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Determination of Ratio of Wood Deterioration Using NDT Technique*[1]

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ABSTRACT

In ancient wooden structures, the mechanical properties of the structural members have been reduced by time-dependent degradations such as fatigue or creep. Also, the external and internal deterioration was caused by environmental condition, fungi, bacteria, or insect, and then reduced the quality of structural members. However, the previous methods for evaluating the deterioration have been mainly depended on the visual inspection. In this study, therefore, ultrasonic stress wave test, accelerometer stress wave test were used to evaluate the deterioration of structural wood members in ancient wooden structures. Based on the results, the quantitative criteria of stress wave transmitted velocity were proposed to evaluate the deterioration of structural member. The proposed criteria were related to the degree of deterioration. In accelerometer stress wave, the criteria of deterioration of wave reciprocal velocity was below 1800 μs/m at incipient deterioration (below 12% ratio of deterioration), between 1800 and 2200 μs/m at moderate deterioration (12~17%) and above 2200 μs/m at severe deterioration (above 17%). The ultrasonic stress wave, the criteria of deterioration were 800 and 950 μs/m at below 8% and above 15% of the degree of deterioration respectively.

Keywords : deterioration, ultrasonic stress wave test, accelerometer stress wave test, criteria of deterioration, ratio of deterioration

1. INTRODUCTION

Lee *et al.*(2002) asserted that sound wood had a strong cell wall structure, but physical and chemical variations were occurred by the invasion of deterioration organisms within the individual cells. The mechanical properties of wood have been reduced by fatigue, creep for time-dependant, change of moisture contents, insect, weathering, and so on. The structural members of ancient wooden structures have exposed to the conditions as above. It makes it possible to reduce mechanical properties of structural wood members. It might lead to the collapse of the structures. Zabel & Morrell (1992) insisted that reliable decay detection is a

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Table 1. Description of the specimens

	Post			Beam		
Rectangular cross section	Width	Depth	Length	Width	Depth	Length
	15~16	15~16	190~236	8.5~14	13~22	143~264
Circular cross section	Diameter		Length	Diameter		Length
	18~26		147~306	17.5~21		152~160

*Unit : cm

major challenge, and it is especially important to detect decay before serious damage occurs. However, the previous methods were not sufficient to evaluate the deterioration for repairing and replacing the structural members because these methods could not exactly take out the deteriorated degree or location of wood. Especially, the deterioration by termite can't be detected with these methods. Consequently, the location and degree of deterioration should be evaluated exactly for effective conservation and maintenance of ancient wooden structures.

By definition, nondestructive testing (NDT) is the science of identifying physical and mechanical properties of a piece of material without altering its end-use capabilities. The requirement of NDT is expanding because an increasing amount of resources has been devoted to repair and rehabilitation of existing structures rather than to new construction. As more resources are devoted to repair, an increasing emphasis must be placed on the in-place assessment of structures. This, in turn, requires accurate, cost-effective NDT techniques.

In this study, the structural members were evaluated by the scientific NDT method for assessment of internal state. That is, the deteriorations of the structural member were evaluated by two types of stress wave timer (accelerometer stress wave test, ultrasonic stress wave test) based on NDT and drilling resistance tester was used to aid results of the NDT. Based on the result of this study, the criteria of deterioration for the stress wave according to the degree of deterioration were proposed. It was not voluntary, subjective criteria but objective, scientific criteria for degree of deterioration used by the NDT. It helps to us for conservation of disappearing ancient wooden structures.

2. MATERIAL and METHODS

A total of 27 specimens were used in the study and were mainly post and beam which had various diameters and lengths. Also, the specimens had both rectangular and circular cross section(Table 1). The specimens, which were replaced with new members, have been obtained from ancient wooden structures because they were suspected of deterioration.

All specimens were Korean Pine (*Pinus densiflora*). Specific gravity, which was measured following ASTM D 2395 Method A (Volume by measurement), was 0.41 ~ 0.52. The moisture content was 13.04 ~ 14.07(%) and followed ASTM D 4442-92 Method A (Oven-Drying (primary)). All specimens for the specific gravity and the moisture content were obtained from each cross-section after NDT.

