Bending rigidity of laminated fabric taking into account the neutral axes of components

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Abstract: The bending rigidity of laminated fabric was investigated considering the positions of the neutral axes in bending for components in addition to the tensile and in-plane compressive moduli of components. Theoretically derived equations were proposed to obtain the position of the neutral axis and to predict bending rigidity of laminated fabric. Eight face fabrics, ten adhesive interlinings and eighty laminated fabrics of those combinations were used for experimental samples. Tensile properties, bending rigidities and thicknesses of samples were measured and used to investigate the validity of the theory. The positions of the neutral axes for the face fabrics were obtained and they were not close to the centroid of the fabric. The calculated bending rigidities of laminated fabrics using the obtained position of neutral axes were more agreed with the experimental ones than the results by the method without considering the position of neutral axis. Therefore, it was found that the bending rigidity of laminated fabric can be predicted more precisely considering the position of neutral axis.

Introduction

Clothing is made up of a number of subsidiary component fabrics. Among them, interlining is used to give garments a suitable appearance and stability. The interlining is one of the most important subsidiary materials because of its role in the final appearance and function of the garment. An adhesive interlining using a thermoplastic resin is taken as a representative example. The properties of a fabric are considerably changed by laminating on an adhesive interlining. Therefore quantifying the effects of adhesive interlining properties is desirable. Particularly, the prediction of mechanical properties for laminated fabric bonded with adhesive interlining is great interest.

There are some studies about prediction for mechanical properties of laminated fabric made of face fabric and adhesive interlining from the properties of components. Shishoo et al. [1] investigated mechanical properties of laminated fabric with adhesive interlining and analyzed the relationships between 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. [2] investigated the relationship between the low stress mechanical properties of fused composites and the ones of component fabrics. Based on the relationships, they suggested a set of equations to predict the low stress mechanical properties of fused composites composed of fabric and fusible 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 because of its insufficient accuracy. Moreover, the relationship between the mechanical properties of adhesive interlining and laminated fabric is still unclear. If it become clear, more precise prediction will be possible.

Among the mechanical properties of laminated fabric, it is well-known that bending rigidity of laminated fabric is much greater than the sum of bending rigidity for each component. Some researchers investigated the prediction for bending rigidity of laminated fabric through the theoretical approaches using the laminate theory of composite structures. Kanayama et al [3 and 4] suggested prediction models for bending rigidity of a composite based on the laminate theory considering the rigidity of adhesive. They verified those models with different type of interlinings. In the laminate theory, the increase amount of bending rigidity is explained as resulting from the strains by compression and extension at the original neutral axes of each component. When a fabric is bent, axial strain does not arise in the neutral axis. However, due to the laminating, strains by an extension and a compression of the original neutral axes will arise. Thus, the strains by these extension and compression of the neutral axis form stress so that the bending rigidity of a laminated fabric will increase as the amount of the moment by the resultant force. If the elastic moduli in tensile and bending are the same, bending rigidity of laminated fabric per unit breadth is given by Equation (1):

$$B_{12} = 3B_1B_2\frac{(h_1+h_2)^2}{(B_1{h_2}^2+B_2{h_1}^2)}+B_1+B_2, \quad (1)$$

where B_{12}, B_1 and B_2 are bending rigidities per unit breadth of laminated fabric, adhesive interlining and face fabric, respectively. h_1 and h_2 are the thicknesses of adhesive interlining and face fabric. Kim et al [5] verified Equation (1) taking into account the change on the mechanical properties of face fabric and adhesive interlining by press used in the laminating process.

In Equation (1), it was assumed that the components are 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 [6]. 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 of both fabrics are independent and the neutral axes in bending are assumed to lie in the centroid of the cross section, the bending rigidity of laminated fabric is given by

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

where T_{1C} and T_{2T} are the apparent in-plane compressive modulus of adhesive interlining and apparent tensile modulus of face fabric assumed to be a constant. Kim et al. [7] proposed a method to obtain T_{1C} from laminated fabric with the different combinations of face fabric and adhesive interlining. Using the obtained T_{1C}, they confirmed the validity of Equation (2). In the predicted results by Equation (2), most of the predicted data were close to the experimental ones than the ones by Equation (1).

