Measurement of Fiber Board Poisson's Ratio using High-Speed Digital Camera

Seung-Ryul Choi[1], Dong-Soo Choi[1]*, Sung-Sik Oh[1], Suk-Ho Park[1], Jin-Se Kim[1], Ho-Hyun Chun[2]

[1]*National Academy of Agricultural Science, Rural Development Administration, Jeonju, Korea*
[2]*World Institute of Kimchi an Annex of Korea Food Research Institute, Gwangju, Korea*

Abstract

Purpose: The finite element method (FEM) is advantageous because it can save time and cost by reducing the number of samples and experiments in the effort to identify design factors. In computational problem-solving it is necessary that the exact material properties are input for achieving a reliable analysis. However, in the case of fiber boards, it is difficult to measure their cross-directional material properties because of their small thickness. In previous research studies, the Poisson's ratio was measured by analyzing ultrasonic wave velocities. Recently, the Poisson's ratio was measured using a high-speed digital camera. In this study, we measured the transverse strain of a fiber board and calculated its Poisson's ratio using a high-speed digital camera in order to apply these estimates to a FEM analysis of a fiber board, a corrugated board, and a corrugated box. **Methods:** Three different fiber board samples were used in a uniaxial tensile test. The longitudinal strain was measured using the Universal Testing Machine. The transverse strain was measured using an image processing method. To calculate the transverse strain, we acquired images of the fiber board before the test onset and before the fracture occurred. Acquired images were processed using the image processing program MATLAB. After the images were converted from color to binary, we calculated the width of the fiber board. **Results:** The calculated Poisson's ratio ranged between 0.2968−0.4425 (Machine direction, MD) and 0.1619−0.1751 (Cross machine direction, CD). **Conclusions:** This study demonstrates that measurement of the transverse properties of a fiber board is possible using image processing methods. Correspondingly, these processing methods could be used to measure material properties that are difficult to measure using conventional measuring methodologies that employ strain gauge extensometers.

Keywords: Fiber board, High-speed digital camera, Image processing, Poisson's ratio, Transverse strain

Introduction

Since time and cost of sample production can be reduced through the application of various experimental parameters, finite element analysis is proved to be very economical compared to experimental analyses. It would be very advantageous if the finite element method (FEM) was used for designing corrugated fiber boards and corrugated boxes, since both the shape of the structure and the various constituent materials can be considered and analyzed (Park, 2005). To analyze the corrugated fiber board using the FEM, the physical properties (elastic modulus, shear modulus, Poisson's ratio, etc.) of each fiber board must be known. Generally, all of these properties are measured experimentally. While measurement of the longitudinal elastic modulus (Young's Modulus) is not difficult, it is very difficult to experimentally measure the shear modulus and the Poisson's ratio owing to the thickness of the paper (Yokoyama and Nakai, 2007). The Poisson's ratio and shear modulus are usually measured based on the transmission velocity of ultrasonic waves (Mann et al., 1979). Yokoyama (2007) measured the shear properties of paper using a high-speed digital sensor. A high-speed digital image sensor consists of a CCD camera and an optical extensometer. On the other hand, many other researchers have used the assumed values of the Poisson's ratio in various FE analyses.

---

*Corresponding author: Dong-Soo Choi
Tel: +82-63-238-4130; **Fax:** +82-63-238-4105
E-mail: choi0ds@korea.kr

Paper processed by a machine possesses orthotropic properties, i.e., its physical property varies according to whether the direction measuring properties of fiber board is parallel to the paper manufacturing direction [machine direction (MD)] or perpendicular to the MD [cross-machine direction (CD)] (Baum et al., 1981; Schulgasser, 1981). Accordingly, the elastic modulus needs to be measured both along the CD and the MD. Park (2003) reported that the difference between experimental results and analytical results ranged between 18–33% in the bending balance of a corrugated fiber board. He used the Poisson's ratio values of 0.36 (MD) and 0.12 (CD) considering that the proportion of the Poisson's ratio of the MD to the CD was theoretically equal to three. He also reported that the shape and size of the air hole of the corrugated board box, designed using the FEM, were verified by experimental results in cases where the Poisson's ratio, longitudinal strain, and transverse strain, were assumed to be 2.4, 0.28, and 0.12, respectively (Park, 2002). Lee et al. (1998) reported that the characteristics of the paper impact absorber were analyzed using FEM with an assumed Poisson's ratio of 0.3. Lee (Lee, 2009) further reported that the FEM analysis of the deformation of the corrugated board box exhibited significant differences with the expe-rimental results when the longitudinal strain and transverse strain were assumed to be 0.28 and 0.12, respectively. As described above, the Poisson's ratio of the fiber board in the FEM analyses conducted in Korea employ an assumed value. Therefore, a method to easily measure the Poisson's ratio of the fiber board is required for accurate simulations using the FEM.