2.1. Nondestructive Testing

Before NDT, a visual inspection was carried out and the specimens were classified to progressive deterioration and sound for surface. And then, the NDT was performed. In this study, deterioration of specimens was evaluated by the accelerometer, ultrasonic stress wave tester of devices for NDT. And then drilling resistance tester was used to aid the NDT.

Accelerometer stress wave timer (Metriguard 239-A) have range of time to 0~9,999 (μs) and resolution of ± 1 (μs). Ultrasonic stress wave timer (PUNDIT-PLUS) was consisted of two 54 kHz transducers coupled to an ultrasonic transmitter and receiving unit which have a diameter of 50 mm and have the resolution of ± 0.1 (μs). transit times are used to be a qualitative evaluation for inner deterioration of wood. The stress wave transmitted time increase along the increment of transmitted length and have a deep correlation to density of material.

In general, the transit time increases along the decrease of density caused by a progressive deterioration.

Drilling resistance test is a quasi-nondestructive test which has been used to detect decay in trees and timber. It is classified as quasi-nondestructive because a small diameter (3 mm) hole remains in the specimen after testing. Dirk & Peter(1994) showed that this hole is small enough to have only negligible structural effects on the remaining cross section, and may be sealed to prevent an access for agents of decay. Drilling resistance tester (IML-RESI F-400) operates under the premise that resistance to penetration is correlated with material density.

Drill resistance is determined as measuring the power required to penetrate through the material. Frank(1994) showed that plotting drill resistance versus drill tip depth results in a drill resistance profile which can be used to evaluate the internal condition of a tree or timber member and identify locations of various stages of decay.

Each member was marked at 50 mm intervals along the length as shown in Fig. 1. Accelerometer stress wave test was carried out in six directions at each marked position, approximately 30 degrees apart. And then, ultrasonic

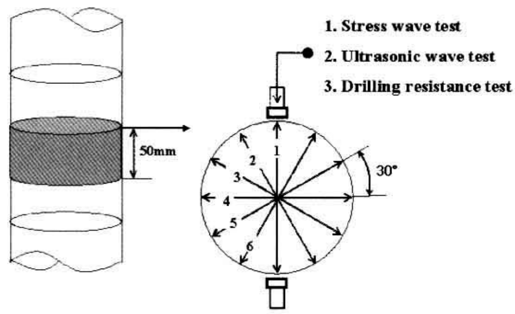

Fig. 1. Measured points for the nondestructive testing in the specimens.

stress wave test and drilling resistance test were performed by a sequence at the same position where accelerometer stress wave test was carried out. Drilling resistance test was used to assist the NDT in this study and to calculate ratio of deterioration by Resistograph which was profiled by drilling resistance test. That is, criteria of deterioration of stress wave were based on the relation between stress wave transmitted time and ratio of deterioration at the same position.

After NDT and drilling resistance test, each member was cut at the position where the NDT was carried out. And then, the boundary of deteriorated part was marked.

2.2. Ratio of Deterioration

The Resistograph produces two forms of profile. One is a simple trace on a special waxed paper strip which slides in along the top of the instrument. The other can be stored in an onboard computer, and then downloaded to a desktop system for review, analysis, and printing as shown in Fig. 2.

The horizontal axis of Fig. 2 indicates the length passed through the specimen, and the drill moves from right to left. The vertical axis has no unit, but indicates relative density. For example, a high point indicates relatively higher

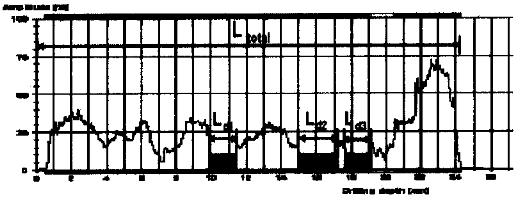

Fig. 2. Resistograph for detecting the extent of deterioration.

density of wood than a lower point. The length of deterioration could be investigated by the change of amplitude in Resistograph and was used to calculate the ratio of deterioration (%).

$$R_d = \frac{\sum_{i=1}^{n} L_{d(i)}}{L_{total}} \times 100(\%) \tag{1}$$

where,

R_d : ratio of deterioration (%)
L_d : length of deteriorated parts (m)
L_{total} : total path length (m)
i : 1, 2, 3, ...

