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Analysis of Woven Fabric Structure using X-ray CT Images

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In this paper, a novel method for analyzing a woven fabric structure, particularly a multi-layered one, is proposed to obtain positional information regarding each yarn of a sample woven fabric using X-ray computed tomography (CT) images. The method can reconstruct a positional relationship between the yarns. The positional information is defined as a sequence of points on the center line of each yarn of the sample in this study, since the sequence can be regarded as the representative position of the yarn and is therefore robust against measurement errors. The sequence is obtained by estimating the center of the yarn cross-section of the same yarn on each of the CT images in succession. The center of the yarn cross-section is estimated by correlating the CT image with a yarn cross-sectional model. The effectiveness of the proposed method is confirmed by experimentally applying the method to CT images of a twill fabric. Furthermore, the experimental results of applying the method to CT images of a double-layered woven fabric indicate that even if this method is applied to a multi-layered woven fabric, the correct location of each yarn of the fabric can be estimated.

Key Words: analysis of woven fabric structure, image processing, X-ray CT image

1. Introduction

In the textile industry a process called "woven fabric analysis" is used to analyze the structures of a woven fabric. This process plays an important role in the designing of new fabrics, in which the information from the analysis is used to develop fabrics with new functions and designs. This process, however, is tedious and complicated and places considerable strain on the operator, requiring operation of the microscope while disentangling the fabric using needles and scissors. As fabrics have become extremely complex in recent years, an enormous amount of knowledge and experience is required for this process. Also, the number of younger operators with this skill has reduced as the skilled laborers are reaching retirement age. Taking this background into consideration, it is highly desirable to automate this process in order to analyze the woven fabric structure in a reliable and precise manner.

The automation of analyzing woven fabric structures has been researched since the mid 1980's. For example, Huang et al.[5] obtained the intersection of the warp and weft using the vertically and horizontally summed brightness of the surface image, while understanding the intersecting conditions of the warp and weft by utilizing the geometric characteristics of the fabric structure. There are also other reports[1)~4)] of the automated analysis of woven fabric structures.

Since the research on automated analysis of woven fabrics has focused on surface image processing, analysis has been limited to fabrics with a single layer. In fact, the above-mentioned studies point this out as an issue for future study, stating that surface image processing does not reveal enough information to decipher the internal structures of complex fabrics such as multi-layered fabrics. Thus, we previously proposed the use of cross-sectional images to analyze multi-layered fabrics since such a method can reveal its internal multi-layered structures[6),7)].

In this paper, we propose a novel method of analyzing woven fabric structures by utilizing cross-sectional images. First, analysis of fabric structures using cross-sectional images will be examined; the method for acquiring images, the purpose of our study, and the method for utilizing the images will be mentioned, and the type of sample fabric used in this study will also be discussed. Next, the method to estimate the center points of the yarn will be presented; that is, the novel method to estimate the center point of the yarn by calculating the correlation of the cross-sectional images and a function called the yarn cross-sectional model is proposed. Also for comparison, the method to estimate the center point of the yarn cross-section by calculating the correlation of two consecutive cross-sectional images will be discussed.

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The advantages of the proposed method to estimate the center points of the yarn is clarified by comparing the correlation analyses of woven fabrics using the two methods. The problems of the proposed method that arose after experimentation have been improved and the effectiveness of the improved method is then verified by a second analysis. Lastly, the proposed method is applied to a multi-layered fabric and it is shown that the structures of multi-layered fabrics can be successfully analyzed.

2. Examination of the Analysis of Woven Fabric Structures Using Cross-sectional Images

2.1 Acquiring Cross-sectional Images

In our previous studies, samples were cut in order to acquire cross-sectional images [6]. Although the cutting of samples is of relatively low cost, the pre-treatments that include cutting, polishing, and taking photographs are tedious and troublesome to complete. Also, margin of errors may arise for the cross-sectional image intervals and alignment of the positions of each cross-sectional image. In addition to these disadvantages, the cutting of samples cannot be carried out with historically valuable samples.

In the present study, a non-destructive method of acquiring cross-sectional images using X-ray computed tomography (CT) is adopted. Advantages of this method are that the same area can be imaged from various angles since the samples are not destroyed prior to analysis, and it allows automated acquisition of cross-sectional images if the equipment is set up as such. In fact, compact and high resolution CT equipment with automation capabilities allowing images to be taken in μm resolution and intervals are currently being developed (e.g. Ref. 10).

