QUANTITATIVE EVALUATION OF DETERIORATION OF TIMBER BY INDIRECT METHOD NON-DESTRUCTIVE EVALUATION

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ABSTRACT: Wooden buildings designated as cultural properties in Korea are often hundreds of years old. Maintenance and repair of wooden cultural properties is based on the principle of reusing original members. For the reuse of original members, it is important to detect performance degradation due to decay or weathering of major members as early as possible. This is because early detection of decay or deterioration can be decision criteria for determining the repair, reinforcement, or replacement of major structural members. In this study, the coefficient (n) of Hankinson's Formula that can predict the elastic wave velocity by indirect non-destructive testing was calculated for red pine (*Pinus densiflora*). The coefficient n for Hankinson's Formula was 2.0 for ultrasonic and 1.7 for stress wave. Based on the completed Hankinson's Formula, the foundation for effectively detecting internal defects of wood was prepared. In order to detect internal defects of red pine by non-destructive test, the area where potential deterioration was selected by indirect method test of stress wave and ultrasonic wave. This was confirmed by a drill resistance test. The threshold velocity for stress wave was 2000m/s and 3300 m/s for ultrasonic test. As a result, the possibility of detecting internal defects by indirect methods in both stress wave and ultrasonic tests was confirmed.This study showed that the non-destructive test method can be used as a reliable tool in the diagnosis and management of degradation of wood structures.

KEYWORDS: non-destructive test, ultrasonic wave, stress wave, indirect method

1 – INTRODUCTION

Wood is a non-uniform material obtained from nature. Defects or deteriorations of wood may be included additionally due to environmental or biological factors. Defects or deteriorations change the physical and mechanical properties of the wood, especially leading to a decrease in strength. Deteriorated wood threatens the structural safety of the structure and may cause problems of the constructions during its use. Wood suspected of deterioration requires periodic check of deterioration for safe use of the wood.

However, in traditional or heritage wooden buildings, wood is often used with other materials, making visual inspection difficult or impossible. For this reason, an indirect inspection method capable of evaluating the strength non-destructively without disassembling the wooden structure is required.Early detection and assessment of decay or deterioration of wood members cam be a criterion for determining repair, reinforcement, or replacement of structural members. Minor deterioration that has little effect on structural performance can be repaired. When the structural performance is deteriorated, but it may be maintained by reinforcing the member, the original member can be used by reinforcing treatment. However, if the performance degradation is significant and the structural performance cannot be played by reinforcement treatment, it should be replaced with a new material.

Therefore, this study was conducted to quantitatively evaluate the degradation of wood members by applying ultrasonic and stress wave non-destructive tests. Hankinson's formula of the elastic wave according to the wood grain direction was obtained for the red pine (*Pinus densiflora*) small clear specimen. In addition, the actual size timber with defects was tested and assessed the defects by the indirect method of ultrasonic and stress waves non-destructive test. The non-destructive test result was verified by a drilling resistance measurement. Through this, it was performed to find the possibility of quantifying the defects or deteriorations of wood

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members of timber constructions with non-destructive test.

2 – MATERIALS AND METHODS

2.1 MATERIALS

Wood Specimen for Hankinson's Formula

The test wood species is over 90 years red pine (*Pinus densiflora*) grown in Bonghwa, Gyeongsangbuk-do, Republic of Korea. The measurement of the elastic wave velocity according to the wood grain direction to determine the coefficient of Hankinson's formula was performed on 15 pine clear board (400×400×50 mm).

For the elastic wave test, ultrasonic transmission velocity measurement equipment (pundit Lab , Proceq, Switzerland) and stress wave transmission velocity measurement equipment (Micro Hammer, IML, Germany) were used. For ultrasonic measurement, the transducers and the specimen were brought into close contact using couplant (Ultrasonic Couplant, SLT, Korea). Fifteen specimens were humidity-treated at a moisture content of 12% using a constant temperature and humidity chamber (20°C temperature and 65% relative humidity).

The specimen numbers were assigned according to the divided plate and testing area as shown in Figure 1. The specimen numbers were determined in the order of plate number, front and back, and within the plate.