In this study, the ratio of deterioration was related to the stress wave transmitted time. After analysis of the relation between the ratio of deterioration and the stress wave transit time, the criteria of deterioration were proposed according to the degree of deterioration.

3. RESULTS and DISCUSSION

3.1. Comparison Between Accelerometer and Ultrasonic Stress

Stress wave propagation in wood is a dynamic process which is related to the physical and mechanical properties of wood. Several different types of wave can propagate in wood structures, such as longitudinal wave, shear wave, and surface(or Rayleigh) wave. Longitudinal wave among these waves travels to wood at the fastest velocity and are commonly used to evaluate wood properties.

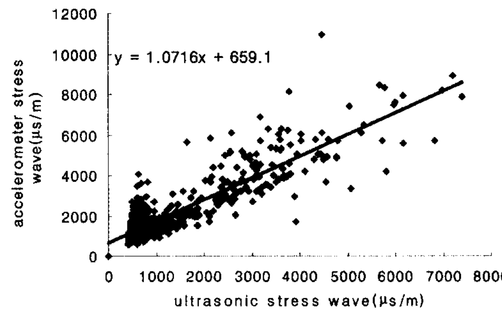

Fig. 3. Relationship between the accelerometer and the ultrasonic stress wave reciprocal velocity.

Robert *et al.*(1998) showed that the behavior of wave in sound wood differs from that in decay wood. Particularly, a stress wave will attenuate more rapidly in decayed wood than in sound wood. Therefore, if the reciprocal velocity would higher than others, it means that there was a possible deterioration in estimated parts.

In Fig. 3, it showed the relationship between the accelerometer stress wave reciprocal velocity and the ultrasonic stress wave reciprocal velocity. Ross(1999) insisted that speed-of-sound transmission is a frequently used parameter that correlates well with various wood properties. The values in Fig. 3 were measured at the same position of specimen.

However, the more a stress wave reciprocal velocity was high, the more a dispersion of data was large. It means that the result of between the two test devices was different in spite of measuring the transmit time at the same position. It was followed reasons that a generated wave from the PUNDIT-PLUS was easy to diffuse and attenuate while passed through the wood and then, the received transducer was not received the signal since a low sound pressure of it. Also, surface of a post was sound when a visual inspection was performed before the NDT but experimental errors could be occurred to the interface between the post and the

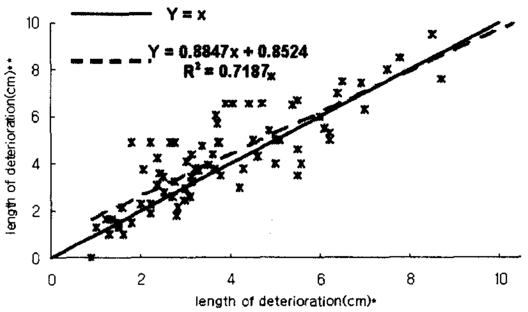

Fig. 4. The comparison between the Resistograph and visual inspection for extent of deterioration.

transducers because the surface of a post might not flat cause by drying checks.

A stress wave reciprocal velocity was high, it was indicated that deteriorations could be possible to exist in wood. In this case, the transmission of wave was affected by deterioration. That is, if the deterioration would exist, a generated wave could not be transmitted directly at the deteriorated part but be transmitted reflectively or diffractively.

A main difference of between Pundit-plus and Metriguard 239A was the principle upon which a wave was generated. In the Metriguard 239A, it could use the wave which was generated by impact of hammer on a specimen but Pundit-plus could use a piezoelectric transducer to generate the wave. A transit time could be measured by Metriguard 239A at the part which could not be measured by ultrasonic stress wave because the vibration caused by impact of hammer might be affected to the received transducer.

3.2. Analysis of Resistograph Pattern

Deterioration marks the change of wood density at the beginning. Once decay became well advanced, the wood structure was broken down and wood density decreased drastically. The change from sound to incipient deterioration and from incipient to advanced deterioration could be detected by the drilling resistance tests, although the extent also depends upon the species and growth patterns of the individual specimen.