2.2 The Role of Structure Analysis

The objective for the analysis of woven fabric structures typically varies, and may include making a weave diagram or analyzing the 3-dimensional structure of the fabric. The current study focuses on obtaining fundamental information of the fabric in order to meet the various needs encountered in the analysis of woven fabric structures, since the fundamental information can be applied in various ways. The term "structural analysis" will be used in this paper when referring to obtaining fundamental information. The term "fundamental information" refers to information which can be used to reconstruct the positional relationship of the yarns, which in turn corresponds to the positional information of each yarn. It is to be noted that the relative positional information of each yarn, as opposed to the absolute positional information, is necessary to reconstruct the fabric structure. Yarn can be modeled as a trajectory made by moving a circle perpendicular to an arbitrary continuous curve. Additionally, the trajectory of the center point of the circle is referred as the center line of the yarn in this paper. The positional information of this center line is understood as the positional information. This center line represents the yarn position and is robust against errors of estimation in reconstructing the relationship of the yarns. In fact, since we use discrete cross-sectional images, the yarn center points are accordingly regarded as the positional information of the yarns.

As one of applications of the positional information of the yarns, we have investigated reconstructing the structure of a fabric in 3-dimensions [6),7)] by using the Generative Model proposed by Liao and Akanur [8)]. By 3-dimensionally expressing a fabric structure, the conditions of the ebb and flow and the tension of the warp and weft can be observed, and thus a new method for analyzing fabric structures with various designs, feel, and structural functionality can be offered. This method differs from constructing a weave diagram showing only the ebb and flow in 2-dimensions. Since fabric structures reconstructed in 3-dimensions utilize positional information, each yarn can be expressed individually, and this method is therefore considered useful for understanding the structures of complex fabrics such as multi-layered fabrics.

2.3 Utilizing Cross-Sectional Images for the Structural Analysis of Fabrics

Here we discuss methods to obtain the center points of yarn by using cross-sectional images. The center points of each yarn are equivalent to the center points of the yarn cross-sections in the cross-sectional images. The number of center points of each yarn directly correlates with the amount of details in the positional information. In order to increase the number of center points per unit length, it is most efficient to obtain cross-sectional images that are perpendicular to the yarn direction as shown in **Fig. 1**(a), rather than to obtain cross-sectional images slantendicular to the yarn direction as shown in Fig. 1(b).

Taking this information into account we consider the characteristics of fabrics. Fabrics are cloth in which the warp and weft are interlaced and intersect perpendicularly. Typically the warp runs parallel with the warp, while the weft runs parallel with the weft, thus never intersecting one another. In order to obtain the center

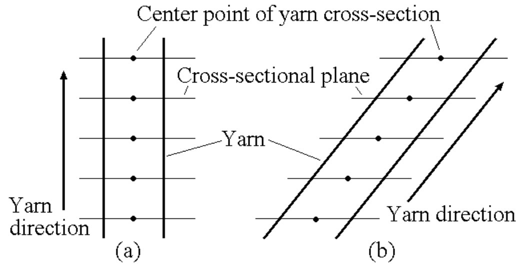

Fig. 1 Schematic diagram of the relationships between a cross-sectional plane and a yarn direction, where (a) the cross-sectional plane is perpendicular to the yarn direction and (b) the cross-sectional plane is slantendicular to the yarn direction

points of the warp, cross-sectional images of the warp are taken perpendicular to the warp direction, while to obtain the center points of the weft, cross-sectional images of the weft are taken perpendicular to the weft direction. This ensures that many center points for both the warp and weft are obtained.

Taking into account the above considerations, cross-sectional images are taken perpendicularly for both the warp and weft in order to estimate the center points of the yarn cross-sections.

2.4 Analytical Sample

In the proposed structural analysis method, it is important to distinguish the cross-sections of the yarns on the cross-sectional image in order to obtain the necessary positional information. In fabrics with high yarn densities, however, the cross-sections of the yarns come into close contact with each other, thus making it difficult to distinguish the different cross-sections of the yarns by image processing. In order to avoid the difficulties associated with distinguishing the cross-sections of high yarn density fabrics, the present study will use fabrics with relatively low yarn density where the cross-sections seldom come into close contact with one another. Analysis of fabrics with high yarn density or fabrics with complex yarn cross-sectional shapes will be the subject of future study.