However, some fabrics still showed relatively larger prediction errors than other fabrics. In this study, the reason of the errors was considered in detail. In Equation (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 shown. Accordingly, it will be necessary to understand the effect of the position of neutral axes in components on the laminate bending rigidity.

In this study, 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 which showed relatively large prediction errors by Equation (2).

Theoretical

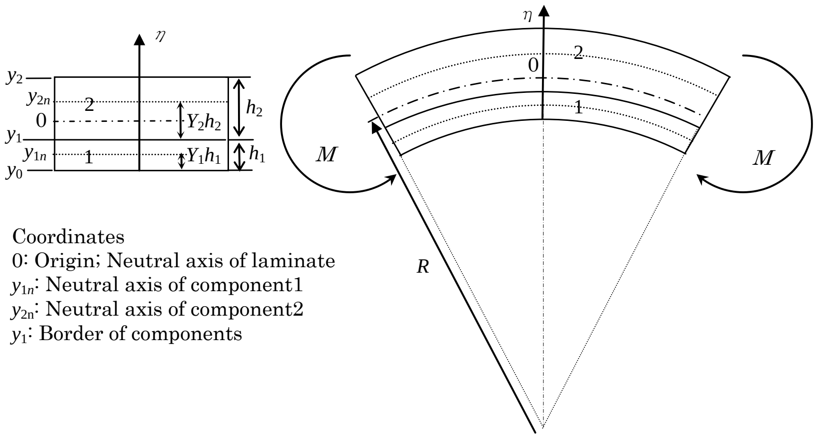

Figure 1 Bending of two-component laminate

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 1. In Figure 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, the component1 is compressed and the 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 strain in component, a couple of forces will be occurred due to the stresses by the strains.

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

$$\varepsilon_1 = \frac{y_{1n}}{R} \qquad (3)$$

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

$$\sigma_1 = \frac{y_{1n} E_{1C}}{R} \qquad (4)$$

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

$$F_1 = \frac{y_{1n} E_{1C} h_1 b}{R} \qquad (5)$$

where b is the breadth of each component.
Similarly, the total force of component2, F_2 is

$$F_2 = \frac{y_{2n} E_{2T} h_2 b}{R} \quad (6)$$

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.

$$T_{1C} \equiv E_{1C} h_1,\ \ T_{2T} \equiv E_{2C} h_2 \quad (7)$$

For no external axial force, the sum of two resultant forces in Equations (5) and (6) should be zero.

$$y_{1n} T_{1C} + y_{2n} T_{2T} = 0 \quad (8)$$

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:

$$Y_1 = y_{1n0}/h_1 \quad (9)$$

$$Y_2 = y_{2n0}/h_2 \quad (10)$$

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

$$y_{1n} = y_1 - h_1 (1 - Y_1) \quad (11)$$

$$y_{2n} = y_1 + Y_2 h_2 \quad (12)$$

Substituting Equations (12) into (8), we can obtain

$$T_{1C} (y_1 - h_1 (1 - Y_1)) + T_{2T} (y_1 + Y_2 h_2) = 0 \quad (13)$$

Then, y_1 is as follows:

$$y_1 = \frac{T_{1C} h_1 (1 - Y_1) - T_{2T} Y_2 h_2}{T_{1C} + T_{2T}} \quad (14).$$

That gives the neutral axis of the laminate. Substituting Equation (14) into (12), y_{2n} can be obtained:

$$y_{2n} = \frac{T_{1C} \{h_1 (1 - Y_1) + Y_2 h_2\}}{T_{1C} + T_{2T}} \quad (15)$$

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

$$y_{1n} = -y_{2n} \frac{T_{2T}}{T_{1C}} = -\frac{T_{2T} \{h_1 (1 - Y_1) + Y_2 h_2\}}{T_{1C} + T_{2T}} \quad (16).$$