Resistograph showed the internal state of wood and could reveal several defects as crack, knot, hole, insect, and fungi. By plotting out the depths of sound and deterioration area in the specimens, it made it possible to map an approximate extent of deterioration. The ratio of deterioration was based on the analysis of Resistograph and could be a foundation to propose criteria of deterioration. Therefore, accurate analysis of Resistograph was very important in this study.

It could be understood the properties of density profile on Resistograph through the comparison between real cross-section and pattern of Resistograph. Based on these results, the length of deterioration was measured in real cross-section and then it was compared with the calculated length of deterioration used by drilling resistance test.

Also, it made it possible that the error, which as ratio between a real length of deterioration and length of deterioration calculated by the Resistograph, was about 1.14.

$$Error = \frac{Visual\ inspection}{Resistograph} = 1.14 \qquad (2)$$

This indicated that the real length of deterioration was much closed to the result of drilling resistance test. However, it was not equal because of following reason.

First of all, the penetration of drill needle couldn't pass straight. As drilling resistance tester contacted to the evaluated specimens, the penetration of drill needle might be curved by various properties for the internal wood.

3.3. Proposition of the Criteria of Deterioration

The experimental results of accelerometer and

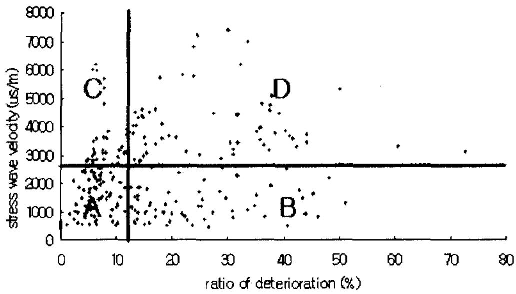

Fig. 5. The analytical method for determining the criteria of deterioration.

ultrasonic stress wave were not quantitative but qualitative evaluation. So, the criteria of deterioration of accelerometer and ultrasonic stress wave reciprocal velocity had to be determined for quantitative analysis according to the degree of deterioration because they were needed to evaluate the internal deterioration in wood.

The internal defects of structural members were investigated and the ratio of deterioration was calculated to propose the criteria of deterioration. In order to find out the adequate criteria of deterioration, the horizontal line (β) which indicated the stress wave reciprocal velocity was moved to upward simultaneously from origin in a vertical axis when the vertical line (α) which meant the ratio of deterioration was moved horizontally with 1 percent interval.

$$S=\left[\frac{A_N}{(A+B)_N}+\frac{D_N}{(C+D)_N}\right]\times 100/2(\%) \quad (3)$$

where,

N : Number of data in each range

A, B, C, D : Separated area by the intersection between stress wave reciprocal velocity and ratio of deterioration

The stress wave reciprocal velocity increased as the ratio of deterioration was improved. When the percent in the area of A and D was maximum values, the lines(α,β) were determined.

The S_{max} which was calculated by the formula (3) was presented to determine the criteria of deterioration according to the degree of deterioration (Table 2).

When S was maximal value till less than 8%, the ultrasonic stress wave reciprocal velocity was 800(μs/m) and the value of S was maximum as it was 950(μs/m) from 9 to 15 percent. Therefore, the criteria of deterioration for the stress wave reciprocal velocity could be determined to quantitative evaluation of the deterioration and the accelerometer stress wave reciprocal velocity was analyzed as the same method. And then, the deterioration was divided into 3 grades according to the ratio of deterioration. The criteria of deterioration and the classified degree of deterioration were following (table 3).

In the case of accelerometer stress wave, wave reciprocal velocity was below 1800 (μs/m) until the ratio of deterioration of 12% and was 1800～2200 (μs/m) as ratio of deterioration increases from 12% to 17%. When accelerometer stress wave reciprocal velocity was above 2200 (μs/m), ratio of deterioration was increased above 17%. Consequently, we might decide the incipient stage (grade Ⅰ) of deterioration at the below 1800 (μs/m), the moderate stage (grade Ⅱ) at the between 1800 and 2200 (μs/m) and the severe stage (grade Ⅲ) at the above 2200 us/m.

