moduli. Osawa et al. [3] investigated the relationship between the extensional and in-plane compressive behavior of the fabrics using homogeneous plastic film, for which the Young's modulus is known, and showed the differences between extensional and bending moduli of the fabrics. Accordingly, the relationship between tensile moduli and bending moduli on a single fabric are independent. In the case of a single fabric, no extension or compression on the neutral axis occurs while bending. However, while bending a laminated fabric, both composed fabrics separately undergo deformation, such as extension and compression.

At the same time, neutral axes of both fabrics could be extended or compressed, respectively. The extension or compression of neutral axes for both fabrics should be considered as a matter of bending rigidity for laminated fabric. Therefore, in this study, elastic moduli from tension and in-plane compression for each fabric before laminating and elastic moduli from bending rigidity were considered independently and a new prediction method for the bending rigidity of laminated fabric with adhesive interlining, considering tensile and in-plane compressive moduli, was proposed.

Dawes et al. [4] suggested a similar idea for predicting bending rigidity, which considers the difference between tensile and bending properties. They used four types of face fabrics, adhesive interlinings and a paper to measure the apparent tensile and in-plane compressive moduli. They made the two types of laminated fabrics, namely an adhesive interlining with a paper and a face fabric with a paper with a water-based polyvinyl alcohol adhesive. The tensile and in-plane compressive moduli were measured and calculated with those laminated fabrics. However, the predicted results did not agree with the experimental ones in their study, and the number of experimental samples was insufficient.

Thus, in this chapter, we proposed an equation for calculating the in-plane compressive modulus, considering adhesive agent properties by theoretical derivation from the relationship between tensile and bending properties. From an experimental point of view, laminated fabrics with woven fabrics and adhesive interlinings were used for measuring those values. Consequently, the new prediction method for the bending rigidity of laminated fabric with adhesive interlining was verified with theoretical and experimental results.

4.2 Theoretical discussion for bending rigidity of laminated fabric considering tensile and in-plane compressive moduli

4.2.1 Basic assumptions and structure model of laminated fabric

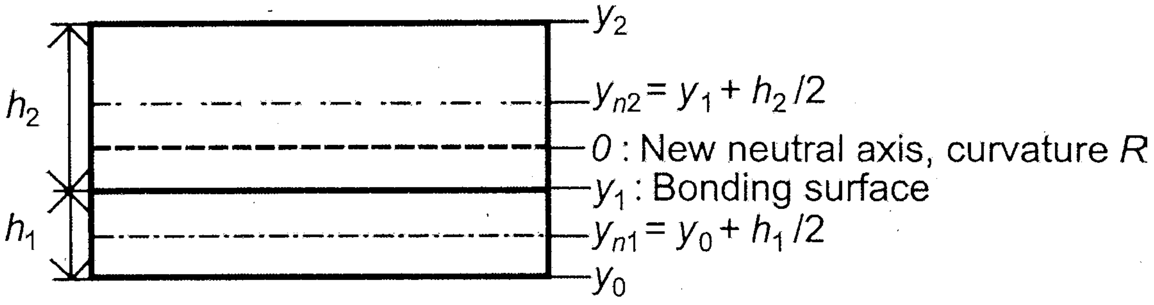

Figure 4.1 Structure model of laminated fabric

Bending laminated fabric made of two fabrics, such as woven fabric and adhesive interlining, of which the moduli are different, was investigated in this study. The adhesive and pressing effects for bonding those samples were considered already included by preparing pressed samples. The relationships between the tensile and in-plane compressive moduli and the bending deformation of laminated fabric with adhesive interlining were derived under the assumptions as follows, for simplicity.

Firstly, the neutral axes of the face fabric and adhesive interlining before bonding pass through the centroid of those while bending. Secondly, the bending rigidities of the face fabric and adhesive interlining are independent from the tensile and in-plane compressive moduli of both fabrics at those centroids and the tensile and in-plane compressive moduli are considered as constants.

The structure model of laminated fabric with adhesive interlining, cloth$_1$ and face fabric, cloth$_2$ is shown in Figure 4.1. h_1 and h_2 are the thickness of cloth$_1$ and cloth$_2$, respectively. b is the breadth of cloths, y_{n1} and y_{n2} are the coordinates of the original neutral axis of cloth$_1$ and cloth$_2$, respectively, from the neutral surface in the cross section of the laminated fabric. y_0 and y_1, y_2 are the coordinates of surface and boundaries from the neutral surface in the cross section of the laminated fabric.

4.2.2 Moment of face fabric, adhesive interlining and laminated fabric

When the laminated fabric is bent, the strain distribution in the cross section is continuous. However the stress distribution is discontinuous at the boundary. The neutral surface is not consistent to the symmetry axis of the cross section. Stress of a laminated fabric can be express with the sum of stress from bending by neutral surface and that from strain by neutral surface.

From $\sigma=\varepsilon E=E\eta/R$, where σ is the stress, ε is the strain, E is the modulus, R is the radius of curvature of the neutral surface for the laminated fabric after bending and η is the distance from the neutral surface in the laminated fabric, assuming Bernoulli-Euler law, the bending moment, M_1, of cloth $_1$ is given by as follows:

$$M_1=\int_{A_1}\eta\sigma dA_1=\int_{A_1}\frac{E}{R}\eta^2 dA_1=\int_{y_0}^{y_1}\frac{E}{R}\eta^2 b d\eta=\frac{Eb}{R}\left[\frac{\eta^3}{3}\right]_{y_0}^{y_1}=\frac{Eb}{R}\left\{\left[\frac{\eta^3}{3}\right]_{y_0}^{y'_{n1}}+\left[\frac{\eta^3}{3}\right]_{y'_{n1}}^{y_1}\right\} \tag{4.1}$$

where $y_{n1}=y_0+h_1/2$.

On the other hand, we can divide the strain as follows:

$$\varepsilon=\frac{\eta}{R}=\frac{y_{n1}}{R}+\frac{\eta-y_{n1}}{R}$$

The first term in the right is the uniform strain over the cross section of cloth$_1$ in the laminated fabric as bent. The second term is the strain from curvature, R at the neutral plane cloth$_1$ as bent alone.

When we set different elastic moduli for each strain as E_{1T}, modulus for tension or compression of cloth$_1$ and E_{1B}, modulus for bending, the stress on the section corresponding to the strain is

$$\sigma=\frac{y_{n1}}{R}E_{1T}+\frac{\eta-y_{n1}}{R}E_{1B}$$

The moment of the stress is as follows:

$$
\begin{aligned}
M_1 &= \int_{A1} \eta\sigma dA_1 = \int_{A_1} \eta\left(\frac{\eta - y_{n1}}{R}E_{1B} + \frac{y_{n1}}{R}E_{1T}\right)dA_2 \\
&= \frac{E_{1T}}{R}y_{n1}\int_{A1}\eta dA_1 + \frac{E_{1B}}{R}\int_{A1}\left(\eta^2 - \eta y_{n1}\right)dA_1 = \frac{E_{1T}}{R}y_{n1}\int_{y_0}^{y_1}\eta b d\eta + \frac{E_{1B}}{R}\int_{y_0}^{y_1}\left(\eta^2 - \eta y_{n1}\right)b d\eta \qquad (4.1)' \\
&= \frac{E_{1T}}{R}y_{n1}b\left[\frac{\eta^2}{2}\right]_{y_0}^{y_1} + \frac{E_{1B}}{R}b\left[\frac{\eta^3}{3} - y_{n1}\frac{\eta^2}{2}\right]_{y_0}^{y_1}
\end{aligned}
$$

where $y_0 = y_{n1} - h_1/2$ and $y_1 = y_{n1} + h_1/2$, Equation (4.1)' is as follows:

$$M_1 = \frac{1}{R}\left(E_{1T}A_1 y_{n1}{}^2 + E_{1B}I_1\right) \qquad (4.2)$$

The bending moment of cloth$_2$, M_2 can be also expressed as follows:

$$M_2 = \frac{1}{R}\left(E_{2T}A_2 y_{n2}{}^2 + E_{2B}I_2\right) \qquad (4.3)$$

where $A_1 = bh_1$, $A_2 = bh_2$ and I_1 and I_2 are the moment of inertia of area for cloth$_1$ and cloth$_2$, respectively.

The first term in Equation (4.2) can be regarded as the bending moment by the uniform stress caused by tensile or compressive strain, of the *neutral axes*, y_{n1} during bending. The second term can be considered as bending moment by curvature, R. From the assumptions, the each modulus in Equation (4.2) were considered independently and those moduli were considered respectively as E_{1B}, modulus for bending and E_{1T}, modulus for tension or compression of cloth$_1$.

Similarly, for Equation (4.3), E_{2B} is the modulus for bending and E_{2T} is the modulus for tension or compression of cloth$_2$. The case of $y_{n1}>0$ means that the modulus is for the tensile strain and the case of $y_{n1}<0$ means the modulus is for the compressive strain.

With those calculations, the bending moment of a laminated fabric, M is given by

$$M = M_1 + M_2 = \frac{1}{R}\left(E_{1T}A_1 y_{n1}{}^2 + E_{2T}A_2 y_{n2}{}^2 + E_{1B}I_1 + E_{2B}I_2\right) \qquad (4.4)$$

In Equation (4.4), $E_{1B}I_1$ and $E_{2B}I_2$ are the bending rigidities of cloth$_1$ and cloth$_2$, respectively, and the terms in parentheses refer to bending rigidity of laminated fabric.

4.2.3 Neutral surface of laminated fabric

In Equation (4.4), y_{n1} and y_{n2} are unknown. If the neutral axis of the laminated fabric is given, they can be obtained. Because both resultant forces of the stress by the bending of cloth$_1$ and cloth$_2$ are zero, the resultant stress by extension and compression of each neutral axis by the bending becomes zero. Then

$$N = \frac{E_{1T} y_{n1} A_1}{R} + \frac{E_{2T} y_{n2} A_2}{R} = 0 \qquad (4.5)$$

where y_{n1}/R is the strain of the neutral surface for cloth$_1$ and y_{n2}/R is the strain of the neutral surface for cloth$_2$.

Therefore, we derive

$$E_1 h_1 y_{n1} + E_2 h_2 y_{n2} = 0 \qquad (4.6)$$

Between E_{1T} and E_{2T}, if one is the modulus for tension, the other is the modulus for compression and the opposite case is also possible according to the direction of the curvature.