The yarns used in the present study are single yarns where the shapes of the yarn cross-sections are simple. Complex yarns such as fancy yarns will be considered in the future.

3. Considerations for the Estimation of the Yarn Center Points

3.1 Estimation of the Yarn Center Points

In this section, the method to estimate the center points of yarns will be discussed with the presupposition that cross-sectional images are obtained perpendicularly from the axis of the yarns.

3.1.1 Estimation of Yarn Center Points Using the Cross-Sectional Model Correlation Method

The procedure to estimate the center points of yarns using the yarn cross-sectional model correlation method is discussed below. The yarn cross-sectional model correlation method estimates the center point of a yarn cross-section from a cross-sectional image.

First, the initial setting to estimate the center points of yarn is performed, where approximate center coordinates are manually assigned to the yarn cross-sections of the first cross-sectional image. Next, the center point of the yarn cross-section is estimated using the yarn cross-sectional model correlation method. Then the estimated center point from the first image is succeeded to the second cross-sectional image. It should be noted that when the position of the center point is succeeded to the next image, it is presupposed that the interval between the two cross-sectional images are small, to the degree that the estimated center point can be directly succeeded to inside the same yarn cross-section on the next cross-sectional image. With the aforementioned presupposition satisfied, the center point of the yarn cross-section on the second cross-sectional image is estimated by the yarn cross-sectional model correlation method using the succeeded position of the center point as the starting point. By repeating this procedure until the Nth cross-sectional image, the center points of the yarn can be obtained.

Next, the yarn cross-sectional model correlation method is discussed. In this method a correlation is made between the cross-sectional image and a function called the yarn cross-sectional model. Since this paper deals with single yarns, the shape of the yarn cross-section taken perpendicularly to the yarn axis is relatively circular. Therefore the yarn cross-sectional model is given a circular shape, and in order to decrease the effects of other yarns and background noise, a weighting function is applied to the yarn cross-sectional model. A correlation is made between this function and the cross-sectional image by the following equations:

$$J_2(x_c, y_c) = \sum_{i=-m}^{m} \sum_{j=-n}^{n} h(x_c, y_c, i, j) f(i, j), \qquad (1)$$

$$h(x_c, y_c, i, j) = \exp\{-s\ r(x_c, y_c, i, j)^2\}, \qquad (2)$$

$$r(x_c, y_c, i, j) = \sqrt{(i - x_c)^2 + (j - y_c)^2}, \qquad (3)$$

where, (x_c, y_c) is the coordinates of the yarn cross-section center point, (i, j) is the coordinates of the calculating point, h is the weight of the yarn cross-sectional model,

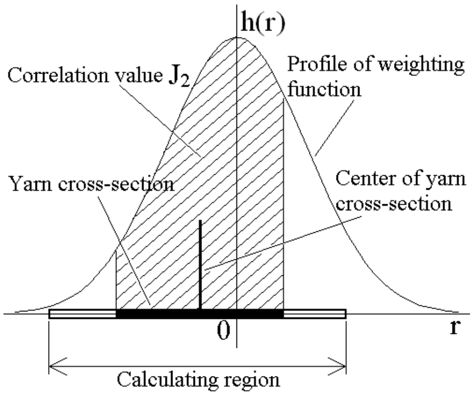

Fig. 2 Profile of the weighting function h(r), the yarn cross-section, its center, the calculating region, and the correlation value J_2, which are described in two dimensions, respectively

f is a binarizing function for the cross-sectional image where it is 1 in the yarn region and 0 in the background region, and r is the distance between the center point and the calculating point of the cross-sectional model. Also, $((2m+1) \times (2n+1))$ is the size of the calculating region and s is a variable that decides the shape of the weighting function. The size of the calculating region and the variable s is fixed to make the half-value width of h equivalent to the diameter of the yarn and also to make the calculating region one size larger than the yarn cross-section. The method to decide the values of these variables, however, still has room for consideration.

The correlation between the yarn cross-sectional model and the cross-section of the yarn is highest when the correlation value J_2 is at maximum. At this condition the two positional relations match and the center of the yarn cross-sectional model can be estimated as the center point of the yarn cross-section.

As shown in **Fig. 2**, where the function is shown in two dimensions for simplicity, J_2, the shaded area in the figure, corresponds to the area of the weighting function at the yarn cross-section. It is apparent that J_2 is at maximum when the center of the yarn cross-section matches the center of the yarn cross-sectional model.

