목재공학 27(4) : 43~50
Mokchae Konghak 27(4) : 43~50, 1999

Stress Wave Technique for Detecting Decay of Structural Members in Ancient Structures[*1]

Jun-Jae Lee[*2] and Jung-Kwon Oh[*2]

ABSTRACT

The safety-evaluation of ancient wood structures has been executed with only visual inspection. The application of NDE(nondestructive evaluation) is required because the visual inspection has many restrictions. Among many NDE techniques, the stress wave technique was used in this research.

This study focused on evaluating the extent of decay in members of ancient structures, using stress wave nondestructive technique. For application of stress wave technique to ancient structures, the threshold time which divides members into categories according to degree of decay should be determined in advance.

Stress wave timer (Metriguard Model 239A) was used in this study, specimens used in this research were the members obtained from six ancient structures. All specimens were identified as Hard Pine(*Pinus densiflora* S. et Z. or *Pinus thunbergii* P.) by microscope. Each member was tested with stress wave passing radially through the pith. In this study, the stress wave time of 12μs/cm could distinguish between sound and decayed specimens with accuracy of 77.5 percent. Also, decayed specimens could be separated into moderate and severe categories by stress wave time of 20μs/cm. Among the three decay location groups (exterior, mixed, interior), the exterior group could be classified into sound, moderate and severe decay with the greatest accuracy. Stress wave transit time was not sensitive to small decay pockets located in interior of the member.

Key words: stress wave, decay, NDT, NDE, ancient structure, safety-evaluation, nondestructive.

INTRODUCTION

Generally, wood structures are subject to degradation of their structural integrity due to biological attack such as fungi, bacteria, insect and so on. Periodic inspection of wood structures is necessary to insure continued performance. Most of ancient Korean structures were built hundreds of years ago and are national historic treasures. All members in these ancient structures have to be used as long as possible and the structure must be kept safe. If

---

[*1] Received on December. 1. 1998
The authors wish to acknowledge the financial support of the Korea Research Foundation made in the program year of 1997

[*2] College of Agriculture and Life Sciences. Seoul National University. Suwon 441-744. Korea

properly maintained and monitored, these structures will last a long time.

The present safety-evaluation of ancient structures mostly depends on visual inspection. However, because visual inspection can inspect only the surface, it has many limitations. When visual inspection is used, it can overestimate the performance of the member because it cannot inspect inner portions of the member. The members would be overloaded and in bad cases the structure could collapse. In other cases, the members with sufficient structural capacity are replaced, because decay is observed on the surface.

In general, the members used in ancient structures have large cross sections. These large cross sections may make it easy to remove the member with sufficient performance. The decayed members with sufficient performance have to be used continuously after treatment. However, in practice, these members with sufficient performance are frequently replaced under maintenance.

Furthermore, once ancient structures are repaired, many parts of the original architectural styles are transformed. In order to preserve our ancestors' architectural styles without transformation, repairing has to be minimized, and only unsafe structures have to be repaired. In order to reduce replacements and improve the safety of the structures, the performances of members have to be evaluated exactly without disassembly. Therefore, it is necessary to apply nondestructive evaluation (NDE) to ancient structures.

The fundamental hypothesis for NDE of wood materials was initiated by Jayne (1957). The fundamental hypothesis have been verified on various species of wood degraded by fungi, bacteria and so on, using various techniques. Wang *et al.*(1980) found that wood decay significantly affected the frequency of oscillation of small, eastern pine, sapwood, cantilever bending specimens. Pellerin *et al.*(1985) showed that stress wave speed could be successfully used to monitor the degradation of small clear-wood specimens exposed to brown-rot fungi. And Armstrong *et al.*(1991) effectively detected skips in the gluelines of edge-glued red oak panels using stress wave measurement. Volny (1991) applied stress wave technique to two timber bridges. He detected decay in members of two timber bridges and mapped out the location and the extent of rot, using stress wave passing through members in a transverse direction. Ross *et al.*(1994) successfully divided bacterially infected white oak and red oak board into normal, mixed and severe categories using stress wave measurement. Fuller *et al.*(1995) successfully evaluated honeycomb and surface checks in red oak lumber. Schad *et al.*(1996) detected internal defects in logs, using three NDT techniques ; sound wave, computed tomography (CT) and impulse radar. He reported that these three techniques were able to detect large voids, knots and areas of degradation and CT resulted in the highest resolution for voids, knots, and high moisture content areas, but at a very high price. Jang(1998) applied ultrasonic nondestructive evaluation to finger-jointed lumber and observed the effect of transducer position. He reported that the velocity of ultrasonics propagation decreased as finger slope increased.