Because the two forces, Equations (5) and (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

$$M_1 = -y_{1n} T_{1C} \cdot \frac{(h_1 + h_2)}{2} \quad (17)$$

or

$$M_2 = y_{2n} T_{2T} \cdot \frac{(h_1 + h_2)}{2} \quad (18)$$

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:

$$B_{12} = -T_{1C} y_{1n} \cdot \frac{(h_1 + h_2)}{2} + B_1 + B_2 \quad (19)$$

or

$$B_{12} = T_{2T} y_{2n} \cdot \frac{(h_1 + h_2)}{2} + B_1 + B_2 \quad (20)$$

By substituting Equation (15) into (20), we can finally express bending rigidity of the laminated fabric as follows:

$$B_{12} = \frac{T_{1C} T_{2T} ((1 - Y_1) h_1 + Y_2 h_2)(h_1 + h_2)}{2(T_{1C} + T_{2T})} + B_1 + B_2 \quad (21).$$

Bending rigidity of laminated fabric with two components which neutral axes do not exist on those centroids can be predicted with Equation (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 (21) can be expressed as follows:

$$B_{12} = \frac{T_{2T} T_{1C} (h_1 + 2 Y_2 h_2)(h_2 + h_1)}{4(T_{1C} + T_{2T})} + B_1 + B_2 \quad (22).$$

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

$$B_{12} = \frac{T_{1C}T_{2T}\left(2(1-Y_1)h_1 + h_2\right)(h_1+h_2)}{4(T_{1C}+T_{2T})} + B_1 + B_2 \qquad (22)'.$$

Furthermore, if Y_1=Y_2=1/2, we obtain Equation (23) and it is the same with Equation (2).

$$B_{12} = \frac{T_{2T}T_{1C}(h_2+h_1)^2}{4(T_{1C}+T_{2T})} + B_1 + B_2 \qquad (23)$$

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

$$Y = \frac{\sqrt{E_{BT}}}{\sqrt{E_{BC}} + \sqrt{E_{BT}}} \qquad (24)$$

then the bending rigidity, B of the fabric is expressed as follows[8].

$$B = \frac{E_{BT}E_{BC}h^3}{3\left(\sqrt{E_{BC}}+\sqrt{E_{BT}}\right)^2} = \frac{Y^2h^3E_{BC}}{3} = \frac{(1-Y)^2h^3E_{BT}}{3} \qquad (25)$$

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 (22). If Y_1=1/2, bending rigidity of laminated fabric can be predicted using Equation (22) with B_1, B_2, T_{1C}, T_{2T}, h_1, h_2 and Y_2. In 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 [9 and 10]. 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, indirect method can be used. From Equation (23), T_{1C} can be expressed as Equation (26), and then T_{1C} can be obtained.

$$T_{1C} = \frac{(B_{12}-B_1-B_2)T_{2T}}{(B_{12}-B_1-B_2) - T_{2T}\left(\frac{h_2+h_1}{2}\right)^2} = \frac{1}{\frac{1}{T_{2T}} - \frac{(h_2+h_1)^2}{4(B_{12}-B_1-B_2)}} \qquad (26)$$

Using Equations (23) and (26), Kim et al. [7] predicted the bending rigidities of laminated fabrics with face fabrics and adhesive interlinings with an assumption that those neutral axes lie in those centroids. In the study, with T_{1C} from two twill fabrics using Equation (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 (22) as well.

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

$$Y_2 = \frac{2(B_{12}-B_1-B_2)}{h_2(h_1+h_2)}\left(\frac{1}{T_{2T}}+\frac{1}{T_{1C}}\right) - \frac{h_1}{2h_2} \qquad (27).$$

Therefore, when the neutral axis of component1 is assumed to lie in the centroid, bending rigidity of laminated fabric with component2 which neutral axis is unknown can be predicted using Equation (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 (27).

Let us consider Equation (22)'. Equation (22)' can be applied to a reverse bending of Equation (22) that component1 is outward and the component2 is inward in bending. In Equation (22)', T_{2C} of a component2 which neutral axis does not lie in the centroid will be necessary. 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 (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.