In the case of ultrasonic stress wave, similarly, the ultrasonic stress wave reciprocal velocity was below 800 (μs/m) until the ratio of deterioration of 8% and was 800～950 (μs/m) when ratio of deterioration increases from 8% to 15% respectively. As ultrasonic stress wave reciprocal velocity was above 950 (μs/m), ratio of deterioration increases at above 15%.

CONCLUSIONS

Based on the results of this study, we concluded the following and propose the criteria of deterioration of stress wave reciprocal velocity

Table 2. The S_{max}[1] under the criteria of deterioration according to the degree of deterioration

	Ultrasonic stress wave reciprocal velocity (μs/m)							Accelerometer stress wave reciprocal velocity (μs/m)				
RD[2]	~800	~900	~950	~1000	~1050	~1100	RD	~1800	~1900	~2000	~2100	~2200
(%)	S_{max}						(%)	S_{max}				
1	91.20	90.94	90.46	89.64	89.04	88.14	1	80.18	79.86	79.37	78.19	77.98
2	91.13	90.86	90.64	89.81	89.20	88.30	2	80.07	79.74	79.51	78.32	78.10
3	91.20	90.89	90.65	90.05	89.68	88.75	3	80.47	80.37	80.36	79.13	78.88
4	91.24	90.92	90.66	90.04	89.66	88.72	4	80.68	80.56	80.53	79.55	79.29
5	90.67	90.24	90.20	89.77	89.33	88.31	5	80.34	80.15	80.03	78.93	78.61
6	89.23	88.66	88.84	88.29	87.75	86.92	6	79.40	79.38	79.09	78.70	78.28
7	88.51	88.06	88.17	87.44	86.77	85.82	7	78.47	78.30	78.14	77.59	77.37
8	87.41	86.83	86.88	86.02	85.25	84.20	8	76.86	76.58	76.28	75.59	75.28
9	86.68	86.37	86.84	85.43	84.59	83.47	9	75.97	75.62	75.58	74.80	74.81
10	85.78	86.03	86.55	85.05	84.14	83.35	10	76.21	76.16	76.03	75.53	75.50
11	86.39	86.37	86.83	85.14	84.13	83.26	11	76.65	76.53	76.32	75.73	76.07
12	85.36	85.81	86.69	84.45	83.80	82.88	12	76.17	75.99	75.71	75.05	75.37
13	84.74	84.92	85.58	83.35	82.62	81.62	13	76.08	76.27	75.87	75.55	75.83
14	84.73	85.00	85.87	83.60	82.71	82.07	14	77.35	77.94	77.83	77.36	77.58
15	84.14	84.66	85.51	82.51	81.15	80.80	15	76.37	76.90	76.66	76.07	76.24
16	80.89	83.43	83.01	83.10	84.58	84.13	16	77.20	77.69	77.90	77.17	77.30
17	80.83	83.75	83.25	83.08	84.05	83.06	17	76.90	77.35	77.49	76.67	79.21
18	80.72	83.25	82.69	82.72	83.66	84.67	18	76.13	77.19	77.27	76.36	78.99
19	80.42	82.58	81.95	82.25	83.14	84.14	19	76.91	77.96	77.95	76.91	79.66
20	80.81	83.26	82.55	83.15	83.99	84.99	20	76.79	77.84	78.47	77.32	80.17
							21	76.37	77.42	78.03	76.82	79.72
							22	76.46	77.50	78.08	76.78	79.77
							23	76.33	77.37	77.90	76.47	79.58
							24	76.44	77.48	77.97	76.43	79.65
							25	76.32	77.36	77.79	76.08	80.36

*1 : Ratio of the data count of A and B in total data count, 2:Ratio of Deterioration

which were based on the ratio of deterioration with evaluating for deteriorated members of ancient wooden structure by NDT.

1) The internal state of structural members was evaluated by NDT and the ratio of deterioration could be calculated used by the analysis of Resistograph which was profiled by drilling resistance test. Also, the location and area of internal deterioration were detected by drilling resistance test but it was qualitative analysis.