From $y_{n2}=y_1+h_2/2$ and $y_{n1}=y_0+h_1/2$, $y_1=y_0+h_1=y_{n1}+h_1/2$ and $y_2=y_1+h_2$, we obtain

$$y_{n2} = y_{n1} + \frac{(h_1 + h_2)}{2} \qquad (4.7)$$

By substituting Equation (4.7) into (4.6), we obtain

$$E_{1T} h_1 y_{n1} + E_{2T} h_2 y_{n1} + E_{2T} h_2 \frac{(h_1 + h_2)}{2} = 0 \qquad (4.8)$$

Then,

$$y_{n1}\left(E_{1T}h_1+E_{2T}h_2\right)=-E_{2T}h_2\frac{\left(h_1+h_2\right)}{2}$$

Therefore, when $E_{1T}h_1+E_{2T}h_2\neq 0$, we obtain

$$y_{n1}=-\frac{E_{2T}h_2\left(h_1+h_2\right)}{2\left(E_{1T}h_1+E_{2T}h_2\right)} \tag{4.9}$$

In the same way, we obtain

$$y_{n2}=\frac{E_{1T}h_1\left(h_1+h_2\right)}{2\left(E_{1T}h_1+E_{2T}h_2\right)} \tag*{(4.9)'}$$

4.2.4 Bending rigidity of laminated fabric

With Equation (4.4) and (4.9), we can obtain the moment of a laminated fabric as follows:

$$M=\frac{1}{R}\left(E_{1T}A_1y_{n1}{}^2+E_{2T}A_2\left(y_{n1}+\frac{h_1+h_2}{2}\right)^2+E_{1B}I_1+E_{2B}I_2\right) \tag{4.10}$$

With Equation (4.10), we also derive

$$y_{n2}=y_{n1}+\frac{h_1+h_2}{2}=\frac{E_{1T}h_1\left(h_1+h_2\right)}{2\left(E_{1T}h_1+E_{2T}h_2\right)} \tag{4.11}$$

and Equation (4.9) can be rewritten as follows by substituting Equation (4.11):

$$M=\frac{1}{R}\left(\frac{bE_{1T}h_1E_{2T}h_2}{E_{2T}h_2+E_{1T}h_1}\left(\frac{h_1+h_2}{2}\right)^2+E_{1B}I_1+E_{2B}I_2\right) \tag{4.12}$$

where

$$\overline{EI}=\frac{bE_{1T}h_1E_{2T}h_2}{E_{2T}h_2+E_{1T}h_1}\left(\frac{h_1+h_2}{2}\right)^2+E_{1B}I_1+E_{2B}I_2 \tag{4.13}$$

If we express Equation (4.13) per breadth, and use $A_1 = bh_1$ and $A_2 = bh_2$, the bending rigidity of a laminated fabric per breadth is

$$\frac{\overline{EI}}{b} = \frac{1}{b}\frac{E_{1T}A_1E_{2T}A_2}{E_{2T}A_2 + E_{1T}A_1}\left(\frac{h_1+h_2}{2}\right)^2 + \frac{E_{1B}I_1}{b} + \frac{E_{2B}I_2}{b} \tag{4.14}$$

Bending rigidity per breadth can be measured by bending test such as KES-FB2 [4].

4.2.5 Calculating bending rigidity of laminated fabric

The bending rigidities, B_1 and B_2 of cloth$_1$ and cloth$_2$, respectively, can be expressed as per width.

$$B_1 = \frac{E_{1B}I_1}{b}, \quad B_2 = \frac{E_{2B}I_2}{b} \tag{4.15}$$

If the moment is proportional to the curvature, the measured bending rigidity by KES-FB2 can be used for these.

When we set T_2 and T_1 as apparent tensile modulus and apparent in-plane compressive modulus, they can be expressed as follows:

$$T_1 = \frac{E_{1T}A_1}{b}, T_2 = \frac{E_{2T}A_2}{b} \tag{4.16}$$

In addition, the bending rigidity per unit breadth of a laminated fabric with adhesive interlining is

$$\frac{\overline{EI}}{b} = B_{12} = \frac{T_1T_2}{T_1+T_2}\left(\frac{h_1+h_2}{2}\right)^2 + B_1 + B_2 \tag{4.17}$$

where B_{12} is the bending rigidity of laminated fabric with adhesive interlining and face fabric.

The concept of Equation (4.17) was also proposed by Dawes et al. [4]. In Equation (4.17), it is found that the bending rigidity of a laminated fabric with adhesive interlining is affected extremely by thickness of both cloths. In assumptions, we considered that T_1 and T_2 are linear function on bending rigidity if they are constant. Here, it should be noticed that T_2 is apparent tensile modulus and T_1 is apparent in-plane compressive modulus when cloth$_1$ is in outside and cloth$_2$ is in inside of laminated fabric while bending. On the other hand, T_2 is an apparent tensile modulus and T_1 is an apparent in-plane compressive modulus in the opposite case.

In this equation, the apparent tensile modulus, T_2 can be obtained by a tensile tester. However the apparent in-plane compressive modulus, T_1 is hard to measure by a test especially in the case of fabric. Even though the apparent in-plane compressive modulus cannot be measured directly, T_2, B_1, B_2, B_{12}, h_1 and h_2 can be obtained experimentally. Therefore, from Equation (4.17), we can derive as follows:

$$T_1 = \frac{-T_2\{B_{12} - (B_1 + B_2)\}}{B_{12} - (B_1 + B_2) - T_2\left(\frac{h_1 + h_2}{2}\right)^2} \qquad (4.18)$$

With the same calculations, we can obtain the opposite case of in-plane compressive modulus as follows.

$$T_2 = \frac{-T_1\{B_{12} - (B_1 + B_2)\}}{B_{12} - (B_1 + B_2) - T_1\left(\frac{h_1 + h_2}{2}\right)^2} \qquad (4.19)$$

Therefore, T_1 can be obtained with Equation (4.18).

To confirm Equation (4.18), the tests with one kind of cloth$_2$, several kinds of cloth$_1$ and those laminated fabrics need to be carried out. In the case of laminated fabric with cloth$_2$ at outside and cloth$_1$ at inside, if the T_1 values of cloth$_1$ in the cases of laminated fabrics with different cloth$_2$ from Equation (4.18) are similar, the T_1 values are the apparent in-plane compressive modulus of cloth$_1$. When T_1 values were obtained, the bending rigidities of different laminated fabrics can be predicted with Equation (4.17) with obtained T_1 values.

4.3 Experimental

To verify the proposed equations, four types of face fabric, 10 types of adhesive interlining and combined 40 types of laminated fabric bonded with adhesive interlining which were the same samples in Chapter 3 (tables 3.1, 3.2 and 3.3) were also prepared as experimental samples. Those bending rigidities, tensile properties and thicknesses were measured by the Kawabata Evaluation System (Katotech Co. KES-FB). We controlled the weft density of five adhesive interlinings gradually increasing and we call those as CE-interlining. We also controlled the number of adhesive agent dots per area of five adhesive interlinings gradually increasing and we call those as DP-interlining. Bonding interlining to the face fabric was carried out by a press machine (KOBE DENKI KOGYOSYO, BP-V4812D) and the bonding condition was at 150°C, under 29.4 kPa loads and for 10 s of pressing time.

Furthermore, it was clear from Chapter 3 that the pressing effect on the mechanical properties of laminate fabric after the laminating procedure needs to be considered. Therefore, pressed samples, which were pressed under the same bonding condition of laminating adhesive interlining with face fabric, were also prepared as samples in this study. Face fabric samples were pressed alone under the same condition of bonding interlining. For pressing adhesive interlining alone, polytetrafluoroethylene (PTFE) film (NITTO, No.900, 0.05mm, 300mm) was prepared for bonding the adhesive interlining. We bonded the adhesive interlining to PTFE film and removed the PTFE film from those laminated fabrics. Those samples were called 'pressed face fabric' and 'pressed adhesive interlining', respectively.

Every test was carried out under standard conditions (a temperature of 20±1°C and a relative humidity of 65±5%). All samples were treated under standard conditions for 24 hours. Every test was conducted for five samples and the average was used.

Bending properties of each sample were measured by the KES-FB2 pure bending tester. [5] The thickness of each sample was measured by the KES-FB3 compression tester at 49 Pa load. The tensile properties of each sample were measured by the KES-FB1 tensile tester until the maximum load of 490 cN/cm.

To determine the T_2 values of face fabric, it was necessary to consider the strain occurring during bending a fabric by KES-FB2. The curvature range of the bending rigidity by KES-FB2 is 0.5~1.5 cm^{-1}. If the neutral surface, η, is determined as 0.025 cm, which is assumed to be about one-quarter of the laminated fabric thicknesses, the strain range of a laminated fabric is 1.25%~3.75%. Therefore, the T_2 values were obtained from the load at about 2.5% of the load-elongation curve, which is the elongation at curvature 1 cm^{-1}, by a tensile tester, KES-FB1. With those obtained T_1 values, T_1 values were calculated by Equation (4.18), and the bending rigidities of laminated fabric with adhesive interlining were predicted by Equation (4.17)

4.4 Results and discussion

4.4.1 The difference between moduli from tensile and bending of face fabrics and adhesive interlinings

Before verifying Equations (4.17) and (4.18), the difference between E_b, a modulus for bending rigidity, and E_t, a modulus for tensile properties, which was mentioned previously, was investigated by comparing those moduli of prepared samples. It was shown by some research that the compressive modulus was lower than the tensile modulus. [6] The tensile strain by bending will be smaller than compressive strain. Therefore, the values of E_t were obtained from the load at 2.5% of the load elongation curve by the tensile tester, KES-FB1.

In this study, B values of KES-FB2 in the case where a face fabric is outside while bending were used, because an adhesive interlining is usually used inside of clothing in the field. The values of E_b were obtained from B values by KES-FB2, a pure bending tester. Woven fabrics and adhesive interlinings were considered as a rectangle. Figure 4.2, Figure 4.3 and Figure 4.4 show the difference between E_b and E_t of face fabrics and adhesive interlinings. The values of E_b and E_t were subsequently different and the values of Et were higher than those of E_b. The difference between the tensile and bending modulus of adhesive interlining is larger than that of face fabrics. As a result, it was confirmed that E_b and E_t are apparently different experimentally.

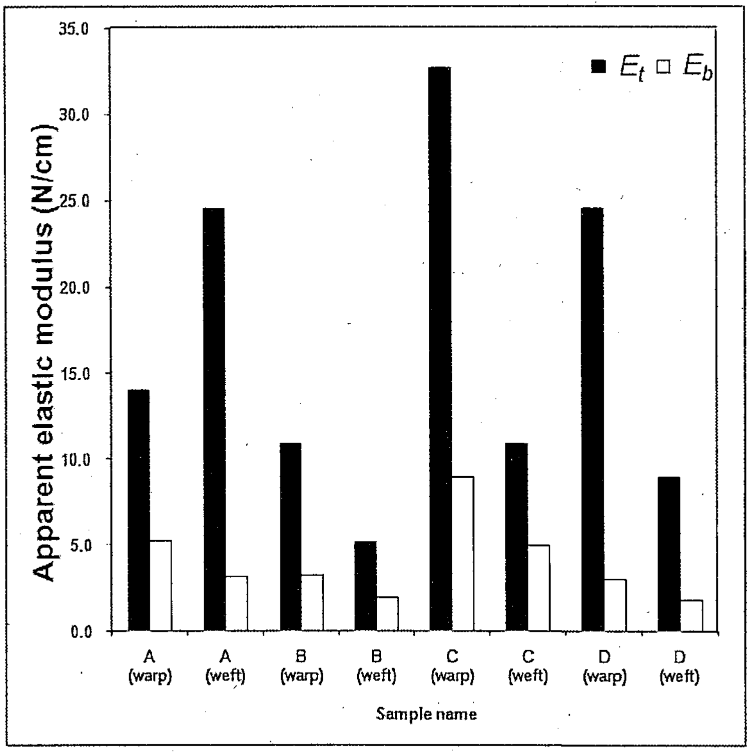

Figure 4.2 Comparison moduli from tension and bending of face fabric.