3.1.2 Estimation of Yarn Center Points Using the Cross-Sectional Images Correlation Method

The correlation of consecutive CT images is extremely high as the intervals of the cross-sectional images are narrow. Using this to its advantage, in the cross-sectional images correlation method the center point of the yarn cross-section is estimated by making a correlation between consecutive cross-sectional images. The advantages and disadvantages of the cross-sectional images correlation method and the yarn cross-sectional model correlation method for the estimation of the yarn center points will be compared and discussed below.

The procedure for the estimation of the yarn center points using the cross-sectional images correlation method is as follows. First, the initial setting to estimate the center points of yarn is carried out, where center point coordinates are given to the first cross-sectional image of the yarn cross-sections. Similar to the yarn cross-sectional model correlation method, the center coordinate is assigned by human inspection; however, the center point coordinate should be carefully chosen as the subsequent cross-sectional images will use the original center point coordinate. It should be noted that, in contrast with the yarn cross-sectional model correlation method, a new center point coordinate is not assigned for each cross-sectional image. Next, the center point of the yarn cross-section of the second cross-sectional image is estimated using the cross-sectional images correlation method. The center point of the yarn cross-section of the third cross-sectional image is then again obtained by the cross-sectional images correlation method. This procedure is repeated until the final Nth cross-sectional image to obtain the center points of the yarn.

In the cross-sectional images correlation method, the correlation between the lth cross-sectional image and the $(l+1)$th cross-sectional image is calculated [9] by the following equation:

$$S(x_{c(l+1)}, y_{c(l+1)}) = \frac{\sum_{i=-m}^{m} \sum_{j=-n}^{n} D_l(i,j) \times D_{(l+1)}(x_{c(l+1)}, y_{c(l+1)}, i, j)}{(2m+1)(2n+1)\sqrt{\sigma^2(I_l) \times \sigma^2(I_{(l+1)})}}, \tag{4}$$

$$D_l(i,j) = I_l(x_{cl}+i, y_{cl}+j) - \overline{I_l(x_{cl}, y_{cl})}, \tag{5}$$

$$D_{(l+1)}(x_{c(l+1)}, y_{c(l+1)}, i, j) = I_{(l+1)}(x_{c(l+1)}+i, y_{c(l+1)}+j) - \overline{I_{(l+1)}(x_{c(l+1)}, y_{c(l+1)})}, \tag{6}$$

$$\overline{I_k(x_{ck}, y_{ck})} = \sum_{i=-m}^{m} \sum_{j=-n}^{n} \frac{I_k(x_{ck}+i, y_{ck}+j)}{(2m+1)(2n+1)}, \tag{7}$$

$$\sigma(I_k) = \sqrt{\frac{\sum_{i=-m}^{m} \sum_{j=-n}^{n} {I_k}^2(x_{ck}+i, y_{ck}+j)}{(2m+1)(2n+1)} - \overline{I_k(x_{ck}, v_{ck})}^2}, \tag{8}$$

where (x_{ck}, y_{ck}) is the estimated yarn cross-section center point of the kth cross-sectional image, I_k is the brightness, $\overline{I_k(x_{ck}, y_{ck})}$ is the average I_k value of the $((2m+1) \times (2n+1))$ region with (x_{ck}, y_{ck}) as the center, and $\sigma(I_k)$ is the standard deviation. The S value lies in the range of -1 and 1 and the correlation is higher when the value is close to 1.

When the correlation value S is at maximum, the point of the yarn cross-section on the $(l+1)$th cross-sectional image, which corresponds to the center point of the yarn cross-section on the $(l+1)$th cross-sectional image, is estimated as the center point of the yarn cross-section on the $(l+1)$th cross-sectional image.

3.2 Validity Verification of the Yarn Center Point Estimation Method

The validity of the yarn center point estimation method using the yarn cross-sectional model correlation method is verified. This is done by obtaining CT images of actual fabrics and estimating the yarn center points using the yarn cross-sectional model correlation method and the cross-sectional images correlation method.