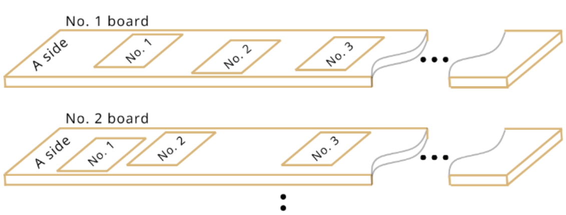


Figure 1. Specimen numbering

Actual Size Wood Specimens for Defect Detection

An elastic wave test for defect detection was performed on a 50×400×3600 mm plate collected from the same condition of red pine log for Hankinson's formula experiment. The test piece had a moisture content of 10%. It was evaluated as a visual grade number 2 according to the KS F 3020 structural coniferous material.

2.2 DETERMINATION OF COEFFICIENT OF HANKINSON'S FORMULA

Measurement of Elastic Wave Velocity by Grain Angle

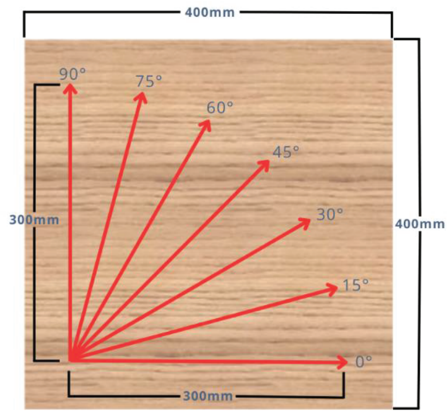
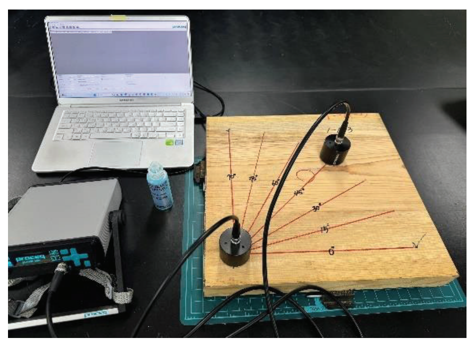
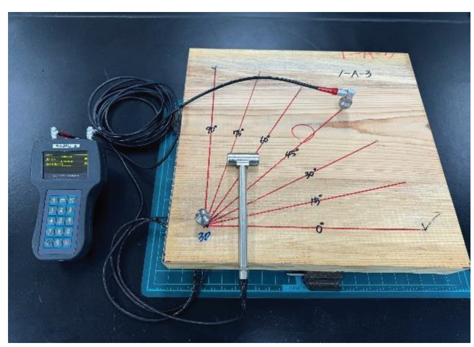


Figure2. Grain angle of elastic wave velocity measurement

On 15 clear red pine boards prepared to determine Hankinson's formula coefficient, the paths for elastic waves were marked along 300 mm distances at 15° intervals from 0° to 90° (fig. 2). At this time, the parallel direction of fiber was set to 0°, and the perpendicular of fiber direction was set to 90°.



(a)



(b)

Figure3. Indirect test method of ultrasocic velocity (a) and stress wave velocity (b) by grain angle

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The elastic wave transmission speed was measured indirectly (fig. 3). This is because, in the case of wooden cultural heritage buildings, direct method is often impossible in many cases where only one side of the timber member is exposed. The elastic wave transmission speed was calculated by dividing the distance between the transmitter and the receiver by the time of the elastic wave passes through the member. The transmission speed was measured 30 times for each angle. Total 210 data were collected for each specimen. During the measurement, the specimen was separated from the test table, a base was placed in 3 points so as not to shake, and the experiment was conducted with the specimen placed.

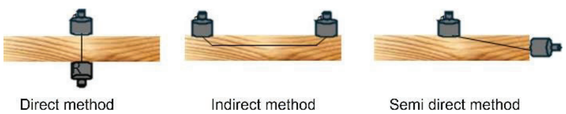

Figure 4. NDT test methods by location of transmitter and receiver

Ultrasonic Transmission Speed Measurement

The frequency of ultrasonic waves is fixed at 54 kHz. The contact surface of the transmitter and receiver is a circular shape having a diameter of 50 mm, and the centers of the transmitter are taken as the measurement distance. For accurate measurement, an ultrasonic contact medium (couplant) was applied to the measurement transmitter and receiver (Fang, Y., Emms, G.W., & Lu, Z. (2017)).

Stress Wave Transmission Speed Measurement

The stress wave transmission velocity is measured by inputting a stress wave generated by hitting the transmitter with a hammer connected to the equipment. The case where the measured, three values within 10% error was taken as measured values. It is measured by inserting the transmitter and receiver screws into the wood members. The insertion depth was 4 cm, in which the screw was stably fixed and not shaken during hammering (Wang, X. (1999); Hansen, H. J. (2006)).