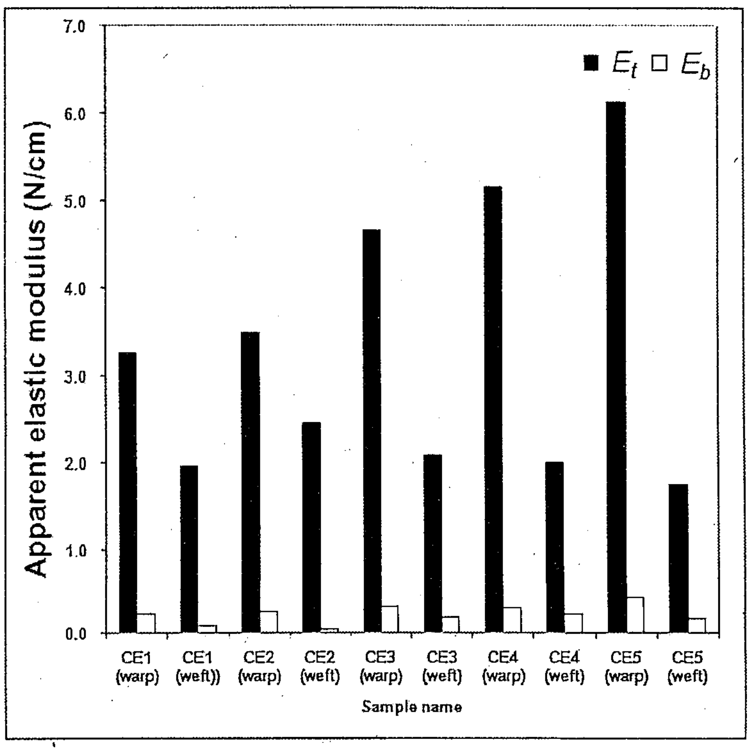

Figure 4.3 Comparison moduli from tension and bending of CE-interlining.

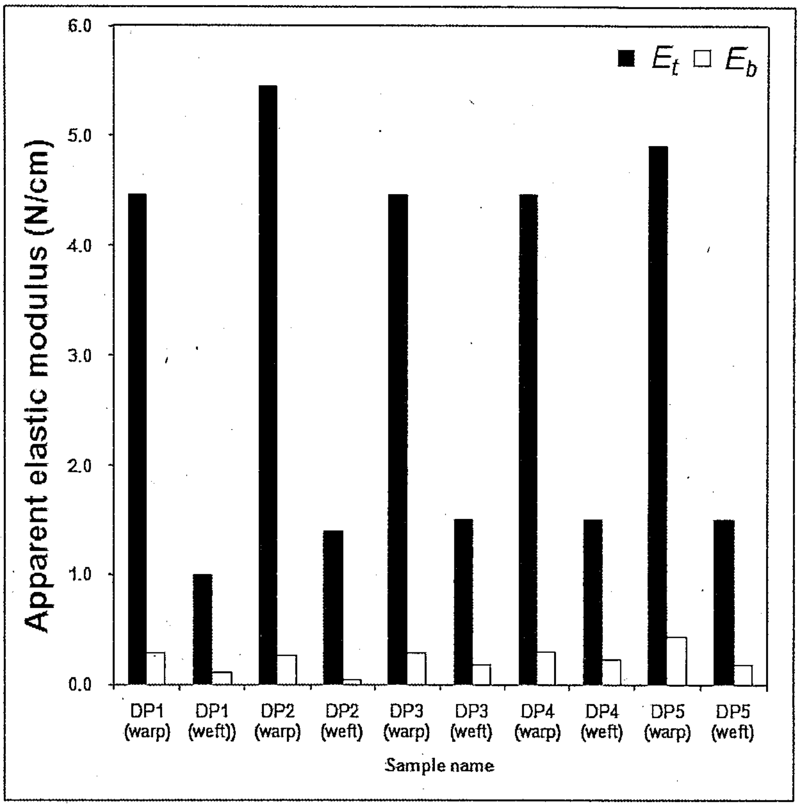

Figure 4.4 Comparison moduli from tension and bending of DP-interlining.

4.4.2 Calculating T_1 and T_2 values of face fabrics and adhesive interlinings

In this study, the pressed samples were used for measuring bending rigidity, thickness and tensile properties; because it was found that the predicted results considering the pressing effect were in better agreed with experimental results in Chapter 3. The measured bending rigidities and thicknesses of pressed samples are shown in Table 4.1 and Table 4.2.

Table 4.1 The bending rigidities and thicknesses of pressed face fabrics

Sample name	Bending rigidity (cN ·cm^2/cm)	Thickness (cm)
P-A(warp)	0.1353	0.0516
P-A(weft)	0.0758	
P-B(warp)	0.0569	0.0497
P-B(weft)	0.0373	
P-C(warp)	0.1389	0.0435
P-C(weft)	0.0647	
P-D(warp)	0.0512	0.0484
P-D(weft)	0.0255	

Table 4.2 The bending rigidities and thicknesses of pressed interlinings

Sample name	Bending rigidity (cN ·cm^2/cm)	Thickness (cm)	Sample name	Bending rigidity (cN ·cm^2/cm)	Thickness (cm)
P-CE-1(warp)	0.0058	0.0265	**P-DP-1(warp)**	0.0064	0.0235
P-CE-1(weft)	0.0051		**P-DP-1(weft)**	0.0024	
P-CE-2(warp)	0.0058	0.0246	**P-DP-2(warp)**	0.0059	0.0239
P-CE-2(weft)	0.0030		**P-DP-2(weft)**	0.0020	
P-CE-3(warp)	0.0060	0.0242	**P-DP-3(warp)**	0.0074	0.0245
P-CE-3(weft)	0.0035		**P-DP-3(weft)**	0.0033	
P-CE-4(warp)	0.0070	0.0237	**P-DP-4(warp)**	0.0059	0.0239
P-CE-4(weft)	0.0039		**P-DP-4(weft)**	0.0027	
P-CE-5(warp)	0.0085	0.0226	**P-DP-5(warp)**	0.0062	0.0247
P-CE-5(weft)	0.0039		**P-DP-5(weft)**	0.0013	

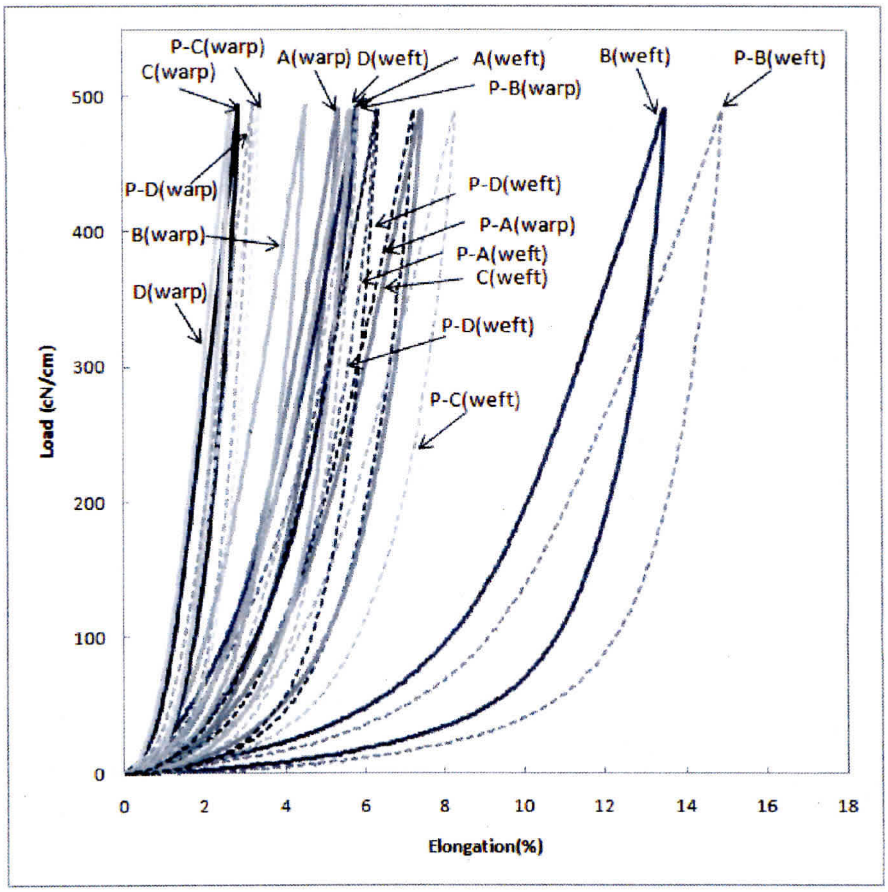

Figure 4.5 Load-Elongation curves of before pressing and after pressing for face fabrics.

In Chapter 3, the parameter changes of bending rigidity and thickness after pressing were considered. However, the changes of tensile properties were not considered. Therefore, the changes of tensile properties by pressing are investigated in this chapter. Load-elongation curves of face fabrics before pressing and after pressing are shown in Figure 4.5. As shown in Figure 4.5, it was found that the elongation of face fabrics at the same load after pressing became larger than those before pressing. It will be necessary to investigate the reasons for the elongation changing in the future. In this study, the case where a face fabric is outside while bending is considered. Therefore, the apparent tensile modulus, T_2, of face fabrics and apparent in-plane compressive modulus, T_1, of adhesive interlinings were considered. Obtained T_2 values, calculated T_1 values and the average T_1 values of all samples are shown in Table 4.3 and Table 4.4.

Table 4.3 T_2 values of face fabrics

Sample name	T_2values (N/cm)
A(warp)	14.7
A(weft)	29.5
B(warp)	23.4
B(weft)	4.3
C(warp)	115.0
C(weft)	13.3
D(warp)	126.4
D(weft)	23.3

Table 4.4 T_1 values of pressed interlinings

Sample name	T_1values from A (N/cm)	T_1values from B (N/cm)	T_1values from C (N/cm)	T_1 values from D (N/cm)	Average of T_1 values (N/cm)
CE-1(warp)	0.70	0.68	0.92	0.62	0.73
CE-1(weft)	0.34	0.37	0.31	0.28	0.33
CE-2(warp)	0.81	0.68	1.06	0.75	0.82
CE-2(weft)	0.39	0.36	0.39	0.32	0.37
CE-3(warp)	0.87	0.63	1.06	0.80	0.84
CE-3(weft)	0.41	0.38	0.40	0.31	0.37
CE-4(warp)	0.93	0.78	1.15	0.90	0.94
CE-4(weft)	0.41	0.39	0.40	0.33	0.38
CE-5(warp)	1.06	0.89	1.24	1.06	1.06
CE-5(weft)	0.40	0.42	0.42	0.35	0.40
DP-1(warp)	1.29	1.08	1.47	1.05	1.23
DP-1(weft)	0.31	0.32	0.36	0.28	0.32
DP-2(warp)	1.39	0.10	1.58	1.09	1.26
DP-2(weft)	0.37	0.34	0.59	0.30	0.40
DP-3(warp)	1.48	1.02	1.67	1.17	1.33
DP-3(weft)	0.35	0.35	0.44	0.30	0.36
DP-4(warp)	1.45	1.06	1.58	1.15	1.31
DP-4(weft)	0.33	0.32	0.38	0.30	0.33
DP-5(warp)	1.32	0.99	1.54	1.07	1.24
DP-5(weft)	0.33	0.30	0.33	0.28	0.31

The T_1 values of adhesive interlining from different face fabrics were close to each other. However, the calculated results were not exactly in agreement with each other, even though small differences were found, depending on samples. The reason could be the nonlinearity of fabric and adhesive permeation. The woven fabric has entirely non-linear tensile properties. However, the method to obtain T_2 values used the load at 2.5% elongation of the load-elongation curve and those curves do not show the non-linearity of woven fabric entirely. Because of the non-linearity of tensile properties for woven fabric, there would be some differences between T_1 values, depending on the types of face fabrics.

