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Field Application of an Ultrasonic Testing for Reconstructing CT Images of Wooden Columns*[1]

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ABSTRACT

This research examined the applicability of using an ultrasonic test to reconstruct CT images of an ancient wooden building. Most of the columns in the building are severely deteriorated due to termite attacks or the effect of weathering. Ultrasonic CT images of the columns were used to create highly accurate digital reconstructions, despite a lack of the data caused by parts of the building walls being buried. Another semi-NDE technique, a drilling test based on resistography, was applied in order to verify the ultrasonic test results. The discrepancy in detection between two methods is believed to be due to the fundamental differences between two methods. The performance of the ultrasonic test was hindered by poor surface conditions and this technique tended to over-estimate the size of cavities produced by termites or other insects. Nevertheless, the deterioration detected was in many ways congruent with the drilling test results

Keywords : ultrasonic test, computed tomography, ancient wooden building, drilling test, resistography

1. INTRODUCTION

Effective preservation and management of national property and heritage sites has become a concern in many countries, including Korea however, most of the practical decisions are based on the opinions of carpenters and not based on scientific methodology (Lee *et al.*, 2006). For the proper management of cultural properties, scientific criteria must be established based on experimental data. Cultural buildings in Korea, similar to in other Asian countries, are normally constructed of wood (Han *et al.*, 2006). Unlike rock, steel, and other construction materials, wood is a biodegradable material. Many biological factors, including fungal or insect attacks, can cause deterioration of wooden members (Kim and Lee, 2006). For scientific detection of biological deterioration and other defects in wood, the proper non-destructive evaluation (NDE) methods must be applied. In particular, major structural members such as columns, beams, and rafters should be carefully studied and analyzed in terms of the structural safety of the buildings.

Many scientists and researchers have studied

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the NDE of wood for various purposes, including the detection of internal defects. During the initial period when NDE techniques were applied, the only method of detection used were qualitative ones focused on determining the existence of defects. The wave transmission method based on Time of Flight (TOF) analysis has been widely used due to its convenience (Beall, 1999; Drai *et al.*, 2000; Kabir *et al.*, 2002). Subsequently, various improved research methods have been developed with respect to experimental procedures and methodology analysis. Currently, ultrasonic and X-ray tests are recognized more accurate for detecting internal defects, despite of the difficulty of obtaining reliable results. In particular, a Computed Tomography (CT) technique was adapted to be used with the ultrasonic test, as well as the X-ray test, for the quantitative detection of internal defects (Kim *et al.*, 2007).

In this study, an ultrasonic test was performed to enable CT image reconstruction for the quantitative detection of inner deterioration. Inner deterioration is a crucial factor in the structural safety of the building. Unlike the preexisting approaches that use indoor facilities, field applications should use simple and portable equipment (Yanagida, 2007; Tamura *et al.*, 1997). This aspect makes it more difficult to derive accurate results. Moreover, there are technical problems associated with acquiring data for members buried by the wall and/or the floor. Therefore, the main purpose of this study was to determine the feasibility of the field application of ultrasonic CT image reconstruction with considering the lack of test data.

2. MATERIALS and METHODS

2.1. Target Building

The Confucian shrine tested in this study

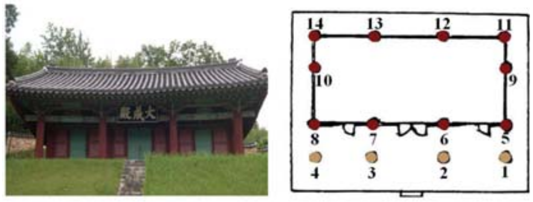

Fig. 1. Photograph and ground plan of the Confucian shrine (*Yeosan Hanggyo*).

(Fig. 1) is located in the middle-western area of South Korea (*Jeollabuk-do Iksan-si*). This building was designated a significant cultural shrine by the Cultural Heritage Administration of Korea. All of the columns, which are one of the major structural members, were tested. The species of the columns was found out to be *pinus densiflora*, and density and moisture content was not able to be investigated for avoiding destructive test.

The heights of the tested cross-sections were equally measured at 1 m above the ground. Among 14 columns, 10 columns (No. 5 to No. 14) are partially buried by the wall.