3.2.1 Experimental

The twill fabric (1) used in the experiment is shown in **Photo. 1**, where the diameter of the yarn is approximately 0.1 mm. A SkyScan 1072 Model Micro CT Scanner [10] was used to obtain the cross-sectional images. The resolution per pixel was 2.1 μm and the interval between consecutive cross-sectional images was 4.1 μm on average. The sample was fixed in place and CT images were obtained such that the plane of the cross-sectional image was parallel with the weft. An example of a cross-sectional image is shown in **Fig. 3**. The white circular region is the cross-section of the warp and the long white region is the cross-section of the weft. For convenience purposes the horizontal axis of the cross-sectional images is defined as the x-axis, the vertical axis as the z-axis, and the depth as the y-axis. The twill structure reconstructed by directly accumulating CT images is shown in **Fig. 4**. The dotted line indicates the portion in which the CT image of Fig. 3 is used. From an image resolution perspective it is usually better to use a $y-z$ cross-sectional CT image for the $y-z$ cross-sectional images to estimate the yarn center points of the weft; however, in the current experiments pseudo $y-z$ cross-sectional images, which are made using the pixels at the same x-coordinates of all the $x-z$ cross-sectional images, are used.

3.2.2 Estimation of Yarn Center Points Using the Yarn Cross-Sectional Model Correlation Method

After binarizing by discriminant analysis, the cross-sectional images undergo erosion-dilation processing for filling holes of the yarn cross-section made by the binarizing and removing noise.

(1) This is called "Six-Twill" as known by experts and is a twill fabric written as $\frac{4}{2}\Big/$.

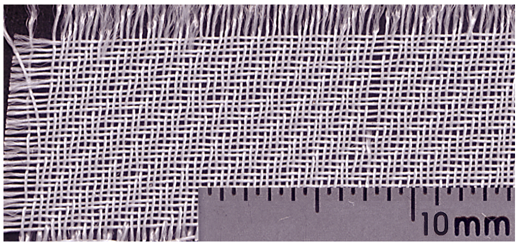

Photo. 1 Photograph of the twill fabric sample

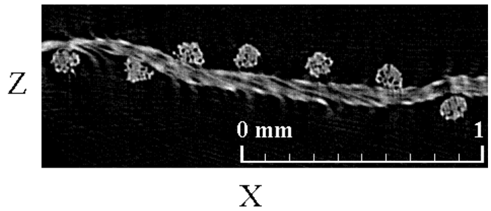

Fig. 3 Example of CT images of the twill fabric sample

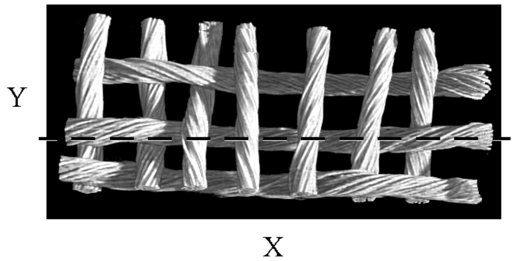

Fig. 4 Twill structure reconstructed by directly accumulating CT images (dotted line indicates the portion for which the CT image of Fig. 3 is used)

Fig. 5 shows the twill structure reconstructed from the center points of each yarn estimated by the yarn cross-sectional model correlation method. Although the yarn is somewhat crooked around the regions where the warp and weft intersect due to the effects from the opposing yarns, the relative positions of each yarn is accurately reconstructed when compared to Fig. 4. Therefore it can be concluded that the positional information of the yarns can be accurately obtained when estimating the yarn center points using the yarn cross-sectional model correlation method.

3.2.3 Estimation of Yarn Center Points Using the Cross-Sectional Images Correlation Method

In the cross-sectional images correlation method the CT images, which are obtained as X-ray absorption coefficient data, are used directly as cross-sectional images. Furthermore, the pixels of the CT images are obtained as grayscale rather than as binary.

Fig. 6 shows the twill structure reconstructed from the center points of each yarn estimated by the cross-sectional

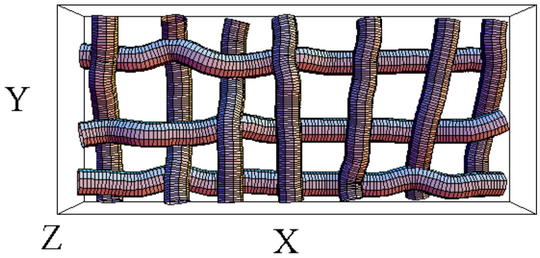

Fig. 5 Twill structure reconstructed from the positional information of each yarn estimated by the yarn cross-sectional model correlation method