Furthermore, the permeation of adhesive agent on the adhesive interlining could be another reason for differences. The permeation of adhesive agent was different depending on different types of face fabric, so the effects on mechanical properties by laminating adhesive interlining could be different. Among the calculated results, the results of T_1 for adhesive interlinings from face fabric C are slightly larger than those of other face fabrics, as shown in Table 4.4. The reason could be due to the assumptions that were mentioned for the first procedure. We assumed that the neutral axis of face fabric and adhesive interlining passes through the neutral axis of those while bending. However, depending on the structure and yarn properties of woven fabric, the placement of the neutral axis could be changed. In particular, face fabric C has the possibility not to pass through the centroid. It will be necessary to investigate this point in the future. Including the differences of face fabric C, the entire calculated results were similar each other. Therefore, it was possible to consider the T_1 values as apparent in-plane compressive moduli of adhesive interlinings.

4.4.3 Predicting the bending rigidities of laminated fabrics

In this study, the averages of T_1 values for adhesive interlinings from all four face fabrics, as shown in Table 4.4, were used for calculating bending rigidity to reduce experimental errors, depending on samples as mentioned previously. T_2 values of face fabric and the average T_1 values for adhesive interlining were used for verifying Equation (4.17) in order to predict the bending rigidity of laminated fabric with adhesive interlining. The predicted results with T_2 and the averages of T_1 values from parameters before pressing and after pressing are shown in Figure 4.6 and Figure 4.7 respectively. The absolute errors (AE-%) and the mean absolute percentage errors (MAPE-%) for overall absolute errors are shown in Table 4.5.

Table 4.5 Mean absolute percentage error (MAPE-%) for aver all absolute errors (%) of all samples

Mean absolute percentage error (MAPE-%) for aver all absolute errors (%) of all samples		
Laminated model	New model with before pressing	New model with after pressing
14.74	7.79	6.31

The entire predicted results were significantly close to the experimental results. In particular, the results of weft direction for all samples were closer to the experimental ones than those of warp direction for all samples, as shown in Figure 4.6. The reason why the results in the weft direction were closer than the results in the warp direction was due to the T_2 values from tensile properties, which were less non- linear properties. The load-elongation curves of the weft direction showed linear properties between 0% and about 2.5% elongation, closer to the experimental results than those of warp direction. The differences with predicted results of face fabric C were larger than those of the others, as shown in Figure 4.6.

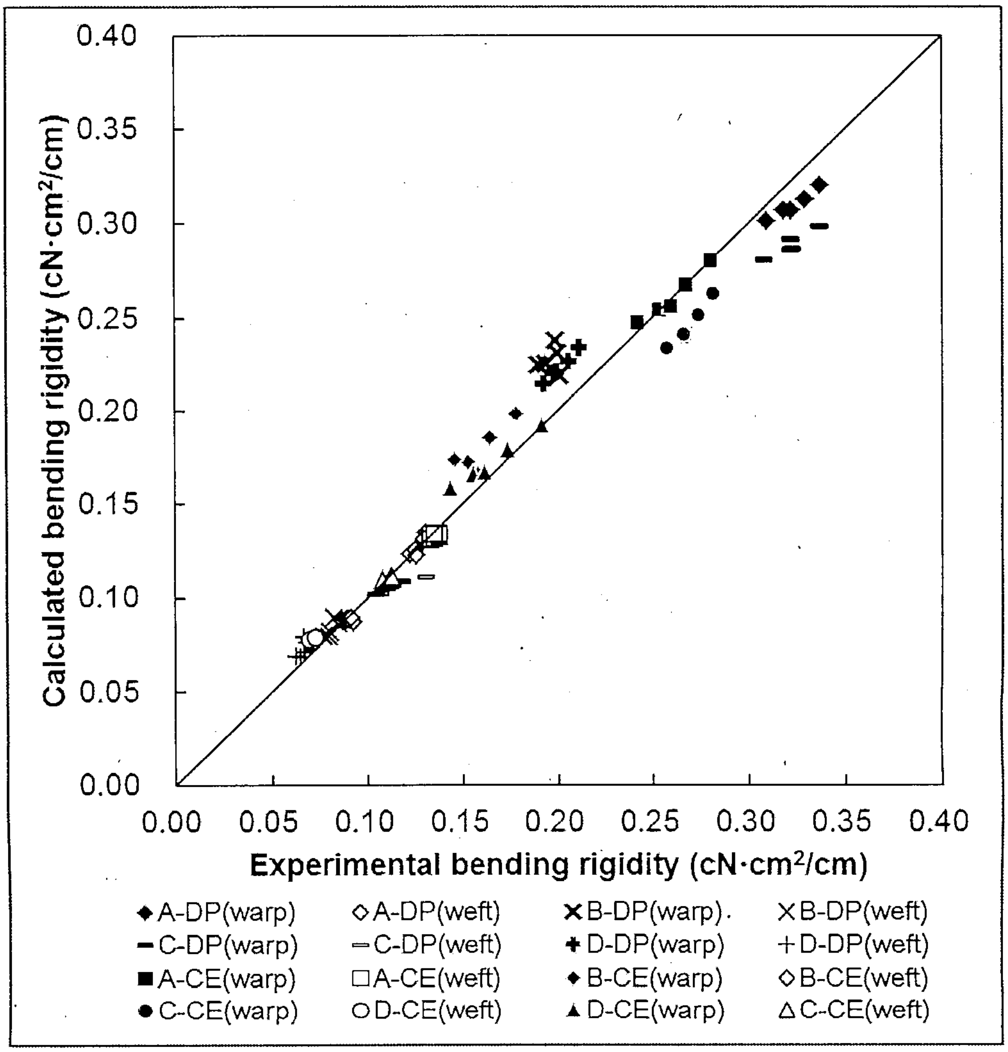

Figure 4.6 Comparison calculated bending rigidity and experimental bending rigidity with pressed samples.

The reasons for some differences in the results of face fabric C were considered to be the errors of the in-plane compressive moduli for face fabric C. Even though the predicted results for the tensile and in-plane compressive moduli with face fabric C showed some differences, the results still showed high agreement with this method compared to results from the laminate model. For the case of face fabric C, it will be necessary to be considered the precise reasons and another method to reduce the errors in the future. Moreover, the predicted results with parameters of samples after pressing were closer to experimental results that those of samples after pressing, as shown in Figure 4.7.

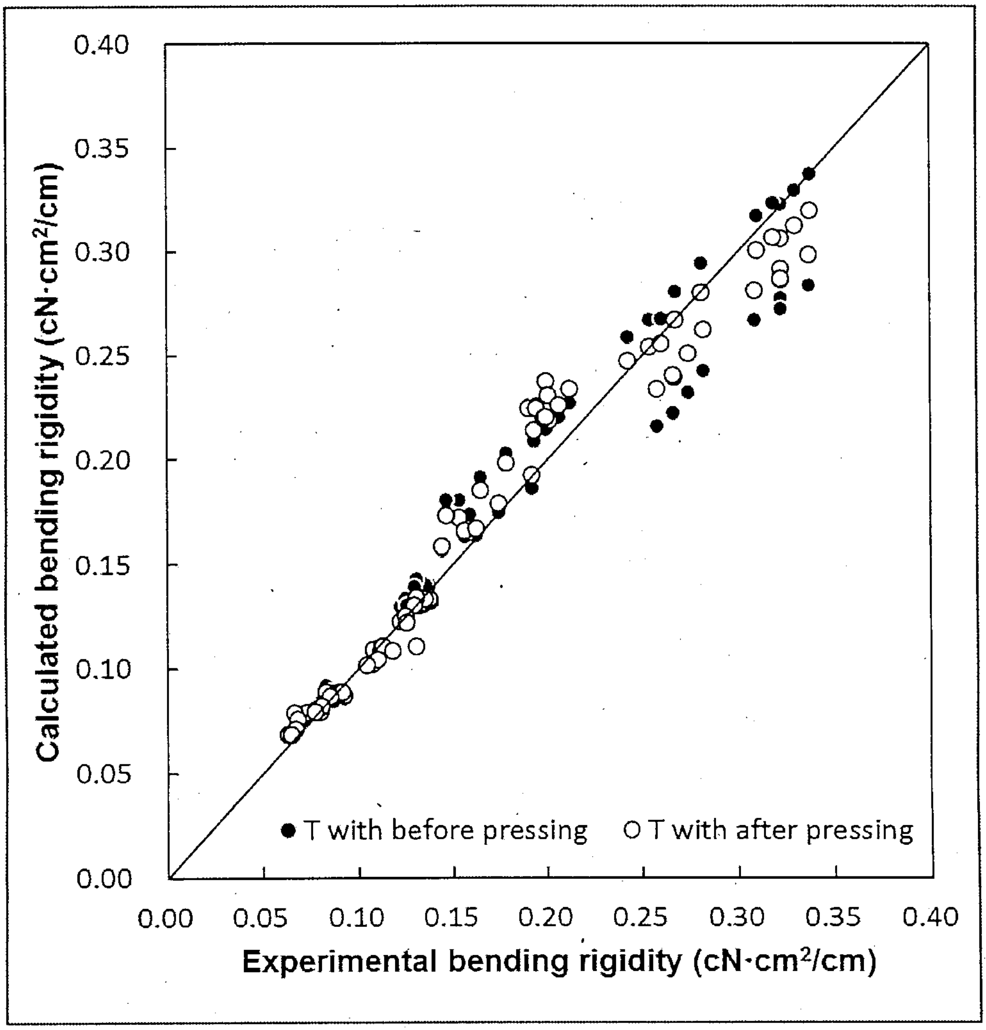

Figure 4.7 Comparison calculated bending rigidity and experimental bending rigidity with after pressing samples and before pressing samples.

These were the same results in the Chapter 3. Pressing effects on the adhesive interlining and face fabric were found to be important factors to predict the bending rigidity of laminated fabric. Elongation at 490 cN/cm load of face fabric after pressing became larger than that before pressing. It was necessary to consider changes of tensile properties in the case of predicting bending rigidities for laminated fabric with adhesive interlining, considering tensile and in-plane compressive moduli.