2.2. Methods

2.2.1. Measurement of the Cross-sectional Shapes

To reconstruct a reliable ultrasonic CT image based on the real shape of the wooden columns of tested height, the cross-sectional shape was measured using the 3-D Tracker (ISOTRAK II). 36 number of position data was measured based on the rectangular coordinate system and calculated mean diameter is detailed in Table 1.

2.2.2. Ultrasonic TOF Measurements and Data Assumptions

270 ultrasonic TOF data points were measured for one reconstructed ultrasonic CT image.

Table 1. Mean diameter of test columns

Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Diameter (mm)	480	400	420	460	430	510	480	360	420	490	390	400	400	420

Table 2. Acquired ultrasonic TOF data from 270 data points

		Column No.													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Incompletely determined TOF data (%)	Inaccessible path data	0	0	0	0	27	21	27	56	21	16	21	21	27	21
	Out of range data	49	75	22	87	35	66	43	3	71	71	58	41	54	15
Measured TOF data (%)		51	25	78	13	38	13	30	41	7	12	21	38	20	64

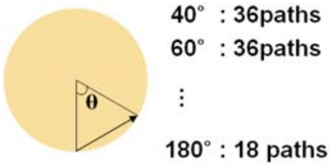

Fig. 2. Measurement of ultrasonic signals.

Ultrasonic signals were acquired from every 20 degrees from 40 to 180 degrees (Fig. 2).

Ultrasonic signals were not detected in two cases (Table 2):

1) inaccessible path data due to buried parts by walls, and

2) out of range data due to a severely damaged surface or inner parts.

These data were generated in different ways. The former (inaccessible path data) were assumed to have the average TOF value for a specific angle tested and the latter (out of range data) were assumed to be deteriorated parts and were given an infinite value.

2.2.3. Verification with the Drilling Resistance Test

A drilling resistance test was performed so as to verify the ultrasonic test results and to predict the actual internal condition of the tested columns (Fig. 3). The line distributions of the drilling resistance values and pixel values of the ultrasonic CT image were then compared. Based on eight line distributions of the drilling resistance values, an image of the specific gravity distribution was composed for effective visualization (Park *et al.*, 2006).

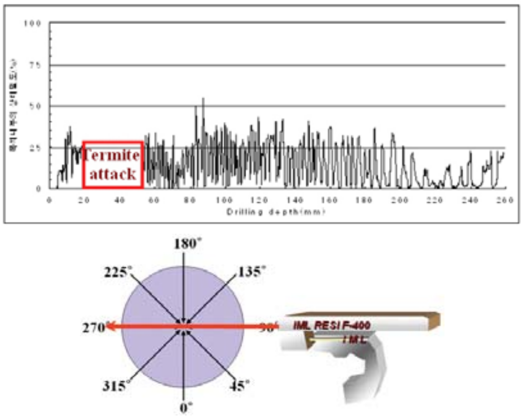

Fig. 3. Example of line distribution from the drilling resistance test.

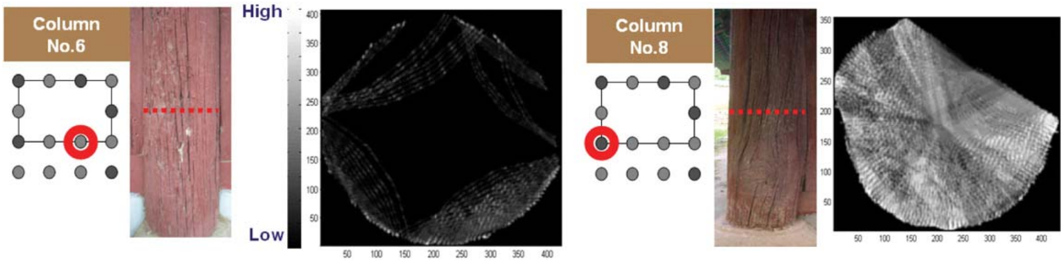

Fig. 4. Ultrasonic CT images of columns No. 6 and No. 8.