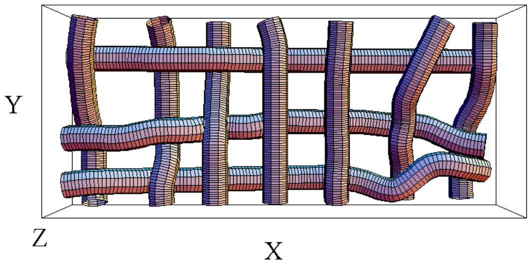

Fig. 6 Twill structure reconstructed from the positional information of each yarn estimated by the cross-sectional images correlation method

images correlation method. Although some regions of the yarns are significantly crooked, the relative position of each yarn is accurately reconstructed when compared to Fig. 4. Various sizes of the calculating region were tested and the best result, when compared to Fig. 4, was selected. The margin of error of the estimated center point and the twisting of the yarn is thought to be the reason for the shape of the yarns to be crooked in the reconstructed twill structure. When the estimated center point starts to deviate from the true center point, the estimated center point rotates when a correlation is obtained between consecutive cross-sections since the yarn is twisted. Therefore the shape of the yarn in Fig. 6 is significantly crooked.

3. 2. 4 Comparison of the Yarn Cross-Sectional Model Correlation Method and the Cross-Sectional Images Correlation Method

The yarn cross-sectional model correlation method is in accordance with the objective of this study for estimating the center points of the yarns, as this method is, in essence, a process to estimate the center point of a yarn cross-section. The results are influenced when image components such as those of other yarns enter into the calculating region. When the image components disappear from the calculating region, however, the effect is adjusted automatically. By changing the weighting function of the yarn cross-sectional model when obtaining the correlation, it may also be possible to reduce the effect of noises associated with other yarns.

On the other hand, the cross-sectional images correlation method in essence obtains the correlation between images. Additionally it is a process that searches for the image that resembles the original image when it is moved, where the center position is also thought to move accordingly. Therefore, as the process proceeds it is likely that the point of interest starts to deviate from the yarn cross-section region and thus there is a high possibility that the estimated center point may lie completely outside the yarn cross-section. Although the effects of yarn twisting were not taken into account when calculating the correlation between the images and there still may be room for improvement, the nature of this method will remain the same.

In conclusion, the yarn cross-sectional model correlation method has an inherent advantage where the process is, in itself, one that estimates the center point, and therefore is suitable for the estimation of yarn center points.

3. 3 Considerations of the Weighting Function for the Yarn Cross-Sectional Model

As mentioned above, the noise from other yarns can be reduced when the weighting function of the yarn cross-sectional model is properly established. Considerations for the weighting function for the yarn cross-sectional model are given below. For simplicity discussions will be limited to a 2-dimensional model. First, the weighting function for the yarn cross-section of the yarn cross-sectional model correlation method is given by the following equation:

$$h(r) = \exp\{-s\ r^2\}. \tag{9}$$

The profile of the weighting function is shown in **Fig. 7**. Using this weighting function, the center point can be estimated for isolated yarns; however, when the yarns come into close contact with each other, the weighting function estimates the center point of the clumped up yarns. In fact, in the aforementioned experiments to estimate the yarn center points using the yarn cross-sectional model correlation method, the yarn center points were estimated in a crooked fashion around the region where the warp and weft intersected due to the effects from opposing yarns. In the worst case the function estimates the center point on a cross-section of a neighboring yarn, thus rendering it impossible to obtain the center points to reconstruct the relative positional information of the yarns.

In order to reduce the effect from neighboring yarns, a new weighting function, which takes into account the background, is proposed as the following equation:

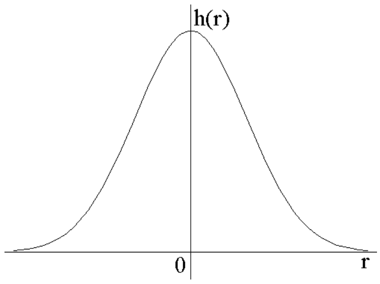

Fig. 7 Profile of the weighting function of the yarn cross-sectional model, $h(r) = \exp\{-s\ r^2\}$