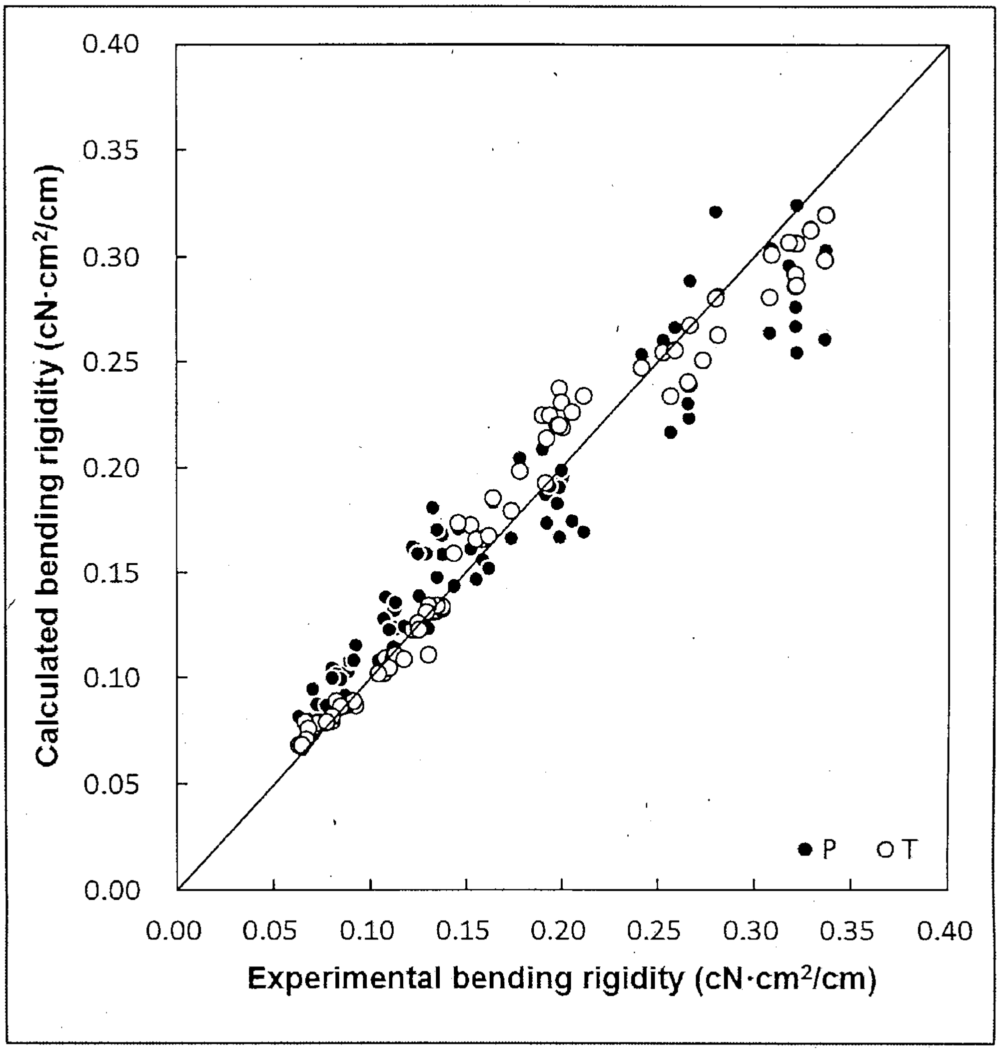

Figure 4.8 Comparison calculated bending rigidity and experimental bending rigidity of P and T methods (P: the method of laminate model with pressed samples, T: the method of tensile and in-plane compressive model with pressed samples).

Furthermore, these predicted results were compared with the ones from the laminated model in Chapter 3 as shown in Figure 4.8. Comparing those two results, the predicted results from tensile and in-plane compressive moduli were closer to the experimental ones than the ones with the laminated model. We controlled the weft density of CE interlining, gradually increasing and bending rigidities in the warp direction of laminated fabrics, increasing with the density. However, this was not found in the predicted results in Chapter 3. On the other hand, the predicted results in this study increased with the density. Therefore, it was revealed that the prediction method, which considers the tensile and in-plane compressive moduli, is more suitable to reflect the effect of properties for adhesive interlinings and face fabric.

Consequently, the prediction method, considering the tensile and in-plane compressive moduli, is able to predict the bending rigidity of laminated fabric with adhesive interlining with high accuracy.

4.5 Conclusion

A new predicting method for bending rigidity for laminated fabric with adhesive interlining considering tensile and in-plane compressive moduli based on laminate theory was proposed and verified experimentally. The apparent tensile modulus, T_2 and the apparent in-plane compressive modulus, T_1 were calculated and used to predict bending rigidities of laminated fabrics with adhesive interlinings. The obtained T_1 values of an adhesive interlining from the proposed equations were closer to each other even though the laminated fabric was made up of the different face fabrics. Therefore, the calculated values can be the in-plane compressive modulus of fabric. In the predicted bending rigidities, the entire predicted ones were agreed with experimental ones.

Moreover, the results from method considered tensile and in-plane compressive moduli were more agreed with experimental results than the results of laminate model. Even though some differences depending on face fabric samples were shown, the entire predicted results were showed high accuracy.

With these results, the predicting method considered tensile and in-plane compressive moduli is able to propose as predicting method of bending rigidity for laminated fabric with adhesive interlining and woven fabric with high accuracy. Moreover, the theoretical approach of this study will be applied to calculate in-plane compressive moduli for textile which cannot be measured that experimentally.

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Chapter 5

Prediction for bending rigidity of laminated fabric with adhesive interlining taken into account the neutral axes of components

Chapter 5 Prediction for bending rigidity of laminated fabric with adhesive interlining taken into account the neutral axes of components

5.1 Introduction

In this chapter, the reasons for the prediction errors by the prediction method in Chapter 3 are investigated. As described in Chapter 3, in the laminate theory, the increased amount of bending rigidity is explained as resulting from the strains of compression and extension at the original neutral axes of each component. When a fabric is bent, axial strain does not arise on the neutral axis. However, due to the laminating, strains by an extension and a compression of the original neutral axes will arise. The strains by these extensions and compression of the neutral axes form stress. The resultant force makes additional moment so the bending rigidity of a laminated fabric will increase. If the elastic moduli in tensile and bending are the same, the bending rigidity of laminated fabric per unit breadth is given by the Equation (5.1) (see chapter 3):

$$B_{12} = 3B_1B_2\frac{(h_1+h_2)^2}{(B_1h_2{}^2+B_2h_1{}^2)}+B_1+B_2, \tag{5.1}$$

where B_{12}, B_1 and B_2 are the bending rigidities per unit breadth of laminated fabric, adhesive interlining and face fabric, respectively. h_1 and h_2 are the thicknesses of the adhesive interlining and face fabric. In Chapter 3, Equation (5.1) was verified, taking into account the change on the mechanical properties of face fabric and adhesive interlining by the press used in the laminating process. In Equation (5.1), it was assumed that the components were perfectly elastic continua. However, textile materials are not elastic continua, so the bending rigidity of laminate fabric has been separated into two parts, the contributions from the bending of the components and their extension and compression [1]. This is equivalent to differentiating between the tensile and bending moduli of the fabrics. Those differences have an effect on the bending rigidity of laminated fabric. If the elastic modulus in bending and tensile modulus of both fabrics are independent and the neutral axes in bending lie in the centroid of the cross-section, the bending rigidity of the laminated fabric is given by

$$B_{12} = \frac{T_{2T} T_{1C}}{T_{1C} + T_{2T}} \cdot \left(\frac{h_2 + h_1}{2} \right)^2 + B_1 + B_2 \tag{5.2}$$

where T_{1C} and T_{2T} are the apparent in-plane compressive modulus of the adhesive interlining and the apparent tensile modulus of the face fabric, respectively. Those are assumed to be constant.

In Chapter 4, a new method was proposed to obtain T_{1C} from laminated fabric with different combinations of face fabric and adhesive interlining. Using the obtained T_{1C}, they confirmed the validity of Equation (5.2). In the predicted results by Equation (5.2), most of the predicted data were closer to the experimental ones than the ones obtained by Equation (5.1).

However, some fabrics still showed relatively larger prediction errors than other fabrics. In this chapter, the reason for the errors is considered in detail. In Equation (5.2), the neutral axes of components were assumed to lie in the centroids. If the assumption is invalid, the bending rigidity of laminated fabric will be affected by it and the errors may be occurred. Accordingly, it will be necessary to understand the effect of the position of neutral axes in components on the laminate bending rigidity.

In this chapter, a detailed bending theory of laminated fabric was proposed taking into account the position of neutral axes of fabrics in components. The theoretical equations of bending rigidity of laminated fabric were verified experimentally with samples that showed relatively large prediction errors by Equation (5.2).

5.2 Theoretical discussion for bending rigidity of laminated fabric taken into account the neutral axes of components

5.2.1 Basic assumptions and structure model of laminated fabric

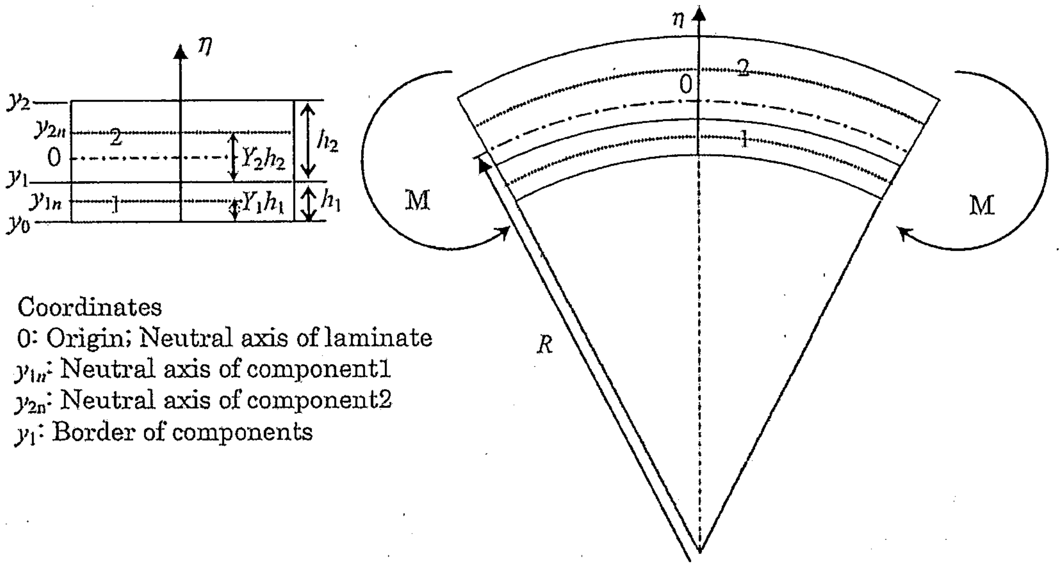

Figure 5.1 Bending of two-component laminate.

Let us consider a laminated fabric with component1 and component2, which neutral axes before bonding do not pass through the centroid. A cross section through a laminated fabric, bent to a radius of curvature R is shown in Figure 5.1. In Figure 5.1, component1 is inward and component2 is outward. η is the distance from the neutral surface in the laminated fabric. We take the origin at the neutral axis of the laminate. y_0 and y_1, y_2 are the coordinates of surface and boundaries. y_{1n} and y_{2n} are the coordinates of the original neutral axes of components. Because the strain of each component is proportional to the distance from the origin, component1 is compressed and component2 is extended while bending. It was assumed that a linear stress and strain relation is valid. Assuming the strains by extension and compression at the neutral axes of components are the mean strains in the component, a couple of forces will occur due to the stresses by the strains.

5.2.2 Bending rigidity of laminated fabric taken into account the placement of neutral axes

The compressive strain at the neutral axis of component1, ε_1 before bonding is given by

$$\varepsilon_1 = \frac{y_{1n}}{R} \tag{5.3}$$

Then, the stress in component1, σ_1 is given by:

$$\sigma_1 = \frac{y_{1n}E_{1C}}{R} \tag{5.4}$$

where E_{1C} is the compressive modulus of component1. The total force of component1, F_1 is

$$F_1 = \frac{y_{1n}E_{1C}h_1 b}{R} \tag{5.5}$$

where b is the breadth of each component.

Similarly, the total force of component2, F_2 is

$$F_2 = \frac{y_{2n}E_{2T}h_2 b}{R} \tag{5.6}$$

where E_{2T} is the tensile modulus of component 2.