Data Processing

450 data were collected per the same angle with 15 specimens and 30 repetitions. Outliers were removed using the IQR (Interquartile Range) method to exclude the possibility of defects such as internal check that cannot be confirmed with the naked eye. The coefficient n of the Hankinson's Formula was substituted by increasing 0.1 from 1.5 to 2.5 according to the Wood Handbook (2021). The coefficient n of root mean square error (RMSE) between 0° and 90° of the measured value with the removed outliers was adopted as the optimal coefficient. The accuracy of prediction model was evaluated by using normalized root mean square error (NRMSE).

2.3 DETECTION OF DEFECTS IN ACTUAL SIZE LUMBER

Evaluation of Deterioration Parts

As for the lumber for the defect detection, 11 lines were drawn to measure at 300 mm intervals in the parallel to the grain, and three areas were divided at 100 mm intervals in the perpendicular to the grain direction.

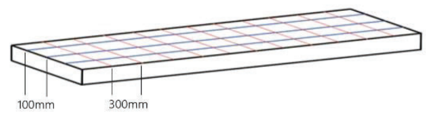

Figure 5. Measurement grid of the lumber

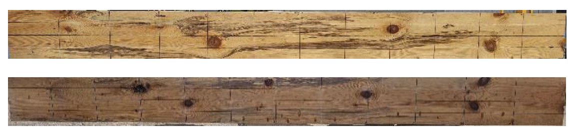

Figure 6. Measured lumber (front and back face)

The stress wave transmission velocity was measured indirectly with the transmitter and receiver arranged in the same row of the same face, and the measurement distance was 300 mm. The stress wave transmission velocity was measured and recorded 30 times in each section, and the average value was calculated.

The ultrasonic transmission velocity was measured using a ultrasonic equipment (Pundit Lab, proceq, Switzerland). The experimental condition were fixed to an amplitude value of 500 V and an amplification value of 100 times.

Based on the indirect method of stress wave test and the ultrasonic test parallel to grain direction, the potential deteriorate area was selected. The determination of deteriorable part was done by a elastic wave velocity lower than the threshold of sound area of wood.

Verification of Deteriorated Area by Drill Resistance Test

In order to verify the deteriorated part by the drill resistance test, the potential deteriorated part was divided into four sections. The ultrasonic transmission velocity was measured and recorded at 150 mm intervals by the elastic wave indirect methods. The drill resistance test was conducted in the perpendicular to the grain direction from the side of the lumber showing the lowest value within the potential deteriorable part. Resi PowerDrill 600, IML (Germany) was used for the drill resistance test. The test conditions of the drill resistance were fixed at an entry speed of 2500r/min and a rotation speed of 150cm/min.

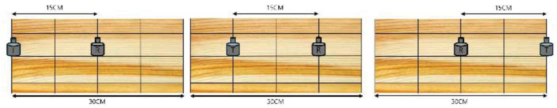

Figure 7. Narrow down the verification area by registograpny

3 – RESULTS AND DISCUSSIONS

3.1 CALCULATION OF THE COEFFICIENT OF HANKINSON'S FORMULA

The transmission velocity of the elastic wave according to the grain direction of red pine was shown (fig 8). In both the ultrasonic and stress wave tests, the average transmission velocity tended to decrease by grain angle from 0° to 90°. It was confirmed that the elastic wave was fastest in the fiber direction of the wood. The elastic wave transfers the cell wall as the medium. Therefore, at 0° in the wood fiber orientation, the cell wall is oriented parallel to the elastic wave transmission, and thus the transmission speed is fast. Where as at 90° in the wood fiber orientation, the transmission velocity is slow because the elastic wave transmits in a direction of perpendicular to the cell wall (Espinosa, L., Prieto, F., Brancheriau, L., & Lasaygues, P. (2019)).