3. RESULTS and DISCUSSION

3.1. Rate of Ultrasonic TOF Acquisition for CT Reconstruction

In the case of column No. 6, the determined ultrasonic TOF data was only 13% of the total data, while the out of range data was 66% and the inaccessible path data was 21%. The out of range data of 66% was the highest value observed. This high value is thought to be caused by the surface condition and an inner empty hole due to previous rough conservation work. The reconstructed CT image reflects this (Fig. 4), only with a small area of the visible outside and a severely distorted image. From the tested angles, the number of the measured TOF data tends to decrease as the angle increases; thus, in many cases, only the outside of the member was visualized, as for column No. 6. The CT image shows very severe damage of this column however, it is not possible to confirm the real inner status.

In contrast, a relatively reliable image was reconstructed for column No. 8. In the case of this column, the inaccessible path data was 56%, which is due to the additional facility in the building. This value is the highest one observed in this study, while the out of range data was only 3%. In spite of a large portion of buried parts, which makes the acquisition of data difficult, a reliable image was reconstructed using only the measured results.

3.2. Verification of the Ultrasonic Test Results

3.2.1. Comparison with the Drilling Resistance Test

Technically, the most reliable data for evaluating the internal state of a tested column is thought to be the line distribution of the drilling resistance test, which is because the drill directly scans the density of wood. Even the annual ring due to the existence of earlywood and latewood can be identified (Fig. 5). In addition, an empty hole, where the resistance value drops to zero, was also identified. This defect was considered to be the termite attack, as termite attacks cause empty holes around the annual ring.

Based on the line distribution of the ultrasonic value, this defect was over-estimated and the pixel values did not perfectly drop to zero. Ultrasound cannot easily penetrate cavities; originally, this result was considered to be a reflection of the nature of ultrasound.

3.2.2. Effect of the Surface and Internal Deterioration

In the case of the four outer exposed columns, lack of test data enabled out of range data only for two of the cases. The rate of meas-

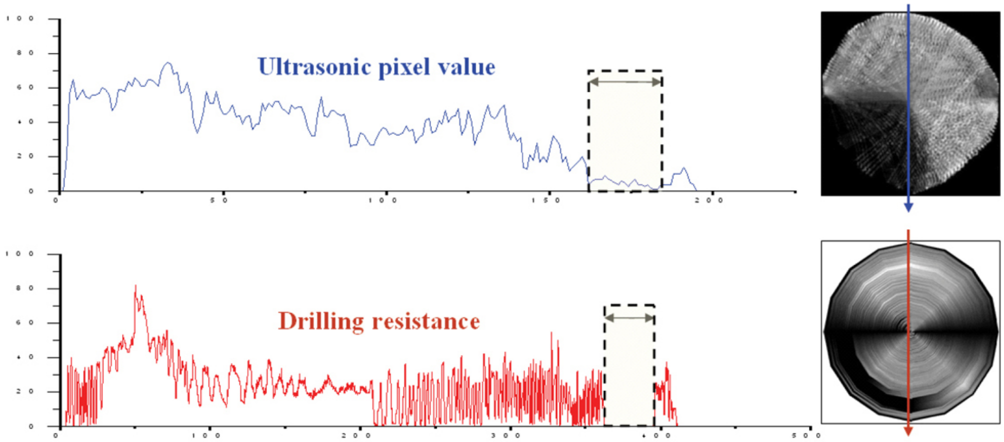

Fig. 5. Comparison of the ultrasonic and drilling resistance results (columns No. 12).

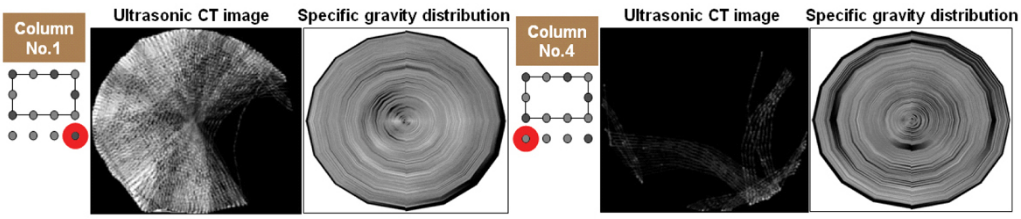

Fig. 6. Comparison of ultrasonic CT image and specific gravity distribution (Column No. 1, 4).

ured TOF data of column No. 1 was 51%, which is relatively high. The specific gravity distribution of column No. 1 (Fig. 6) derived from the drilling resistance test showed slight surface deterioration. However, this defect was over-estimated in the ultrasonic CT image, because the ultrasound is largely affected by the surface condition of the tested member. About one fourth of the area was identified as a defect.