In experiments with fabrics, elastic modulus per breadth is usually used for convenience. Thus, specified moduli T_{1C} and T_{2T} are introduced as follows:

$$T_{1C} \equiv E_{1C}h_1, \ T_{2T} \equiv E_{2C}h_2, \tag{5.7}$$

For no external axial force, the sum of two resultant forces in Equations (5.5) and (5.6) should be zero.

$$y_{1n}T_{1C} + y_{2n}T_{2T} = 0 \tag{5.8}$$

When the distances from the bottom to the neutral axis of each component are denoted by y_{1n0} and y_{2n0}, the relative positions Y_1 and Y_2 are expressed as follows:

$$Y_1 = y_{1n0}/h_1 \tag{5.9}$$

$$Y_2 = y_{2n0}/h_2 \tag{5.10}$$

Then y_{1n} and y_{2n} are expressed as follows:

$$y_{1n} = y_1 - h_1(1 - Y_1) \tag{5.11}$$

$$y_{2n} = y_1 + Y_2 h_2 \tag{5.12}$$

Substituting Equations (5.12) into (5.8), we can obtain

$$T_{1C}(y_1 - h_1(1 - Y_1)) + T_{2T}(y_1 + Y_2 h_2) = 0 \tag{5.13}$$

Then, y_1 is as follows:

$$y_1 = \frac{T_{1C}h_1(1 - Y_1) - T_{2T}Y_2 h_2}{T_{1C} + T_{2T}} \tag{5.14}.$$

That gives the neutral axis of the laminate. Substituting Equation (5.14) into (5.12), y_{2n} can be obtained:

$$y_{2n} = \frac{T_{1C}\{h_1(1 - Y_1) + Y_2 h_2\}}{T_{1C} + T_{2T}} \tag{5.15}$$

From Equation (8), we can obtain y_{1n} as follows:

$$y_{1n} = -y_{2n}\frac{T_{2T}}{T_{1C}} = -\frac{T_{2T}\{h_1(1 - Y_1) + Y_2 h_2\}}{T_{1C} + T_{2T}} \tag{5.16}.$$

Because the two forces, Equations (5.5) and (5.6), are equal and opposite, they form a couple. By the assumption, the forces act at the centroid of components, and then the distance between the forces is $(h_2+h_1)/2$. Accordingly, the couple per unit breadth and unit curvature, M_1 and M_2 is

$$M_1 = -y_{1n}T_{1C} \cdot \frac{(h_1+h_2)}{2} \tag{5.17}$$

or

$$M_2 = y_{2n}T_{2T} \cdot \frac{(h_1+h_2)}{2} \tag{5.18}$$

This is the contribution from extension and compression of components. The bending rigidity of laminated fabric is given by the sum of these contributions and the contributions from the bending of the components.

Therefore, the bending rigidity of a laminated fabric can be expressed as follows:

$$B_{12} = -T_{1C}y_{1n} \cdot \frac{(h_1+h_2)}{2} + B_1 + B_2 \tag{5.19}$$

or

$$B_{12} = T_{2T}y_{2n} \cdot \frac{(h_1+h_2)}{2} + B_1 + B_2 \tag{5.20}$$

By substituting Equation (5.15) into (5.20), we can finally express bending rigidity of the laminated fabric as follows:

$$B_{12} = \frac{T_{1C}T_{2T}((1-Y_1)h_1 + Y_2h_2)(h_1+h_2)}{2(T_{1C}+T_{2T})} + B_1 + B_2 \qquad (5.21).$$

The bending rigidity of laminated fabric with two components, of which neutral axes do not exist on the centroids, can be predicted with Equation (5.21). However, among the parameters, T_{1C}, Y_1 and Y_2 cannot be measured directly [8]. Therefore, a method to obtain those values was considered from the experiments under a specific assumption.

If Y_1=1/2, Equation (5.21) can be expressed as follows:

$$B_{12} = \frac{T_{2T}T_{1C}(h_1 + 2Y_2h_2)(h_2 + h_1)}{4(T_{1C} + T_{2T})} + B_1 + B_2 \qquad (5.22).$$

On the other hand, if Y_2=1/2, we have

$$B_{12} = \frac{T_{1C}T_{2T}(2(1-Y_1)h_1 + h_2)(h_1 + h_2)}{4(T_{1C} + T_{2T})} + B_1 + B_2 \qquad (5.22)'.$$

Furthermore, if Y_1=Y_2=1/2, we obtain Equation (5.23), which is the same with Equation (5.2).

$$B_{12} = \frac{T_{2T}T_{1C}(h_2 + h_1)^2}{4(T_{1C} + T_{2T})} + B_1 + B_2 \qquad (5.23)$$

5.2.3 Neutral axis of a fabric

Let us consider the position of a neutral axis of a fabric theoretically. As has already been stated, the position of the neutral axis for a bent component cannot be measured experimentally. If the E_{BT} and E_{BC}, which are tensile and compressive moduli in bending, are known, the relative position, Y of the neutral axis can be theoretically given by

$$Y = \frac{\sqrt{E_{BT}}}{\sqrt{E_{BC}} + \sqrt{E_{BT}}} \qquad (5.24)$$

Then the bending rigidity, B of the fabric is expressed as follows [8]:

$$B = \frac{E_{BT}E_{BC}h^3}{3\left(\sqrt{E_{BC}} + \sqrt{E_{BT}}\right)^2} = \frac{Y^2h^3E_{BC}}{3} = \frac{(1-Y)^2h^3E_{BT}}{3} \qquad (5.25)$$

5.2.4 Relative placement of neutral axes for components

However, E_{BC}, E_{BT} and Y are unknown and cannot be measured directly. Therefore, an indirect approach was considered to obtain the necessary parameters with laminated fabrics in this study.

Firstly, let us consider Equation (5.22). If Y_1=1/2, bending rigidity of laminated fabric can be predicted using Equation (5.22) with B_1, B_2, T_{1C}, T_{2T}, h_1, h_2 and Y_2. Here, B_1 and B_2 can be measured by a pure bending test. h_1 and h_2 can be measured. T_{2T} can be measured by a tensile test. T_{1C} is apparent compressive modulus of component1 and there are some studies about measuring it [2, 3]. However those studies only suggested some possibilities of the measurement and a reliable method was not established. It is still difficult to measure it directly. Instead of a direct measuring method, an indirect method can be used. From Equation (5.23), T_{1C} can be expressed as Equation (5.26), and then T_{1C} can be obtained.

$$T_{1C} = \frac{(B_{12} - B_1 - B_2)T_{2T}}{(B_{12} - B_1 - B_2) - T_{2T}\left(\frac{h_2 + h_1}{2}\right)^2} = \frac{1}{\frac{1}{T_{2T}} - \frac{(h_2 + h_1)^2}{4(B_{12} - B_1 - B_2)}} \qquad (5.26)$$

In the study, with T_{1C} from two twill fabrics using Equation (5.26), the predicted bending rigidities of laminated fabrics with adhesive interlinings showed good agreement with experimental ones. Thus, the assumption that the neutral axes of the twill face fabrics pass through the centroid was verified, and thus the T_{1C} can be used in Equation (5.22) as well.

If T_{1C} is obtained, Y_2 can be obtained with the following equation:

$$Y_2 = \frac{2(B_{12} - B_1 - B_2)}{h_2(h_1 + h_2)}\left(\frac{1}{T_{2T}} + \frac{1}{T_{1C}}\right) - \frac{h_1}{2h_2} \qquad (5.27).$$

Therefore, when the neutral axis of component1 is assumed to lie in the centroid, the bending rigidity of the laminated fabric with component2 for which the neutral axis is unknown can be predicted using Equation (5.22) with T_{1C}, h_1 and B_1 of component1 and T_{2T}, h_2, B_2 and Y_2 of component2 obtained by Equation (5.27).

Let us consider Equation (5.22)'. Equation (5.22)' can be applied to a reverse bending of Equation (5.22) that component1 is outward and the component2 is inward in bending. In Equation (5.22'), it will be necessary to obtain T_{2C} of component2, which the neutral axis does not lie in the centroid. However, the measuring method of T_{2C} for the component2 has not been reported yet. To verify the prediction of laminated fabric in the case of Equation (5.22)', further study on the obtaining method of T_{2C} in the case that the neutral axis does not exist in the centroid will be necessary in the future.

5.2.5 Prediction of bending rigidity for laminated fabric

In summary, the bending rigidity of laminated fabric can be predicted with four moduli (T_T, T_C, E_{BT} and E_{BC}) or the relative position of neutral axis, Y instead of E_{BT} and E_{BC} for component fabrics by the proposed method. For the reverse direction bending, due to the different neutral axis on the bending direction, the other relative position of the neutral axis Y' will be necessary.

5.3 Experimental

Experiments were carried out to verify the proposed equations for predicting the bending rigidity of laminated fabric from mechanical properties of face fabric and adhesive interlining before bonding. In this study, the bending rigidity of a laminated fabric was considered except for the stiffness properties of a lining. In the usage of adhesive interlinings, an adhesive interlining is usually used on the inward of clothing and the face fabric was on the outward of the arc of bending. Thus, Equation (5.22) was verified by assuming component1 for an interlining and component2 for a face fabric.

Face fabrics, adhesive interlinings and laminated fabrics with those combinations were prepared as experimental samples. Bending rigidities on warp and weft direction respectively of all samples were measured using a KES-FB2 pure bending tester [4]. The thickness of each sample was measured using a KES-FB3 compression tester at 49 Pa load. The tensile properties of samples were measured by a KES-FB1 tensile tester up to a maximum load of 490cN/cm. The load at 0 to about 2.5% of elongation from the load-elongation curve was used to calculate the T_{2T} for each face fabric [Chapter 4]. Every test was carried out under standard conditions (20±1°C and 65±5% relative humidity). All samples were preconditioned under these standard conditions for 24 hours. Every test was conducted on five samples and the results were averaged.

The T_{1C} was calculated by Equation (5.26) with values obtained by the experiment in the combination of specific face fabric and interlining. Then Y_2 of face fabrics were calculated by Equation (5.27). Using the Y_2 values, the bending rigidities of other laminated fabrics bonded with the face fabrics and different interlinings were predicted with Equation (5.22). Those results were compared with experimental data.

The sample specifications are shown in Table 5.1 and Table 5.2. Particularly, we used face fabrics which showed large prediction errors by Equation (5.2). Hence, six fabrics (S1-6) which showed large prediction errors (over about mean absolute percentage errors (MAPE) 10%) using Equation (5.2) were prepared as face fabric samples assumed to have different tensile and compressive moduli. Ten kinds of adhesive interlinings which were the same samples in Chapter 3 were also prepared as experimental samples (Table 3.2). Two twill fabrics (A and B), which neutral axes can be assumed to lie in the centroid [Chapter 4], were prepared to obtain the compressive moduli of adhesive interlinings. Eighty combinations of laminated fabrics were constructed and examined. Bonding interlining to face fabric was done automatically using a press machine (Kobe Denki Kogyosyo, BP-V4812D). The bonding conditions were 150°C, under 29.4 kPa load and 10s pressing time.