2) Based on the ratio of deterioration, the criteria of deterioration could be proposed to determine the deterioration according to the

Table 3. Criteria of deterioration using the accelerometer and ultrasonic stress wave reciprocal velocity according to the degree of deterioration

Nondestructive Test	Grade of criteria of deterioration		
	I	II	III
Accelerometer stress wave reciprocal velocity(μs/m)	<1800	1800~2200	>2200
Ratio of deterioration(%)	~12%	12~17%	17%~
Ultrasonic stress wave reciprocal velocity(μs/m)	<800	800~950	>950
Ratio of deterioration(%)	~8%	8~15%	15%~

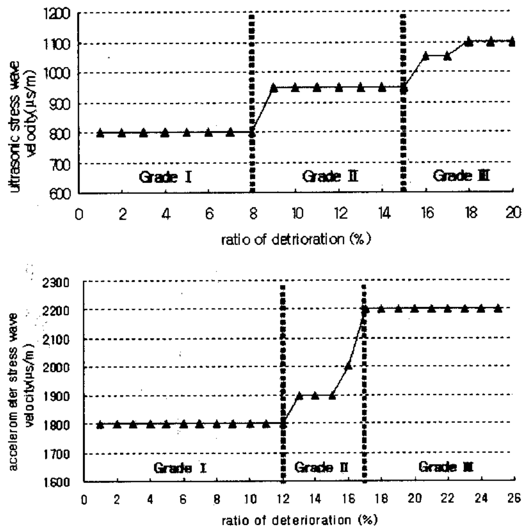

Fig. 6. Determination of the criteria of deterioration.

degree of deterioration by accelerometer and ultrasonic stress wave reciprocal velocity.

3) In accelerometer stress wave, the criteria of deterioration of wave reciprocal velocity was the below 1800 μs/m at the incipient deterioration (below 12%), between 1800 and 2200 μs/m at the moderate deterioration (12 ~ 17%) and the above 2200 μs/m at the severe deterioration (above 17%).

4) In ultrasonic stress wave, the criteria of deterioration of wave reciprocal velocity is the below 800 μs/m at the incipient deterioration (below 8%), between 800 and 950 μs/m at the moderate deterioration (8 ~ 15%) and the above 950 μs/m at the severe (above 15%).

FUTURE WORKS

The results of this study could show the relationship between the ratio of deterioration and the wave reciprocal velocity and then, the deterioration for inside parts of wood was evaluated by the stress wave reciprocal velocity. However, the research on the correlation of NDT and deterioration is still a large field with many open questions. In the future, we will study to reveal a relationship between compressive strength of structural members and wave reciprocal velocity using the criteria of deterioration which were proposed in the study. And then we will be able to predict a residual strength of structural members using the NDT. If it should be produced, the evaluation for safety of ancient wooden structure may be possible.

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REFERENCES

1. Helms, D. and P. Niemz. 1994. New applications of drill resistance method for quality evaluation

of wood and wood products. Ninth International Symposium on Nondestructive Testing of Wood.
2. Rinn, F. 1994. Catalog of relative density profiles of trees, poles, and timber derived from Resistograph micro-drillings. Ninth International Symposium on Nondestructive Testing of Wood.
3. Lee, J. J., G. C. Kim, and M. S. Bae. 2002. Nondestructive assessment of deterioration for structural members in ancient buildings. The proceeding of 7 th World Conference on Timber Engineering. vol (1).
4. Lee, J. J. and J. K. Oh. 1999. Stress wave technique for detecting decay of structural members in ancient structures. Journal of the Korean wood sci. and tech. Mokchae Konghak. Vol (27) : No. 4 pp 43~50.
5. Emerson, N. R., D. G. Pollock, J. A. Kainz, K. J. Fridley, D. L. Mclean, and R. J. Ross. 1998. Nondestructive evaluation techniques for timber bridges. 5th World conference of timber engineering, Pro. vol (1).
6. Ross, R. J. 1999. Using sound to evaluate standing timber. International Forestry Review 1(1).
7. Zabel R. A. and J. J. Morrell. 1992. Wood microbiology : decay and prevention. Academic Press, Inc., USA.