Many studies about nondestructive evaluation of wood have been carried out, but NDT has never been applied to ancient Korean structures for safety-evaluation in Korea.

Stress wave technology is one of the nondestructive testing(NDT) techniques proven to be a successful method of inspecting wood structures (Ross and Pellerin, 1991). If decay is present in the member being tested, the attenuation and propagation time passing through the member is increased.

This study focused on evaluating the extent of decay in members of ancient structures using stress wave technology. For application of stress wave technique to ancient structures, the threshold times, which divide members into categories according to degree of decay, have to be determined in advance.

Accordingly, the purpose of the study described in this paper was to determine the threshold times which can be applied to the wood member of ancient structures.

MATERIALS AND METHODS

Materials

Thirty-one members were obtained from six ancient structures, which had been removed because decay had been observed. The members varied in length (90cm~285cm) and diameter (10cm~21.5cm).

Small pieces(1cm×1cm) were obtained from each member and were observed by microscope to identify the species. Other small pieces were obtained from each member for the measurement of specific gravity and moisture content. Specific gravity and moisture content were measured following ASTM D 2395 Method A (Volume by measurement) and ASTM D 4442-92 Method A (Oven-Drying (primary) respectively.

Methods

Stress wave test

The first test was stress wave test(Fig. 1). The velocity longitudinal to the grain is higher than that transverse to the grain, but can be misleading because parallel paths for the stress wave around unsound areas are provided. For this reason, transverse stress wave velocity is more useful to detect defects.

The members were supported off the ground by two sawhorses. A stress wave was induced in the members by impact and sent through the wood from the start accelerometer to the stop accelerometer. The accelerometers were connected to a Metriguard Stress Wave Timer (Model 239A). The timer displayed the travel time of the stress wave between accelerometers. The start and stop locations were marked to measure the distance between accelerometers. The impact hammer was then moved 15cm and stress wave transit time was measured again; this process was repeated to the end of the member. A member-length set of times was taken in three locations on each member, approximately 120 degrees apart (Fig. 1).

Care was taken to locate the accelerometers away from obvious defects such as cracks and knots. In order to reduce misreading and harm of members by hammer striking during the test, the stop accelerometer was located on the side with exterior decay, not the hammer.

Seven stress wave transit times were obtained in each location. Maximum and minimum values were removed and the rest were averaged.