Table 5.1 Specifications of the face fabrics

Sample name	Yarn Count(Nm)		Weave	Density(/cm) (Warp × Weft)	Material	Pressed face fabric name
	Warp	Weft				
S1	60tex×2; R 120tex	30tex	Satin	50×40	Wool100%	P-S1
S2	42tex×2; R84tex	30tex	Satin	45×33	Wool100%	P-S2
S3	47tex	36tex	Satin	54×37	W75%, P25%	P-S3
S4	36tex	30tex	Satin	53×37	W75%, P25%	P-S4
S5	47tex×2; R94tex	30tex	Satin	42×30	Wool100%	P-S5
S6	14tex×2; R28tex	14tex×2; R28tex	Satin	43×29	Wool 85%, Angora15%	P-S6

Table 5.2 Combinations of face fabric and adhesive interlining

Face fabric Adhesive interlining	S1	S2	S3	S4	S5	S6
CE1	A-CE1	S2-CE1	S3-CE1	S4-CE1	S5-CE1	S6-CE1
CE2	A-CE2	S2-CE2	S3-CE2	S4-CE2	S5-CE2	S6-CE2
CE3	A-CE3	S2-CE3	S3-CE3	S4-CE3	S5-CE3	S6-CE3
CE4	A-CE4	S2-CE4	S3-CE4	S4-CE4	S5-CE4	S6-CE4
CE5	A-CE5	S2-CE5	S3-CE5	S4-CE5	S5-CE5	S6-CE5
DP1	A-DP1	S2-DP1	S3-DP1	S4-DP1	S5-DP1	S6-DP1
DP2	A-DP2	S2-DP2	S3-DP2	S4-DP2	S5-DP2	S6-DP2
DP3	A-DP3	S2-DP3	S3-DP3	S4-DP3	S5-DP3	S6-DP3
DP4	A-DP4	S2-DP4	S3-DP4	S4-DP4	S5-DP4	S6-DP4
DP5	A-DP5	S2-DP5	S3-DP5	S4-DP5	S5-DP5	S6-DP5

The mechanical properties of component fabrics were changed after pressing procedure for laminating and the changes of the mechanical properties for laminated fabrics must be considered when predicting the bending rigidity of laminated fabrics [Chapter 3]. Therefore, samples pressed alone under the same press conditions of laminating and those mechanical properties were measured. The manufacturing method is as follows: Face fabric samples were pressed under the same conditions as bonding interlining. To press the adhesive interlining, polytetrafluoroethylene (PTFE) film (NITTO, No.900, 0.05×300mm) was prepared. Adhesive interlinings were bonded to PTFE films and PTFE films were removed from adhesive interlining. Those samples were referred to as 'pressed samples'. Face fabric and adhesive interlining were referred to as 'pressed face fabric' and 'pressed adhesive interlining'. The conditions for manufacturing the pressed samples were the same as for bonding interlining.

5.4 Results and discussion

The bending rigidities and thicknesses of pressed samples are shown in Table 5.3. Bending rigidities which were taken when the face fabric was on the outside of the arc in bending were used because an adhesive interlining is usually used on the inside of the arc in bending of clothing. The T_{2T} values from the tensile properties of pressed face fabrics are shown in Table 5.4.

T_{1C} values for adhesive interlining samples were obtained using Equation (5.26) from the laminated fabric with twill fabrics A and B [Chapter 4, Table 4.4]. The averages of T_{1C} values were obtained as shown in Table 5.5 and used in the prediction.

To predict bending rigidity of laminated fabric with a face fabric where the neutral axis does not pass through the centroid, Y_2 of face fabric is necessary. With the obtained bending rigidity, thickness and tensile and compressive moduli, Y_2 of face fabrics were calculated by Equation (5.27) and the averages for all samples were shown in Figure 5.2. Y_2 values of the face fabrics were similar for different adhesive interlinings. Thus, it was verified that the position of the neutral axis for the face fabric can be obtained by Equation (5.27).

Table 5.3 Bending rigidities and thicknesses of face fabrics

Sample name	Bending rigidity(cN·cm^2/cm)		Thickness(cm)	
	Average	Standard deviation	Average	Standard deviation
P-S1(warp)	0.084	0.003	0.040	0.001
P-S1(weft)	0.055	0.001		
P-S2(warp)	0.124	0.002	0.044	0.001
P-S2(weft)	0.041	0.002		
P-S3(warp)	0.061	0.002	0.033	0.001
P-S3(weft)	0.041	0.002		
P-S4(warp)	0.058	0.001	0.036	0.001
P-S4(weft)	0.044	0.001		
P-S5(warp)	0.109	0.002	0.044	0.001
P-S5(weft)	0.062	0.002		
P-S6(warp)	0.139	0.004	0.044	0.004
P-S6(weft)	0.065	0.002		

Table 5.4 T_2 values of pressed face fabrics

Sample name	T_2 values(N/cm)
P-S1(warp)	20.9
P-S21weft)	43.7
P-S2(warp)	125
P-S2(weft)	26.0
P-S3(warp)	51.8
P-S3(weft)	39.5
P-S4(warp)	61.3
P-S4(weft)	56.6
P-S5(warp)	56.3
P-S6(warp)	114
P-S6(weft)	13.3

Table 5.5 Average T_1 values of pressed interlinings from face fabric, A and B

Sample name	T_1values(N/cm)	Sample name	T_1values(N/cm)
P-CE1(warp)	0.69	P-DP1(warp)	1.18
P-CE1(weft)	0.39	P-DP1(weft)	0.29
P-CE2(warp)	0.78	P-DP2(warp)	0.78
P-CE2(weft)	0.39	P-DP2(weft)	0.39
P-CE3(warp)	0.78	P-DP3(warp)	1.27
P-CE3(weft)	0.39	P-DP3(weft)	0.39
P-CE4(warp)	0.88	P-DP4(warp)	1.27
P-CE4(weft)	0.39	P-DP4(weft)	0.29
P-CE5(warp)	0.98	P-DP5(warp)	1.18
P-CE5(weft)	0.39	P-DP5(weft)	0.29

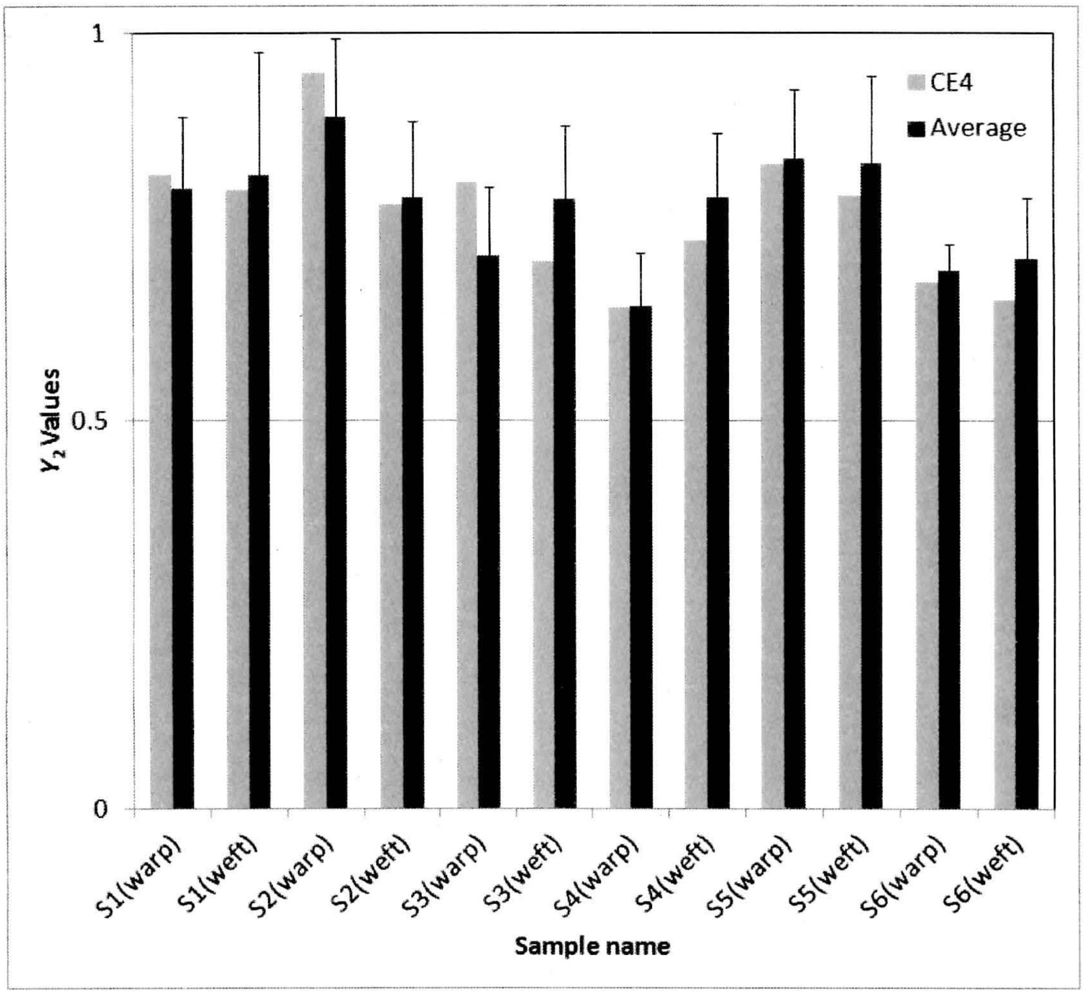

Figure 5.2 Averages of Y_2 values of face fabrics for different adhesive interlinings and Y_2 values from laminated fabric combinations of face fabrics and CE4 interlining.

As shown in Figure 5.2, the averages of Y_2 for all samples were close to 1. If Y_2 is close to 0.5, it means that E_{BC} and E_{BT} are almost the same. In that case, the predicted results will be similar with the results by Equation (5.2). On the other hand, if Y_2 is close to 1, it means that E_{BC} and E_{BT} are very different. In that case, the neutral axis of the face fabric is close to the top of face fabric. Therefore, it was confirmed that the neutral axes of the face fabrics (S1-6) which showed large prediction errors by Equation (5.2) do not lie close to the centroid.

Although the Y_2 values of the face fabrics showed similar ones for different adhesive interlinings, some variations were still shown between samples. The reasons will be the permeation of adhesive agent on face fabric and nonlinear properties of fabrics. However, the variations were not so large that the values can be acceptable.

If the predicted bending rigidities of laminated fabric with the obtained Y_2 are close to the experimental ones, it means that the obtained Y_2 values are reasonably valid and can be used to predict bending rigidity of laminated fabric with other combinations. Thus, the bending rigidities of the laminated fabrics with other interlinings were predicted with the obtained Y_2. In here, Y_2 values of face fabric from laminated fabric with CE4 interlining were used because those showed the closest values to the averages of the obtained Y_2 values as shown in Figure 5.2.