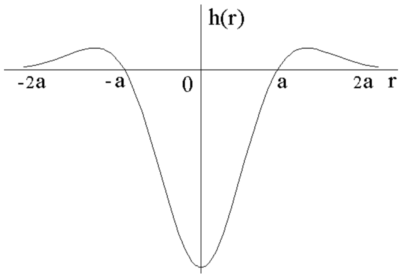

Fig. 8 Profile of the improved weighting function of the yarn cross-sectional model, $h(r) = -2\exp\{-s\ r^2\} + \exp\{-t\ r^2\}$

$$h(r) = -2\exp\{-s\ r^2\} + \exp\{-t\ r^2\}. \qquad (10)$$

The profile of the improved weighting function is shown in **Fig. 8**. The variable s, t is adjusted in two steps; first, the length between the zero-cross points ($2a$) is set to be equivalent with the diameter of the yarn; second, positive values on either side of the weighting function corresponds to the background region and the background region is set to be about two times that of the yarn diameter and surround the yarn region in an annular fashion. Furthermore, the cross-sectional images are binarized such that the yarn region is 0 and the background region is 1. It should be noted that the values of the yarn and background region are reversed in this case. When using this correlation method in which the correlation of the background is also made, the center point of the yarn can be estimated within the cross-sectional image even when the yarn in question comes into contact with another yarn. The center point of the yarn can also be estimated within the cross-sectional image even when the diameter of the yarn is a little larger than the original assumption due to uneveness of the yarn twisting or thickness. When the yarn cross-section becomes a little smaller, the center can be estimated without any problems due to the profile of the weighting function.

The twill structure reconstructed using the positional information of each yarn by applying the CT cross-sectional images to the yarn cross-sectional model correlation method using the improved weighting function is shown in **Fig. 9**. The relative positions of the yarns are accurately reconstructed, while the distortions in the yarn positions are small and effects from the opposing yarns are reduced in the regions where the warp and weft intersect.

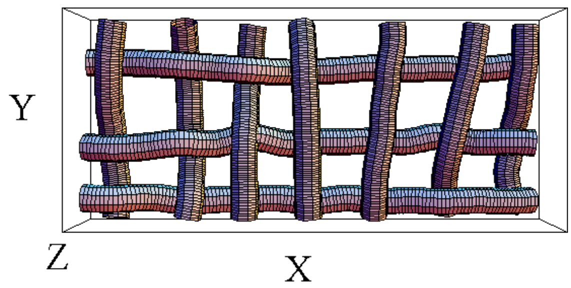

Fig. 9 Twill structure reconstructed from the positional information of each yarn estimated by the yarn cross-sectional model correlation method using the improved weighting function

4. Structural Analysis Experiments of Multi-Layered Fabric

The experimental results for the estimation of the center points of a multi-layered fabric using the yarn cross-sectional model correlation method using the improved weighting function are discussed below.

4.1 Experimental

The photograph of the multi-layered fabric used in the experiment is shown in **Photo. 2**. The fabric is a double-layered woven fabric with a yarn diameter of approximately 0.17 mm. The CT images were taken on the same SkyScan 1072 Model Micro CT Scanner. The resolution per pixel was 2.6 μm, the interval between consecutive cross-sectional images was 8.2 μm, and the images were taken by positioning the sample so the weft was parallel to the plane of the cross-sectional image. An example of a CT image is shown in **Fig. 10**. The white circular region corresponds to the cross-section of the warp and the white long region corresponds to the weft. In accordance with the previous experiments, the horizontal axis of the cross-sectional images is defined as the x-axis, the vertical axis as the z-axis, and the depth as the y-axis. **Fig. 11** shows the structure of the double-layered woven fabrics reconstructed by directly accumulating the CT images. The dotted line is the region where the CT image of Fig. 10 was used. The center points were estimated using the yarn cross-sectional model correlation method using the improved weighting function of the equation (10). Similar to the previous experiments, pseudo $y-z$ cross-sectional images, which are made using the pixels at the same x-coordinates of all the $x-z$ cross-sectional images, are