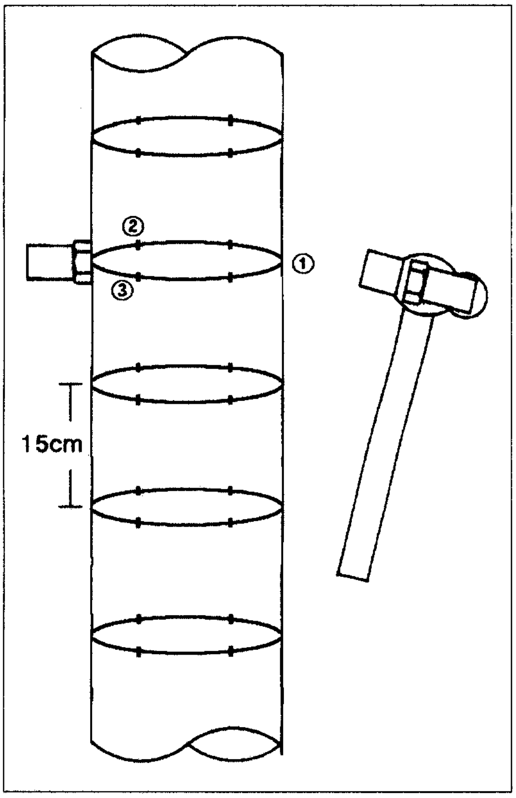

Fig. 1. Stress wave test for structural round timber

Cross section observation

The members were sawn every 15cm to coincide with the locations of the stress wave test and then, the member cross sections were observed and the boundary of the decayed part was marked. The influences of other defects such as knot, crack etc. were avoided by discarding the specimens with these defects on the cross section. The total length of the wave path and the length of the decayed part were measured as shown in Fig. 2 and the degree of decay was calculated as follows :

$$R_d = \frac{\Sigma L_{d(i)}}{L_{tot}} \qquad [1]$$

where,

R_d : Degree of decay
L_d : Length of decayed part (cm)
L_{tot} : Path length (cm)
i : 1, 2, 3, ······

The area of undecayed part and cross section area were also measured using the mesh as shown as Fig. 3. The soundness ratios were calculated by dividing the area of undecayed part by the cross section area.(Eq. 2)

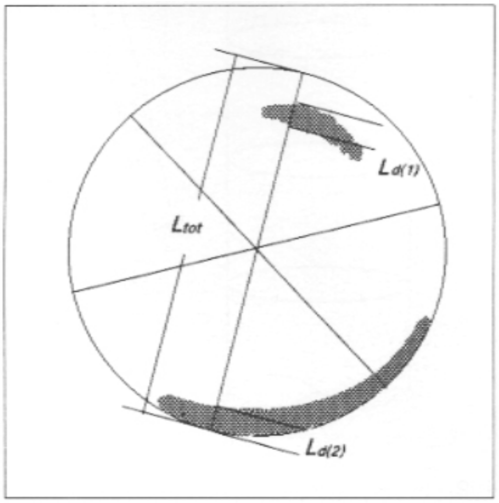

Fig. 2. Measuring method for degree of decay.

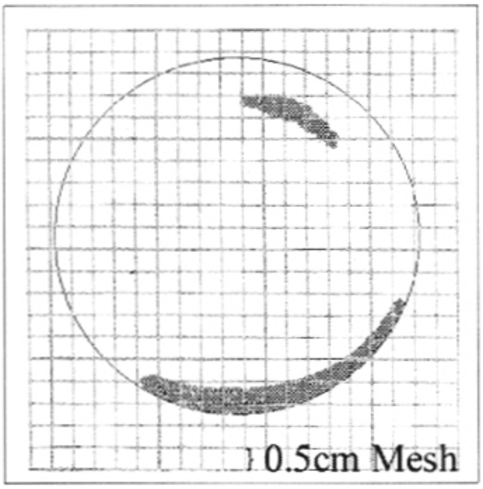

Fig. 3. Mesh for the measurement of soundness ratio.

$$R_{sound} = \frac{A_{ud}}{A_{tot}} \qquad [2]$$

where,

R_{sound} : Soundness ratio
A_{ud} : Undecayed area(cm^2)
A_{tot} : Cross section area(cm^2)

Compression Test

A compression test was carried out following ASTM Standard D 198 (Standard Methods of Static Tests of Lumber in Structural Sizes, Compression parallel to grain (short column, no lateral support, l/r<17)). The strength ratios were calculated by dividing each compression strength, involving decayed specimens, by the average of compression strength of sound specimens(Eq. 3).

$$R_s = \frac{\sigma}{\sigma_{sound}} \qquad [3]$$

where,

σ_{sound} : Average of compression strength of sound specimens
σ : Compression strength
R_s : Strength ratio

RESULTS AND DISCUSSION

Identification of Species

Small pieces were obtained from each member and were observed by microscope to identify the species. The anatomic properties of Hard Pine(*Pinus densiflora* S. et Z. or *Pinus thunbergii* P.) were found in all specimens, such as resin canal, window-like pitting and dentate thickening.