This study was conducted to measure the transverse strain of the fiber board and to calculate the Poisson's ratio of the fiber boards in order to apply the estimated values for the fiber board, the corrugated board, and the corrugated box to FEM analyses.

Materials and Methods

Samples used in this study were the K180, SK180, and S120 fiber boards, manufactured by Dongilpaper MFG. Co., Ltd in Korea. Here, the letters K, SK, and S, were paper types, and the numbers 180, 120 were the basic weights of the fiber board. Specifically, K180 and S120 were made by pasting three sheets of old paper, while SK180 was made by pasting a sheet of pulp and two sheets of old paper. The constructed samples had a size of 180×15 mm

Table 1. Physical properties of samples

Paper Type	Basic weight[†#] (g/m^2)	Thickness[†‡] (μm)	Density[†‡] (kg/m^3)
K	180	269.7±14.2	667.4
SK	180	237.0±6.6	759.5
S	120	181.7±6.7	660.4

[†]Values are presented as mean±SD.
[#]Basic weight values are provided by the manufacturer.
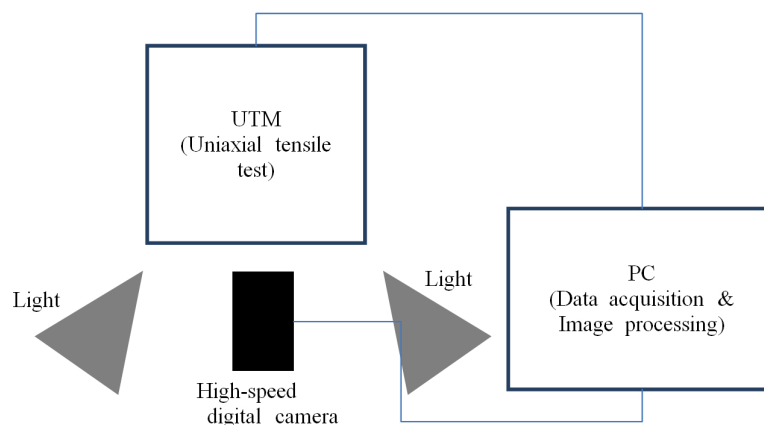[‡]Thickness and density values are measured based on KS M ISO 534.

Figure 1. Schematic diagram of the uniaxial tensile test apparatus with a high-speed digital camera.