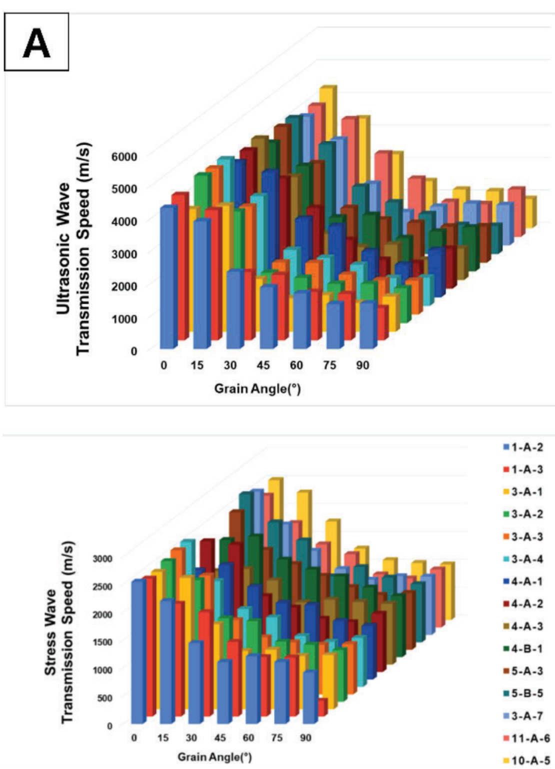

Figure 8. Ultrasonic (top) and Stress Wave (bottom) transmission Speed by grain angle

Table 1 shows the average and standard deviation after removing outliers by the IQR method under the condition of 12% moisture content.

Table 1: Elastic Wave Velocity at 12 % Moisture Content

	Grain angle						
	0°	15°	30°	45°	60°	75°	90°
UW	5297.12	4532.66	2896.57	1946.73	1581.67	1331.87	1257.65
	(200.74)	(377.15)	(431.77)	(455.79)	(316.47)	(310.57)	(272.18)
SW	2465.04	2071.84	1565.06	1246.97	1110.35	1017.22	995.08
	(167.68)	(191.63)	(171.87)	(149.99)	(160.33)	(117.65)	(70.47)

UW : Ultrasonic Wave, SW : Stress Wave, () : Standard Deviation

Hankinson's Formula is a formula that can predict the mechanical properties with a grain angle from the properties in the parallel and perpendicular to the grain direction. Depending on the elasticity, the transmission velocity of the elastic wave showing different velocities varies depending on the grain direction. Therefore, Hankinson's Formula can also be applied to predict the elastic wave transmission velocity in the wood direction.

Hankinson Formula :

$$N = \frac{PQ}{P\sin^{n}(\theta) + Q\cos^{n}(\theta)}$$

Where, N = predicted elastic wave velocity , P = elastic wave velocity in parallel to the grain direction, Q = elastic wave velocity in perpendicular to the grain direction, θ = angle between the elastic wave path and the grain direction, n = Hankinson's Formula coefficient

In Hankinson's Formula, P and Q are measured values of the elastic wave velocity. By determining the coefficient n, the elastic wave transmission velocity of a wood member with a grain slope (θ) can be predicted.

The average of 0° and 90° from which outliers were removed was substituted for elastic wave velocity of parallel (P) and perpendicular (Q) to the grain, and the θ was substituted. At this time, the coefficient n is incremented by 0.1 from 1.5 to 2.5 and substituted to calculate the predicted value of the transmission velocity of the stress wave and ultrasonic wave. The graph according to the coefficient n is presented in Figure 9. The measured values of the ultrasonic wave and stress wave transmission velocity when the coefficient n is shown as v, and the values when the coefficient n is 1.5 to 2.5 are shown by a thin solid line.

The transmission velocity of the elastic wave tended to decrease relatively as the grain angle increased, and the ultrasonic wave showed a relatively higher transmission velocity than the stress wave.

By the calculating RMSE, the coefficient of Hankinson's Formula of the smallest RMSE was adopted as a

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coefficient n. In the case of ultrasonic waves, the coefficient was 2.0. In the case of stress waves, the coefficient value was 1.7 (Fig. 10). These values also match the range of values suggested in previous studies (wood handbook).