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.

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 (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 [11]. 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 KES-FB1 tensile tester up to a maximum load of 490 cN/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 [7]. 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 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 (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 (22). Those results were compared with experimental data.

The sample specifications are shown in tables 1, 2 and 3. Particularly, we used face fabrics which showed large prediction errors by Equation (2). Hence, six fabrics (S1-6) which showed large prediction errors (over about mean absolute percentage errors (MAPE) 10%) using Equation (2) were prepared as face fabric samples assumed to have different tensile and compressive moduli. Ten kinds of adhesive interlinings (CE1-5 and DP1-5) were also prepared as experimental samples. Two twill fabrics (N1 and N2), which neutral axes can be assumed to lie in the centroid [7], 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.

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 [5]. 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. The samples pressed alone were referred to as ‘pressed samples’, and face fabric and adhesive interlining together as ‘pressed adhesive interlining’ and ‘pressed samples’. The conditions for manufacturing the pressed samples were the same as for bonding interlining.

Table 1 Specifications of the face fabrics

Sample name	**Yarn Count(Nm)**		**Weave**	**Density(/cm) (Warp × Weft)**	**Material**	**Pressed face fabric name**
	Warp	Weft				
N1	16.5 tex×2; R33tex	16.5 tex×2; R33tex	Twill	28×22	Wool 100%	P-N1
N2	14tex×2; R28tex	14tex×2; R28tex	Twill	29×24	Wool 100%	P-N2
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 2 Specifications of the adhesive interlinings

Sample name	**Density (/cm)**	**Adhesive dot number(/cm) (warp × weft)**	**Adhesive dot size(mm)**	**Mass per unit area(g/m^2)**	**Adhesive mass without fabric(g/m^2)**	**Pressed adhesive interlining name**
CE1	38×22	10×10	0.17	36.2	8.6	P-CE-1
CE2	38×23	10×10	0.17	35.6	8.0	P-CE-2
CE3	38×25	10×10	0.17	36.5	8.3	P-CE-3
CE4	37×26	10×10	0.17	36.5	8.1	P-CE-4
CE5	37×26	10×10	0.17	35.7	7.7	P-CE-5
DP1	39×24	9×9	0.25	38.5	8.7	P-DP-1
DP2	39×24	10×10	0.23	39.9	10.0	P-DP-2
DP3	39×24	10×10	0.30	41.8	11.6	P-DP-3
DP4	39×24	11×11	0.20	37.5	8.7	P-DP-4
DP5	39×24	12×12	0.10	39.3	10.1	P-DP-5

Table 3 Combinations of face fabric and adhesive interlining

Face fabric / **Adhesive interlining**	**N1**	**N2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
CE1	N1-CE1	N2-CE1	A-CE1	S2-CE1	S3-CE1	S4-CE1	S5-CE1	S6-CE1
CE2	N1-CE2	N2-CE2	A-CE2	S2-CE2	S3-CE2	S4-CE2	S5-CE2	S6-CE2
CE3	N1-CE3	N2-CE3	A-CE3	S2-CE3	S3-CE3	S4-CE3	S5-CE3	S6-CE3
CE4	N1-CE4	N2-CE4	A-CE4	S2-CE4	S3-CE4	S4-CE4	S5-CE4	S6-CE4
CE5	N1-CE5	N2-CE5	A-CE5	S2-CE5	S3-CE5	S4-CE5	S5-CE5	S6-CE5
DP1	N1-DP1	N2-DP1	A-DP1	S2-DP1	S3-DP1	S4-DP1	S5-DP1	S6-DP1
DP2	N1-DP2	N2-DP2	A-DP2	S2-DP2	S3-DP2	S4-DP2	S5-DP2	S6-DP2
DP3	N1-DP3	N2-DP3	A-DP3	S2-DP3	S3-DP3	S4-DP3	S5-DP3	S6-DP3
DP4	N1-DP4	N2-DP4	A-DP4	S2-DP4	S3-DP4	S4-DP4	S5-DP4	S6-DP4
DP5	N1-DP5	N2-DP5	A-DP5	S2-DP5	S3-DP5	S4-DP5	S5-DP5	S6-DP5

Results and Discussions

The bending rigidities and thicknesses of pressed samples are shown in tables 4 and 5. 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 6. T_{1C} values for adhesive interlining samples were obtained using Equation (26) from the laminated fabric with twill fabrics N1 and N2. The averages of T_{1C} values were obtained as shown in Table 7 and used in the prediction.