(a) UTM and high-speed digital camera

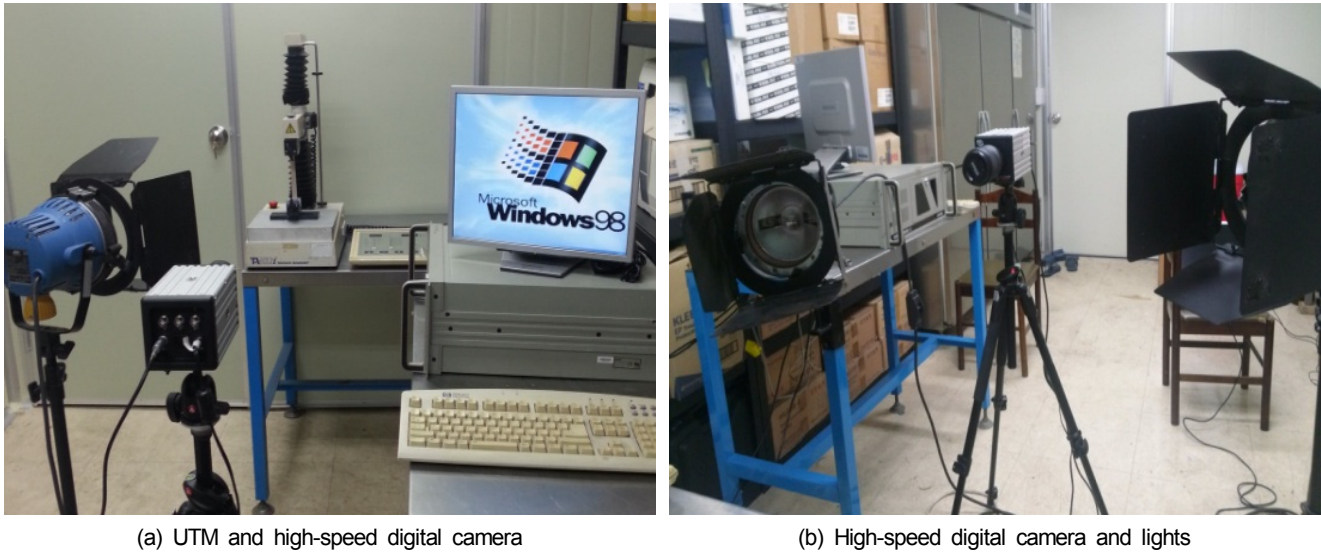(b) High-speed digital camera and lights

Figure 2. Photographs of the uniaxial tensile test apparatus with the high-speed digital camera.

(KS M ISO 1924-3). Because of the material's orthotropic characteristics, the testing samples were made in both the MD and the CD, respectively. Before the uniaxial tensile test, the samples were stored in a thermo-hydrostat at 23±1°C and 50±2% RH for 24 h (KS M ISO 187).

To measure the longitudinal and transverse strains, uniaxial tensile tests were conducted using the Universal Testing Machine (TAxT2i Texture Analyzer, Stable Micro System, UK) and a high-speed digital camera (X-Stream XS-4, IDT, USA). The testing apparatuses were arranged as shown in Figure 1.

The camera was placed 15 cm in front of the testing sample to accommodate an enlarged image view of the specimen. A black-colored background was used at the back of the samples to distinguish the edges of the fiber board clearly. To obtain images at close-proximity, a 60 mm macro lens (AS-F Micro Nikkor, Nikon, Japan) was used. Two 1000 W halogen lights (ARRILITE 1000, ARRI, Germany) were diagonally placed with respect to the center direction at 45° and 135°. The specifications of the high-speed digital camera used in the test are listed in Table 2, whereas the settings of the camera are listed in Table 3.

The uniaxial tensile test of the fiber boards were conducted in accordance to a Korean standard test method (KS M ISO 1924-3). The loading rate was 100 mm/min and the data acquisition rate was 200 Hz. The test was repeated 10 times for each fiber board.

The values for the longitudinal strain were measured using the same universal testing machine. The longitudinal

Table 2. Specifications of high-speed digital camera

Item	Specification
Resolution (pixel)	512×512
Pixel size (μm)	16×16
Max. frame rate (Hz)	5,145
Speed at full resolution (fps)	5,000
Size (mm)	95× 95×162
Weight (kg)	1.9

Table 3. Settings of high-speed digital camera

Item	Specification
Sensor gain	2.00
Data acquisition rate (Hz)	500
Exposure (μs)	482
Pixel	24 bit (512×512)

deformation, as measured by the UTM, and the initial length of the specimens, as measured by a vernier caliper, were all used in the calculation of longitudinal strain. The values for the transverse strain were measured by processing the images acquired with the high-speed digital camera. The commercial program (MATLAB 2007a, MathWorks, USA) was employed for digital image processing. We captured images before the test was started, and just before and after the sample failed. We obtained three images before the test, 20 images before the specimen failed, and 10 after it failed. From the images, we calculated the deformed width of the specimen along the transverse direction.

Image processing

An image can be defined as a two-dimensional function, and the amplitude for each of its constituent pixels (x, y) is called the brightness. A color image consists of the red, green, and blue components, while a grayscale image consists of black and white components ranging in brightness values fro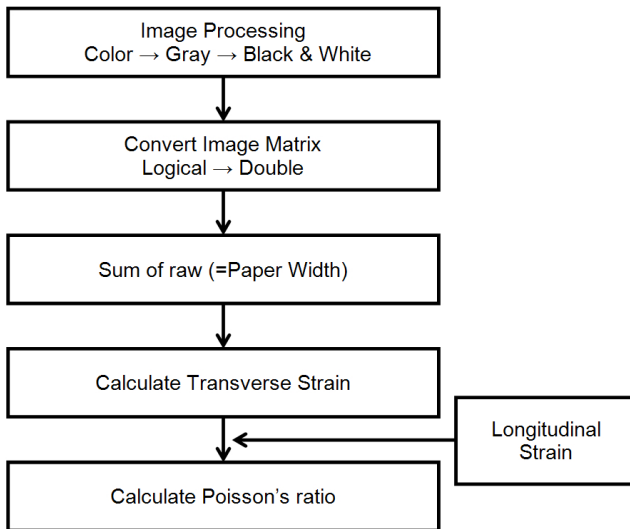m 0 to 255. A binary image consists of the black and white components, where black is assigned the value of 0 and white to the value of 1 (Gonzalez et al., 2004). Figure 3 shows the algorithm that is used to process the image and calculate the Poisson's ratio.