Internal damage was well-reflected in the ultrasonic CT images, exemplified by column No. 4. A large area of deterioration around the annual ring was identified in the drilling resistance test, resulting most likely from a termite attack. The ultrasonic CT image also identified this defect, showing the column to be severely damaged.

3.3. Overview of the Condition of the Columns

Fig. 7 shows the results of the ultrasonic tests derived from the above-mentioned methodology. Severe damage including inner and surface damages of columns made it difficult to analyze the actual internal states specially for columns 2, 4, 6, 9, 10, and 11. Most of these columns were severely damaged by termite attacks and the effects of weathering.

4. CONCLUSIONS

A old wooden building was tested in order to

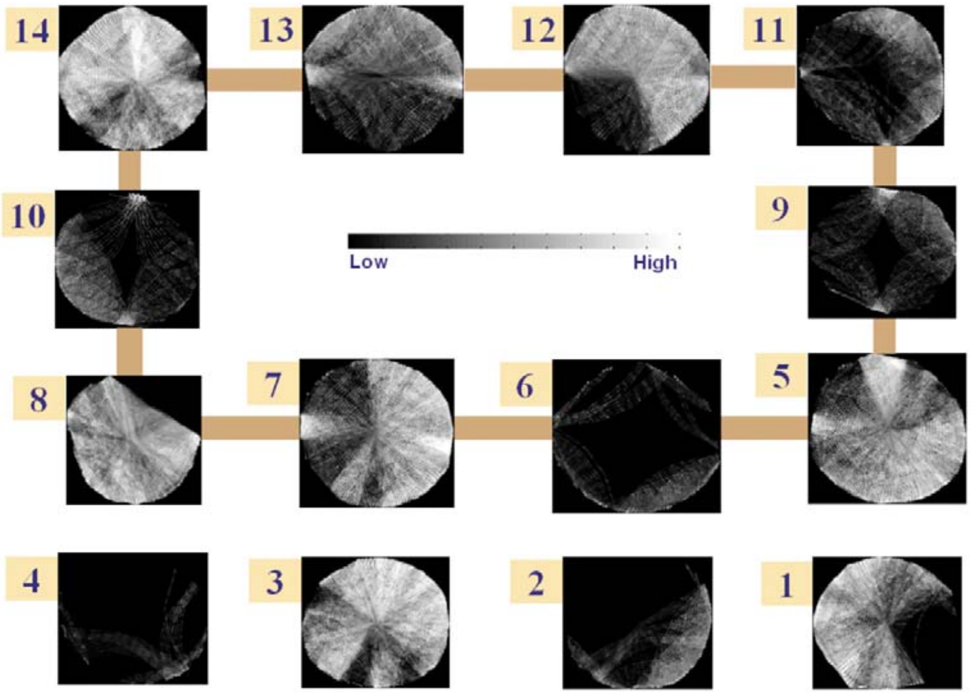

Fig. 7. Ultrasonic CT images of all columns tested in the shrine.

find out the feasibility of on-site ultrasonic test measurements for CT image reconstruction. Findings from this study can be summarized as follows

1) The data required to generate a CT reconstruction are also the most important data when determining the level of deterioration.

2) Reliable ultrasonic CT images can be reconstructed when used in conjunction with proper assumptions of incompletely determined TOF data.

3) To correctly analyze a reconstructed ultrasonic CT image, the nature of ultrasound must be carefully considered.

The tested columns of the Confucian shrine were severely damaged by termite attacks and their surface conditions were relatively poor. These aspects made it difficult to derive reliable ultrasonic CT images; nevertheless, reliable results were derived using approximately 30% of ultrasonic TOF data that was measured. Despite some over-estimation, the sections determined as deteriorated part were in agreement with the results from the drilling resistance test. Incompletely determined TOF data was considered to be the main problem for deriving reliable CT images. Even when the rate of the inaccessible path data exceeded 50% (Column No. 8), a reliable image could be reconstructed using only the measured TOF data.

ACKNOWLEDGMENT

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