To predict bending rigidity of laminated fabric with a face fabric which 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 (27) and the averages for all samples were shown in Figure 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 (27). As shown in Figure 2, the averages of Y_2 for all samples were closed to 1. If Y_2 is close to 0.5, it means that E_{2C} and E_{2T} are almost the same. In that case, the predicted results will be similar with the results by Equation (2). On the other hand, if Y_2 is close to 1, it means that E_{2C} and E_{2T} 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 (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 agreed with 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 2. Figure 3 shows the comparison of predicted and experimental bending rigidities for laminated fabrics using Y_2. The predicted bending rigidities using Equation (2) are also shown in Figure 3 to confirm the effect of considering 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 8. As shown in Figure 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 composites. 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 8. The reason will be due to the variation of Y_2.

Table 4 Bending rigidities and thicknesses of pressed interlinings

Sample name	Bending rigidity($cN \cdot cm^2/cm$)		Thickness(cm)	
	Average	Standard deviation	Average	Standard deviation
P-N1(warp)	0.135	0.002	0.052	0.001
P-N1(weft)	0.076	0.001		
P-N2(warp)	0.057	0.001	0.050	0.002
P-N2(weft)	0.037	0.002		
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 Bending rigidities and thicknesses of pressed interlinings

Sample name	Bending rigidity ($cN \cdot cm^2/cm$)		Thickness (cm)		Sample name	Bending rigidity ($cN \cdot cm^2/cm$)		Thickness (cm)	
	Average	Standard deviation	Average	Standard deviation		Average	Standard deviation	Average	Standard deviation
P-CE1(warp)	0.0058	0.0015	0.027	0.001	P-DP1(warp)	0.0064	0.0009	0.024	0.007
P-CE1(weft)	0.0051	0.0016			P-DP1(weft)	0.0024	0.0010		
P-CE2(warp)	0.0058	0.0016	0.025	0.001	P-DP2(warp)	0.0059	0.0011	0.024	0.006
P-CE2(weft)	0.0030	0.0010			P-DP2(weft)	0.0020	0.0013		
P-CE3(warp)	0.0060	0.0005	0.024	0.001	P-DP3(warp)	0.0074	0.0007	0.025	0.007
P-CE3(weft)	0.0035	0.0009			P-DP3(weft)	0.0033	0.0009		
P-CE4(warp)	0.0070	0.0005	0.024	0.0004	P-DP4(warp)	0.0059	0.0008	0.024	0.007
P-CE4(weft)	0.0039	0.0005			P-DP4(weft)	0.0027	0.0008		
P-CE5(warp)	0.0085	0.0033	0.023	0.001	P-DP5(warp)	0.0062	0.0008	0.025	0.007
P-CE5(weft)	0.0039	0.0013			P-DP5(weft)	0.0013	0.0017		

Table 6 T_2values of pressed face fabrics

Sample name	T_2 values(N/cm)
P-A(warp)	14.7
P-A(weft)	29.5
P-B(warp)	23.3
P-B(weft)	4.3
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 7 Average T_1 values of pressed interlinings from face fabric, N1and N2