Moisture Content and Specific Gravity

Other small pieces were obtained from each member for the measurement of specific gravity and moisture content. The range of specific gravity was measured from 0.35 to 0.56 and moisture content, 13~55%.

The specimens varied in moisture content and specific gravity. It was known that these two properties affect the stress wave transit time. However, in this study, the variances of these properties did not affect threshold time significantly compared with variances due to unsound conditions of the timber. Volny(1991) also reported that these properties are minor factors compared with variances due to unsound conditions of the timber. It seems that these properties can be considered as minor factors in the test for determination of threshold time to classify the members according to degree of decay. Therefore, the variances of moisture content and specific gravity was not considered in this study.

Determination of Threshold time

In this study, the degree of decay was calculated by dividing the length of decayed part by the length of stress wave path(Fig. 2) and it was determined by visual observation of cross section. It was necessary to verify the accuracy of the degree of decay evaluated by this method. Therefore, the compression test was also carried out and compression strength was measured. However, compression strength has to be compared with the area of undecayed part. Therefore the area of undecayed part per unit area, soundness ratio, was evaluated and it was estimated by visual observation of cross section. Fig. 4 indicates a significant relationship between soundness ratio and strength ratio. From this significant relationship, it was concluded that visual observation of cross section is reasonable in estimating the degree of decay.

Sound and Decayed Specimen

Stress wave transit time (or velocity) appeared to distinguish between sound and decayed specimens. Decay was indicated by longer transit times (lower velocity). Fig. 5 shows the

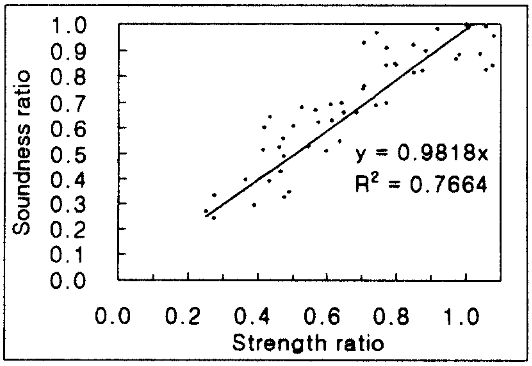

Fig. 4. The relationship between strength ratio and soundness ratio.

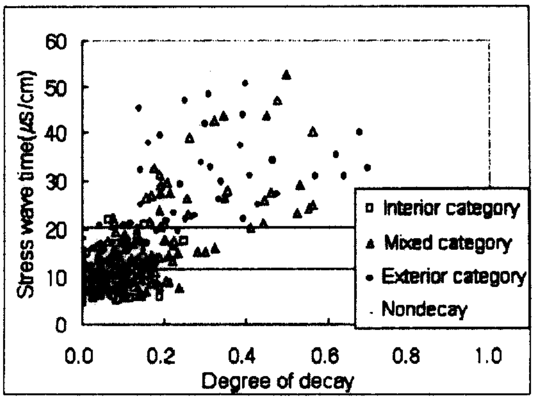

Fig. 5. The relationship between degree of decay and stress wave time.