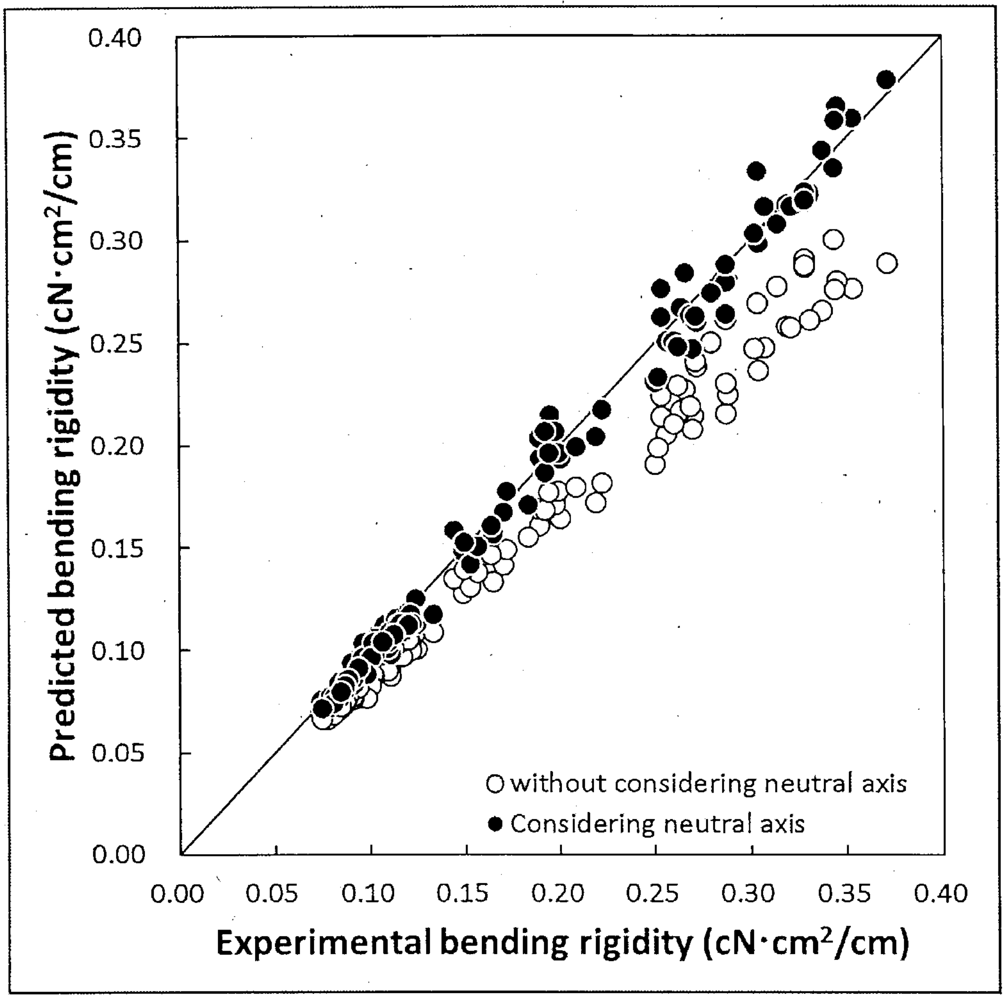

Figure 5.3 Predicted and experimental bending rigidity of the laminated fabrics by the method with and without considering the position of the neutral axis

Figure 5.3 shows the comparison of predicted and experimental bending rigidities for laminated fabrics using Y_2. The predicted bending rigidities using Equation (5.2) are also shown in Figure 5.3 to confirm the effect of the position of neutral axis. The MAPE from the results by the method considered Y_2 and without considering Y_2 are shown in Table 5.6.

Table 5.6 Mean Absolute Percentage Errors (MAPE) between predicted and experimental bending rigidity with and without considering the position of the neutral axis

Laminate condition	Mean Absolute Percentage Errors (%)	
	Method with considering neutral axis	Method without considering neutral axis
S1-all interlining(warp)	4.0	16.2
S1-all interlining(weft)	4.5	11.8
S2-all interlining(warp)	4.7	19.2
S2-all interlining(wet)	3.9	13.9
S3-all interlining(warp)	6.3	11.5
S3-all interlining(weft)	3.6	10.5
S4-all interlining(warp)	3.4	9.7
S4-all interlining(weft)	2.8	11.4
S5-all interlining(warp)	3.1	17.5
S5-all interlining(weft)	3.5	12.8
S6-all interlining(warp)	1.2	9.9
S6-all interlining(weft)	2.3	8.4
All face fabrics -all interlinings	3.6	12.7

As shown in Figure 5.3 and in its MAPE, the predicted bending rigidities with the obtained Y_2 showed closer agreement with the experimental data than those from method without considering Y_2. The reason of the better agreements is the position of the neutral axes of laminated fabrics. Because a fabric is not elastic continua, the assumption that the neutral axis exists in the centroid is not always valid. These results showed that the bending rigidity of a laminated fabric was significantly influenced by the position. The position is necessary to be considered especially for the bending rigidity of a laminated fabric. Thus, the predicted bending rigidities of laminated fabric considered Y_2 were more agreed with the experimental ones than the predicted ones without considering Y_2. It became clear that the bending rigidities of laminated fabric were able to be predicted more precisely with the method considered Y_2 than using method without considering it. MAPE of all samples from the method considered Y_2 (3.6%) was less than the results by method without considering Y_2 (12.7%). This was a valuable improvement so it became clear that the concerning position of the neutral axis is meaningful.

Although the predicted bending rigidities of all samples showed better agreements, the MAPE is different depending on samples as shown in Table 5.6. The reason may be due to the variation of Y_2. The predicted results are influenced by Y_2 directly so the variation of Y_2 may cause the different MAPE depending on samples.

Therefore, it is certain that the bending rigidity of laminated fabric is affected by the position of neutral axes of components. This is equivalent to differentiating between the tensile and compressive moduli in bending of the fabrics. The difference of the moduli was successfully considered in the proposed method. Thus, if the position of the neutral axis of a fabric is obtained, then the bending rigidity of the laminated fabric with the fabric and another adhesive interlining can be predicted. With this new method, the bending rigidity of a laminated fabric can be predicted more precisely.

In this study, the satin fabrics were mainly used as samples which show the large prediction errors (over about MAPE 10%) by the method without considering the position of the neutral axis. However, it should be noted that no all satin fabric will show large prediction errors by the prediction method without considering the neutral axis. The tensile and in-plane compressive moduli of a fabric in bending may be affected by yarn properties in addition to weave structure of a fabric. Therefore, the position of neutral axis may vary in the case of fabric even with the same satin structure.

5.5 Conclusion

A new theory of bending rigidity of laminated fabric was proposed. The position of neutral axis in bending for face fabric is considered in addition to the tensile and in-plane compressive moduli of components.

The proposed method was verified by calculating the bending rigidity of laminated fabrics especially with samples where bending rigidity cannot be predicted precisely with the method without considering the position of neutral axis. As a result, the relative position of the neutral axis of a face fabric was able to be obtained with the proposed method. The obtained neutral axis of the face fabric did not lie close to the centroid. Using the position of the neutral axis, bending rigidity of laminated fabric was predicted. The predicted bending rigidities showed closer agreement with the experimental data than those by method without considering the position of the neutral axis.

Thus, in the proposed theory, it became clear that the obtained position of the neutral axis in a fabric is reasonably valid and it is able to predict the bending rigidity of laminated fabric more precisely with the position of neutral axis.

Until now, the selection of adhesive interlining was carried out based on experiments and previous data. If the data concerning adhesive interlinings and face fabrics has been compiled once, the prediction of the performance of laminated fabrics made of different combination will be possible. Therefore, this new method will help designers and manufacturers to select suitable adhesive interlinings for garments without extra cost and time.

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Chapter 6

Conclusion

Chapter 6 Conclusion

In manufacturing garments, adhesive interlining plays an important role in the aesthetic of garment appearance and bending rigidity is an important factor of garment appearance. The bending rigidity of laminated fabric is much larger than the sum of ones of components and thus it is necessary to predict bending rigidity is necessary. Therefore, in this study, the prediction method of bending rigidity for laminated fabric was investigated.

Firstly, laminate theory and Kanayama's model for bending rigidity of laminated fabric are verified theoretically and experimentally taking into account the changes in mechanical properties for components. It was found that the properties of adhesive interlining changed in the pressing process as well as the properties of face fabric. It was found that laminate theory was useful to predict bending rigidity of laminated fabrics, with mechanical properties of adhesive interlining and face fabric taking into account the pressing effects on it.

For more precise predictions, a new prediction method for bending rigidity for laminated fabric with adhesive interlining, considering tensile and in-plane compressive moduli (T_1 and T_2) based on laminate theory, was proposed and verified experimentally. The obtained T_1 and T_2 values of an adhesive interlining from the proposed equations were reasonable and the entire predicted results using T_1 and T_2 correlated more with the experimental ones than those by laminate theory.

Considering tensile and in-plane compressive moduli, reasonably precise prediction of bending rigidity for laminated fabric became possible. However, some samples still showed prediction errors and the reason why, was due considered as the position of neutral axis in bending for face fabric. For more precise predictions, a new theory of bending rigidity of laminated fabric was proposed taking into account the position of neutral axis in bending for face fabric in addition to the tensile and in-plane compressive moduli of components. A new method to obtain the position of neutral axis in bending was also proposed. The proposed methods were verified by calculating the bending rigidity of laminated fabrics especially with samples where the bending rigidity cannot be predicted precisely with the method without considering the position of the neutral axis. The relative position of the neutral axis of a face fabric was obtained with the proposed method. The obtained neutral axis of the face fabric did not lie close to the centroid. The predicted bending rigidities showed closer agreement with the experimental data than those by methods that did not consider the position of the neutral axis. Thus, a very precise prediction of bending rigidity for laminated fabric with adhesive interlining became possible with mechanical properties of components such as h_1, h_2, B_1, B_2, T_1, T_2 and Y_2.

As a result of comparison with three prediction methods, the properties of each method are as follows: laminate theory is the simplest method which needs thickness and bending rigidity of components. It will be helpful to obtain overall prediction for bending rigidity of laminated fabrics. However, for more high accuracy of prediction, tensile and in-plane compressive moduli will be necessary. Using the moduli, very accurate prediction will be possible. For specific samples which show large prediction errors using tensile and in-plane compressive moduli such as satin fabrics, taking into account the neutral axis of face fabric will be necessary.

Consequently, it is possible to predict the bending rigidity of the laminated fabric more precisely taking into account the position of neutral axis for woven fabric. Until now, the selection of adhesive interlining was carried out based on experiments and previous data. If the data concerning adhesive interlinings and face fabrics has been compiled once, the prediction of the performance of laminated fabrics made of different combination will be possible.

For example, if the manufacturers set up a data base for adhesive interlining and face fabric, the bending rigidity of laminated fabric can be predicted using the proposed methods. When designers would like to select an adhesive interlining for the designated face fabrics and their garment designs, the manufacturers can suggest a suitable adhesive interlining from the data base without experimental laminating. Then the designers can also select the appropriate adhesive interlining efficiently.

Therefore, the proposed new methods will help designers and manufacturers to select suitable adhesive interlinings for garments without extra cost and time.

The theory in this study is a more general theory about the bending of laminate fabric in which the components are not continuum materials. Thus, the proposed theories can be applicable for composite material as well. Furthermore, these can also be used for material in the simulation.

Published papers

The dissertation based on following published papers:

1. KyoungOk Kim, Shigeru Inui, Masayuki Takatera, Verification of prediction for bending rigidity of woven fabric laminated with interlining by adhesive bonding, *Textile Research Journal*, 81(6), pp.598-607, 2011
2. KyoungOk Kim, Shigeru Inui and Masayuki Takatera, Prediction of bending rigidity for laminated fabric with adhesive interlining by a laminate model considering tensile and in-plane compressive moduli, *Textile Research Journal*, 82(4), pp.385-399, 2012
3. KyoungOk Kim, Shigeru Inui and Masayuki Takatera, Bending rigidity of laminated fabric taking into account the neutral axes of components, *Textile Research Journal*, 83(2), pp.160-170, 2013

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