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

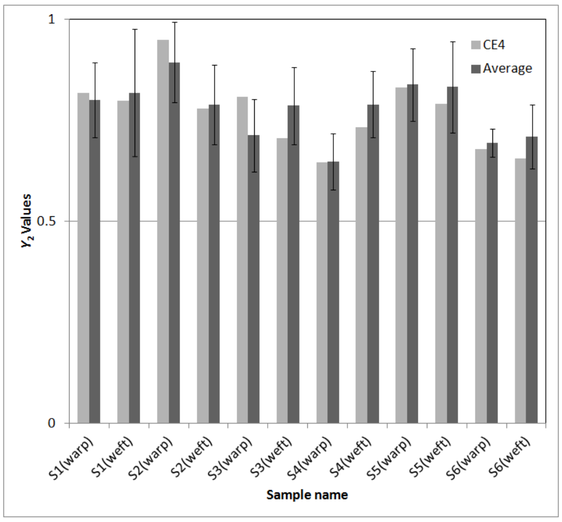

Figure 2 Averages of Y_2 values of face fabrics for different adhesive interlinings and Y_2 values from laminated fabric combinations of face fabrics and CE4 interlining.

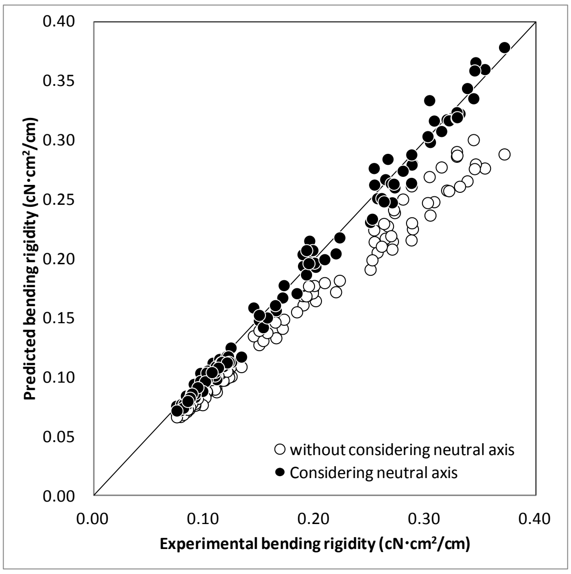

Figure 3 Predicted and experimental bending rigidity of the laminated fabrics by the method with and without considering the position of neutral axis.

Table 8 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 fabric-all interlinings	3.6	12.7

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 composite 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.

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 the samples which 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.

Appendix

Notations:

Component1 adhesive interlining

Component2 face fabric

B_1 bending rigidity per unit breadth of component1

B_2 bending rigidity per unit breadth of component2

B_{12} bending rigidity per unit breadth of laminated fabric with component1and component2

h_1 thickness of component1

h_2 thickness of component2

R radius of curvature

η distance from the neutral axis

0 neutral axis of a laminated fabric

y_0 coordinate of bottom of laminated fabric

y_1 coordinate of the border of components

y_2 coordinate of boundary at the top of laminated fabric

T_{1C} apparent in-plane compressive modulus for longitudinal strain of neutral axis for component1

T_{2C} apparent in-plane compressive modulus for longitudinal strain of neutral axis for component2

T_{1T} apparent tensile modulus for longitudinal strain of neutral axis for component1

T_{2T} apparent tensile modulus for longitudinal strain of neutral axis for component2

ε_1 compressive strain at the neutral axis of component1

σ_1 stress in component1

F_1 total force of component1

F_2 total force of component2

M_1 couple per unit breadth and unit curvature of component1

M_2 couple per unit breadth and unit curvature of component2

E_{1T} elastic modulus of strain in tension of component1

E_{1C} elastic modulus of strain in compression of component1

E_{2T} elastic modulus of strain in tension of component2

E_{2C} elastic modulus of strain in bending of component2

y_{1n0} distance from the bottom to the neutral axis of component1

y_{2n0} distance from the bottom to the neutral axis of component2

Y_1 relative position of neutral axis of component1
Y_2 relative position of neutral axis of component2
E_{BT} tensile modulus of a fabric
E_{BC} in-plane compressive modulus of a fabric
b breadth
y_{1n} original neutral axis of component 1
y_{2n} original neutral axis of component 2
Y, Y' relative position of neutral axis of a fabric

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