Table 1. Accuracy of stress wave measurements for identifying sound and decayed members

Threshold Time (μs/cm)	Sound & Decay		<Threshold Time		>Threshold Time	
	Total	Correctly Identified	Total	Sound Specimen	Total	Decayed Specimen
11	748	555 (74.2%)	440	353(80.2%)	308	202(65.6%)
12	748	580 (77.5%)	501	389(77.6%)	247	191(77.3%)
13	748	573 (76.6%)	544	410(75.4%)	204	163(79.9%)

Table 2. Accuracy of stress wave measurements for identifying moderately and severely decayed members

Threshold time (μs/cm)	Moderate & Severe		<Threshold time		>Threshold time	
	Total	Correctly Identified	Total	Moderate	Total	Severe
19	247	209 (84.6%)	157	143 (91.1%)	90	66 (73.3%)
20	247	211 (85.4%)	162	147 (90.7%)	85	64 (75.3%)
21	247	208 (84.2%)	168	148 (88.1%)	79	60 (75.9%)

relationship between stress wave time and degree of decay. Stress wave measurements could distinguish between sound and decayed specimens with reasonable accuracy. Table 1 shows the accuracy of distinction between sound and decayed specimens. In order to find out adequate threshold time, stress wave times were tried at an interval of 1μs/cm. The accuracy of 12μs/cm and adjacent stress wave times of 11 and 13μs/cm was shown in Table 1. The stress wave time of 12μs/cm distinguished between sound and decayed specimens with the greatest accuracy of 77.5%. From this result, it was concluded that the stress wave time per unit length of 12μs/cm is appropriate to threshold time to distinguish between sound and decayed specimens

Moderately and Severely Decayed Specimen

Although the members have decay, some members of them may have sufficient performance. Therefore, decayed members need to be evaluated again and sub-divided into several category according to the degree of decay.

In this study, decayed specimens were divided into moderate and severe category. The moderate category contains less than 20 percent decay in stress wave path (degree of decay is between 0 and 0.2) and the severe category contains more than 20% decay in stress wave path (degree of decay is 0.2 or more).

In order to divide decayed specimen into these two categories using stress wave technique, the threshold time has to be determined in advance. In order to find out adequate criterion, stress wave times were tried at an interval of 1μs/cm. Table 2 shows that the 20μs/cm could classify decayed specimens with the greatest accuracy of 85.4%. The accuracy of 20μs/cm and adjacent stress wave times of 19 and 21μs/cm was shown in Table 2. From this result, the stress wave time per unit length of 20μs/cm was concluded to be able to separate decayed wood into moderate and severe category with reasonable accuracy.

Accuracy of Each Decay Location Group

All specimens were divided into three groups according to the location of the decay ; exterior decay, mixed decay and interior decay. Specimens of mixed decay contained both internal and external decay.

Sound and Decayed Specimen

Table 3 shows the accuracy of each decay location group in case of distinguishing between sound and decayed specimen using the stress wave time of 12μs/cm. As shown in Table 3, the accuracy of the interior decay group is lower than the mixed and exterior decay. The interior decayed specimen of this research have small decay pockets. Because the decay pocket is so small, this type of decay provides many short paths to avoid it and the length of these paths is hardly longer than that of sound specimens. Stress waves could transit passing along one of these short paths. The difference between the transit times of sound specimen and interior decay specimen with small interior decay pockets is too small to distinguish between them. Therefore, it was concluded that stress wave transit is not sensitive to small pockets of decay. It seems that the size of these small decay pockets can explain the lower accuracy of interior decay.

Table 3 shows lower identification accuracy of mixed decay than that of the sound group. The specimens in the mixed group also have the small interior decay pockets. In the same manner as the case of interior group, it seems that the small decay pocket is responsible for lower accuracy of mixed group.

Moderately and Severely Decayed Specimen

Table 4 shows the success of decay identification between moderate and severe decay in

Table 3. Accuracy of each decay location group, in case of identifying sound and decayed specimens with a threshold time of 12μs/cm.

Location of Decay	Sound Specimen		Decayed Specimen	
	Total	Correctly Identified	Total	Correctly Identified
Exterior			120	90(75.0%)
Mixed			119	84(70.6%)
Interior			42	17(40.5%)
Total	467	389(83.3%)	281	191(68.0%)

Table 4. Accuracy of each decay location group, in case of identifying moderately and severely decayed members with a threshold time of 20μs/cm.