The color image acquired by the high-speed digital camera was converted into an 8-bit grayscale image. After the scaling operation of the allowed 256 gray levels to the range of 0 to 1 was completed, we selected an appropriate threshold value from 0.1 to 0.5 to convert the image to a binary image. The optimal threshold value is the value at which outlines can be clearly visualized without distortion. The image matrix of the binary image was then converted to a numerical matrix. By adding each raw value in the image, we obtained the width of the fiber board. Finally, using the acquired images before the test and the acquired images before failure, we calculated the transverse strain.

The Poisson's ratio was calculated as the ratio of the longitudinal direction strain to the transverse direction strain [see Equation (1)].

$$v = -\frac{\varepsilon_t}{\varepsilon_l} \tag{1}$$

where v is Poisson's ratio, ε_t is the transverse strain, and ε_l is the longitudinal strain.

Figure 3. Flow diagram of the algorithm developed for estimating the Poisson's ratio.

(a) Threshold = 0.10 (b) Threshold = 0.20 (c) Threshold = 0.22 (d) Threshold = 0.25

(e) Threshold = 0.28 (f) Threshold = 0.30 (g) Threshold = 0.40 (h) Threshold = 0.50
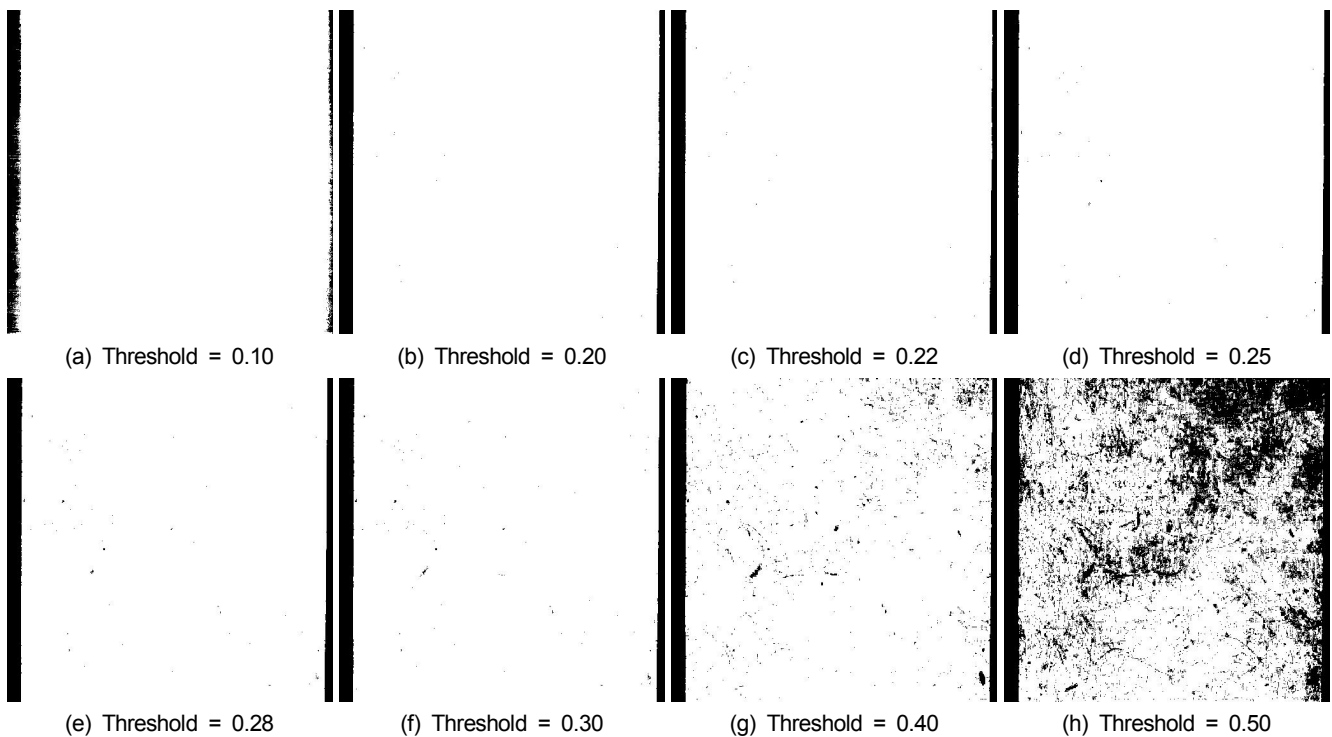
Figure 4. Determination of the optimal threshold value for the binary image conversion process.