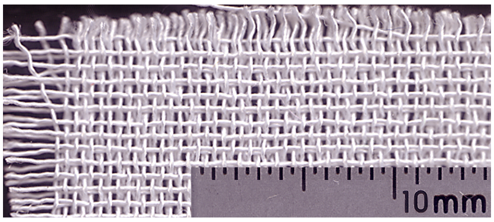

Photo. 2 Photograph of the double-layered woven fabric sample

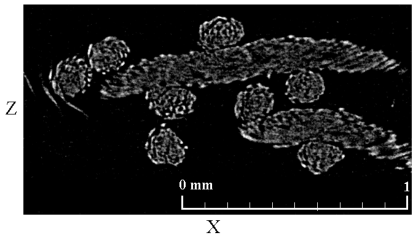

Fig. 10 Example CT images of the double-layered woven fabric sample

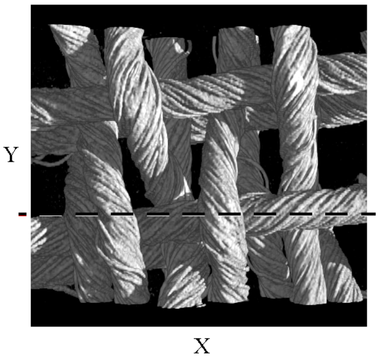

Fig. 11 Structure of double-layered woven fabric reconstructed by directly accumulating the CT images (dotted line indicates the portion for which the CT image of Fig. 10 is used)

used.

4. 2 Experimental Results

The structure of the double-layered fabric reconstructed from the estimated positional information is shown in **Fig. 12**. When compared to Fig. 11, it is clear that the relative positions of the upper layer yarns are accurately reconstructed. It is difficult to directly observe the yarns of the under layer in Fig. 12; however, by independently expressing the under layer of the double-layer fabric as in **Fig. 13**, it can be seen that the reconstructed structure matches the original fabric. Thus the positional information of each yarn was accurately estimated by employing the yarn cross-sectional model correlation method and the improved weighting function.

It has been shown that the proposed method for the structural analysis of fabric is effective since the fabric structure can be easily understood using the estimated

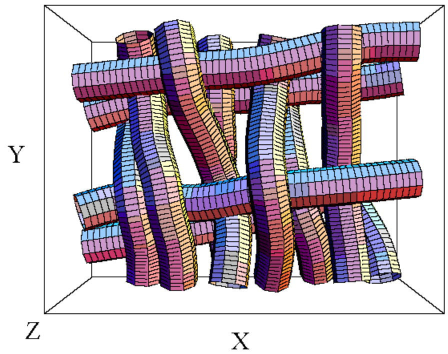

Fig. 12 Structure of double-layered woven fabric reconstructed from the positional information estimated by the yarn cross-sectional model correlation method using the improved weighting function

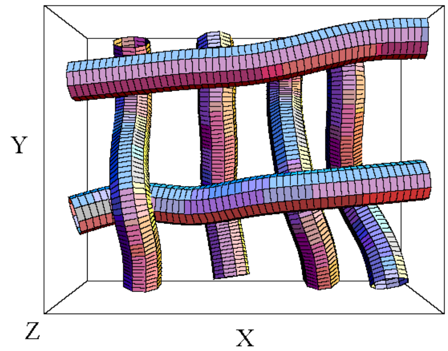

Fig. 13 Independent expression of the warp of the under layer and the weft of the upper layer of a double-layer woven fabric sample

center points of individual yarns. Although the current experiment used a double-layered fabric, it is possible to estimate the center points of more complex fabrics such as those of triple or quadruple-layered fabrics since this will only involve increasing the number of starting points for the estimation of center points.

5. Conclusion

To address the problems associated with conventional weave analyzing systems in order to analyze multi-layered fabrics, we have proposed a new method of utilizing cross-sectional images. The main purpose of this study was to obtain fundamental information for weave analysis using cross-sectional images obtained by X-ray CT. In order to estimate the yarn center points, which correspond to the fundamental information, a method called the yarn cross-sectional model correlation method was proposed and its validity was shown by experimentally applying it to X-ray CT images of actual fabrics. Although the analysis of fabrics with high densities of yarn, where the yarns come into close contact with each other, and those with complex yarn cross-sections are subjects for future study, it was shown that positional information of individual yarns of multi-layered fabrics could be accurately obtained. By using the obtained X-ray CT images as 3-dimensional information and extending the yarn cross-sectional model correlation method to 3-dimensions, we plan to analyze more complex fabrics such as knits as well as to consider the applications of the estimated yarn positional information in the future. Furthermore, by using the CT images, structural analysis can be extended to analyze the yarn size, number of twists, twist angle and unevenness, and yarn unevenness. These issues will be considered in further investigations.

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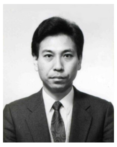

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