Location of decay	Decayed			
	<Threshold time		>Threshold time	
	Total	Moderate	Total	Severe
Exterior	69	68(98.6%)	43	34(79.1%)
Mixed	59	51(86.4%)	39	30(76.9%)
Interior	34	33(97.1%)	3	0(0.0%)
Total	162	147(90.7%)	85	64(75.3%)

exterior and mixed categories using stress wave transit time of 20μs/cm. However, the accuracy of interior decay is zero. As shown in Table 4, there are only three data in the severe interior category. This sample size is too small to be of use. Therefore, additional specimens with severe interior decay have to be collected and tested. More research to divide the specimens with interior decay into moderate and severe categories is needed.

CONCLUSION

In this test with Hard Pine old members, the stress wave time of 12μs/cm could distinguish between sound and decayed specimens with accuracy of 77.5 percent. Also, decayed specimens could be separated into moderate and severe categories. Stress wave time of 20μs/cm was also the most accurate in this case.

Among the three decay location groups (exterior, mixed, interior), the exterior group could be classified into sound, moderate and severe decay with the greatest accuracy. Stress wave transit is not sensitive to small decay pockets located in interior of the member. Additional research for detecting small decay pocket is needed. The number of members with severe interior decay examined in the tests were not enough to validate the results. Therefore, more testing and research for severe interior decay are needed.

REFERENCES

1. American Society for Testing and Materials. 1995. Standard Methods of Static Tests of Lumber in Structural Sizes. ASTM D 198-94, Philadelphia, PA.
2. American Society for Testing and Materials. 1995. Standard Test Methods for Specific Gravity of Wood and Wood-Base Materials. ASTM D 2395, Philadelphia, PA.
3. American Society for Testing and Materials. 1995. 1995. Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials. ASTM D 4442-92, Philadelphia, PA.
4. Armstrong, J. P., Patterson, D. W., Sneckenberger, J. E., Mallory, J. C. and Pellerin, R.F. 1991. Evaluation of a stress wave NDT technique for detecting skips in the gluelines of edge-glued red oak panels. Forest prod. J. 41(11/12): 61~66
5. Fuller, J. J., Ross, R. J., Dramm, J.R. 1995. Nondestructive evaluation of honeycomb and surface checks in red oak lumber. Forest Prod. J. 45(5): 42~44
6. Jang, S.S. 1998. Effects of Transducer Position in Ultrasonics Nondestructive Tests of Finger-Jointed Lumber. Mokchae Konghak 26(1): 1~6
7. Jayne, B.A. 1955. A nondestructive test of glue bond quality. Forest Prod. J. 5(5): 294~301
8. Pellerin R.F., DeGroot, R. C. and Esenther, G.R. 1985, Nondestructive stress wave measurements of decay and termite attack in experimental wood units, Proceedings of Fifth Nondestructive Testin of Wood Symposium, Sept. 9-11, 1985
9. Ross, R.J. and Pellerin, R.F. 1991. Nondestructive Testing for Assessing Wood Members in Structures: A Review. Gen. Tech. Rep. FPL-GTR-70. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
10. Ross, R.J., Ward, J.C. and TenWolde, A. 1994. Stress wave nondestructive evaluation of wetwood. Forest Prod. J. 44(7/8): 79~83
11. Schad, K.C., Schmoldt, D.L., and Ross, R.J. 1996, Nondestructive Methods for Detecting Defects in Softwood Logs. Res. Pap. FPL_RP-546, Madison, WI: U.S.Department of Agriculture, Forest Service, Forest Products Laboratory.
12. Volny, N. J. 1991, Timber bridge inspection case studies in use of stress wave velocity equipment. Proceedings /eighth international nondestrucive testing of wood symposium: 235~246
13. Wang, S., Suchsland, O. and Hart, J. H. 1980, Dynamic test for evaluating decay in wood. Forest Prod. J. 30(7): 35~37