(a) Color image   (b) Gray image   (c) Binary image
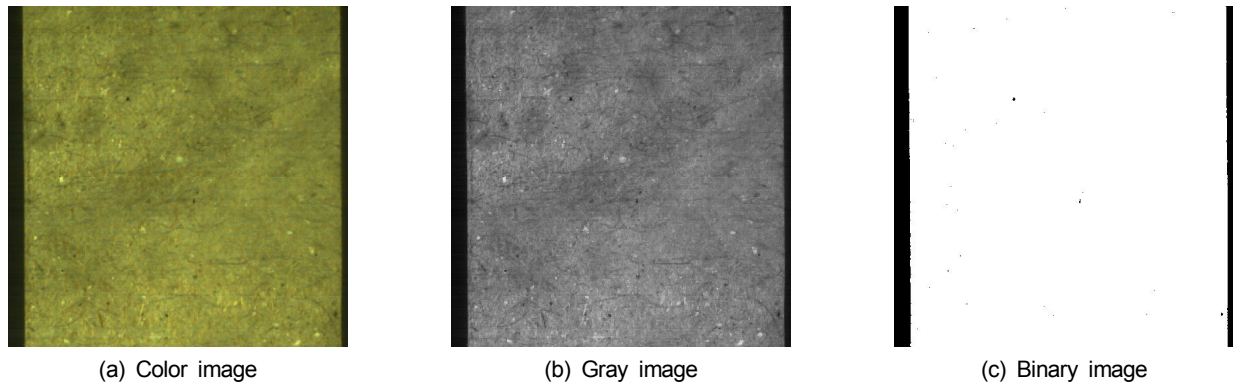
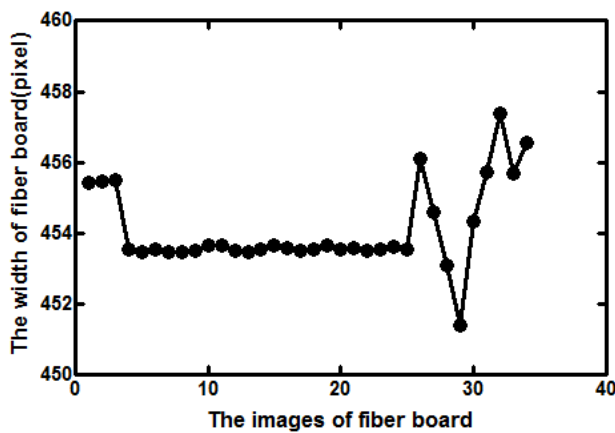**Figure 5.** Image processing results.

Figure 6. Fiber board width (in pixel count) measured along the transverse direction during conducted tensile tests.

Results and Discussion

Figure 4 shows the image results as the original color image was converted to a binary image with the threshold value ranging from 0.1 to 0.5. As seen, the lower the threshold value, the wider is the specimen. As the threshold value increased, the inner part of the specimen was converted to a black region. Under this test condition, the appropriate threshold value was 0.22.

Figure 5 shows the color image, the grayscale image, and the binary image of the fiber board.

Figure 6 shows the variation of the change in the width of the fiber board during the uniaxial tensile test. During the uniaxial tensile test, we obtained a total of 892 images. The width of the specimen in all 20 images before failure was constant. Evidently, the high-speed digital camera was fast enough to allow the measurement of the deformed width based on the acquired images. The entire width of the specimen was 455 pixels before the test and changed to 453 pixels before failure. After failure, the fiber board was restored and the width of the specimen varied from 451 pixels to 457 pixels.

Table 4 lists the transverse strain, longitudinal strain, and Poisson's ratio values of the fiber boards calculated by processing the images acquired using the high-speed digital camera. The Poisson's ratio of the fiber board along the MD ranged between 0.2968–0.4425, and the corresponding value along the CD ranged between 0.1691–0.1805. In prior research publications (Lee et al., 1998; Lee, 2009; Park, 2002; Park, 2003), the value obtained by dividing the Poisson's ratio along the MD by the Poisson's ratio along the CD was assumed to range between 1.0–3.0. In this study, the corresponding value

Table 4. Poisson's ratio estimation results

		Transverse strain[†]	Longitudinal strain[†]	Poisson's ratio[†]
K180	MD	0.0044±0.0011	0.0100±0.0012	0.4425±0.1048
	CD	0.0040±0.0006	0.0231±0.0016	0.1751±0.0238
SK180	MD	0.0041±0.0010	0.0135±0.0020	0.2968±0.0477
	CD	0.0050±0.0012	0.0275±0.0033	0.1805±0.0360
S120	MD	0.0037±0.0013	0.0127±0.0051	0.3016±0.1180
	CD	0.0035±0.0014	0.0212±0.0037	0.1619±0.0446

[†]Values are presented as mean±SD.

was 1.6–2.5. Therefore, it is concluded that the Poisson's ratio estimated using the image processing method could be applied to the definition of the material property values in the FE analysis of the fiber boards.

Moreover, the values obtained by dividing the transverse strain along the MD by the transverse strain along the CD for the K180, SK180, and S120 samples, were 0.91, 1.22, and 0.95, respectively. There was a 5–22% difference between the transverse strain along the MD and that along the CD. The values obtained by dividing the longitudinal strain along the MD by the longitudinal strain along the CD for the K180, SK180, and S120 samples, were 2.31, 2.04, and 1.66, respectively. There was a difference of 66–131% between the longitudinal strain along the MD and that along the CD. Thus, it was determined that the longitudinal strain has more influence in the estimation of the Poisson's ratio than the transverse strain. This finding explains also the fact that longitudinal strain values were larger compared to the transverse strain values.

Conclusions

In this study, an algorithm was developed to measure the Poisson's ratio of a fiber board by analyzing the transverse strain in images acquired with a high-speed digital camera. The measured Poisson's ratio values ranged between 0.2968–0.4425 (MD) and 0.1619–0.1805 (CD). The study demonstrates that the estimation of the transverse property of a fiber board is possible using image processing methods, and that these methods can be used to measure the material properties that are difficult to directly measure through experiments owing to the material's rapidly changing deformations.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

References

Baum, G. A., D. C. Brennan and C. C. Habeger. 1981. Orthotropic elastic constants of paper. Tappi. 64(8):97-101.

Gonzalez, R. C., R. E. Woods and S. L. Eddins. 2004. Digital image processing using MatLab. Prentice-Hall, Inc.

Korean Standard Association. KS M ISO 187 paper, board and pulps - Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples.

Korean Standard Association. KS M ISO 534 Paper and board – Determination of thickness, density and specific volume.

Korean Standard Association. KS M ISO 1924-3 paper and board - Determination of tensile properties Part 3: Constant rate of elongation method (100mm/min).

Lee, Y. S., D. J. Kim, M. H. Choi and I. W. Kim. 1998. The impact characteristics of paper impact absorber. Journal of the Computational Structural Engineering Institute of Korea 11(3):165-172.

Lee, S. Y. 2009. Evaluation of material mechanics of corrugated board structure by finite element analysis. Univ. of Yonsei.

Mann, R. W., G. A. Baum and C. C. Habeger. 1979. Determination of all nine orthotropic elastic constants for machine-made paper. Tappi (IPC Technical paper series number 84:1-17.

Park, J. M. 2005. Finite element analysis and material mechanics of paper angle. Journal of Biosystems Engineering 30(6):347-353.

Park, J. M. 2002. Finite element analysis of a ventilating box structure. Journal of the Korean Society for Agricultural Machinery 27(6):557-564.

Park, J. M. 2003. Buckling analysis of corrugated board using finite element method. Journal of the Korean Society for Agricultural Machinery 28(2):127-136.

Schulgasser, K. 1981. On the in-plane elastic constants of paper. Fibre Science and Technology 15:257-270.

Yokoyama, T. and K. Nakai. 2007. Evaluation of in-plane orthotropic elastic constants of paper and paperboard. *SEM Annual Conference & Exposition on Experimental and Applied Mechanics-Experimental Mechanics Applied to Advanced Materials.*