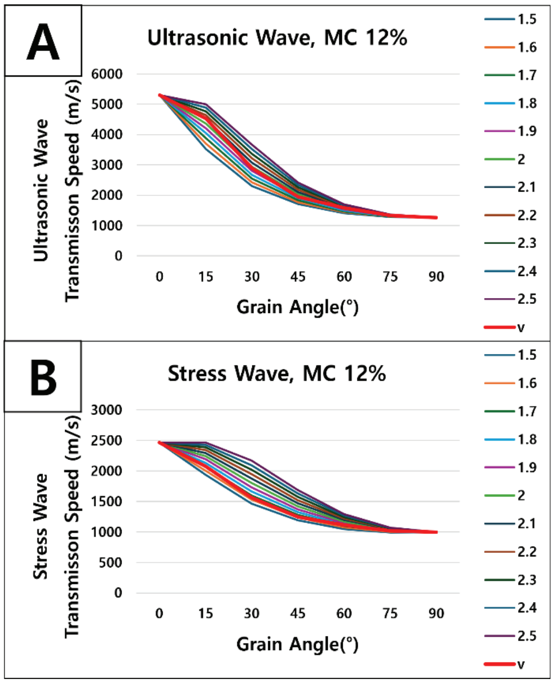

Figure 9. Measured values and Hankinson's formula with the coefficient between 1.5 and 2.5.

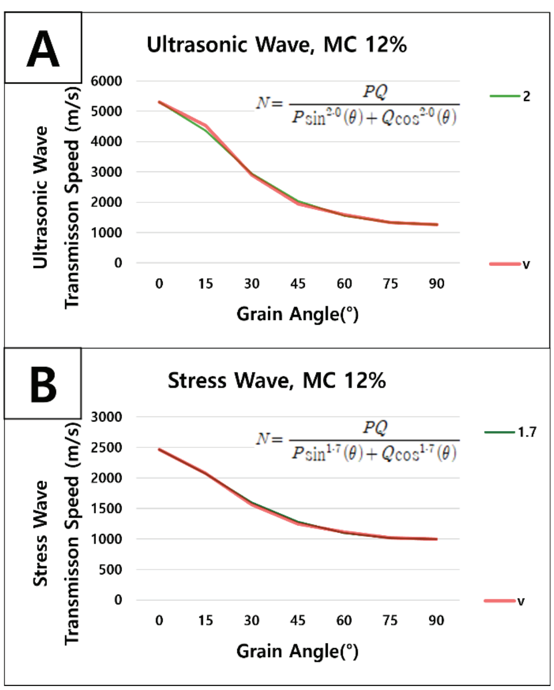

Figure 10. Hankinson's Formula for Red Pine by Ultrasonic and Stress wave

3.2 EVALUATION OF INTERNAL DEFECTS IN RED PINE BY NDT

Stress Wave Test Result

Table 2 is the stress wave velocity for the 300mm section of red pine parallel to the grain by indirect method. Measurement values were recorded on the front and back surfaces. The area where the average of the measured values on the front and back surfaces was lower than 2000 m/sec was set as the potential deteriorated area and marked in yellow.

Table 2: Indirect Stress Wave Velocity of Red Pine

	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
A	1988	2171	1951	2394	2508	2482	2104	2335	2524	2034
B	2137	2410	2248	1957	2517	2432	2153	2218	2369	2216
C	2543	2521	2274	1865	2349	2527	2462	2395	2412	1624

Ulteasound Test Result

Table 3 is the ultrasonic velocity for the 300mm section parallel to the grain by indirect method. Measurement values were recorded on the front and back surfaces. The area where the average of the measured values on the front and back surfaces was lower than 3300 m/sec was set as the potential deteriorated area and marked in yellow.

Table 3: Indirect Ultrasonic Velocity of Red Pine

	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
A	2722	2651	2057	3926	3108	3189	3499	3184	3317	4143
B	3209	3899	4056	3300	3786	4227	3996	3262	3854	3559
C	4047	3886	4443	3351	4490	4509	4871	4855	4271	3140

The threshold was determined based on the stress wave and ultrasonic average velocity and standard deviation for test of clear specimen and parallel to the grain angle. Therefore, 2000 m/s with 3 standard deviation for stress wave test, and 3300 m/s with 5 standard deviation for ultrasonic test was determined.

Drilling Resistance Measurement for Verification

Table 4 is the result of the drill resistance measured based on the threshold value of indirect stress wave and ultrasonic test. In the tables 5 and 6, blue cell showed the location where defect was found by indirect NDT and verified by drilling resistance measuremnt. The red cell in the table 5 is above the threshold of the indirect stress wave test, but a defect was found in the drilling resistance measurement. The yellow cell in table 6 is below the threshold of the indirect ultrasonic test, so there is a high possibility of a defect, but no defect was found in the drilling resistance measurement.

Based on the drilling resistance measurement, the accuracy using the 3 standard deviation threshold of stress wave test was 62.5%. In addition, the accuracy using the 5 standard deviation of ultrasonic was 70.0%.

Table 4: Drilling resistance measurement results

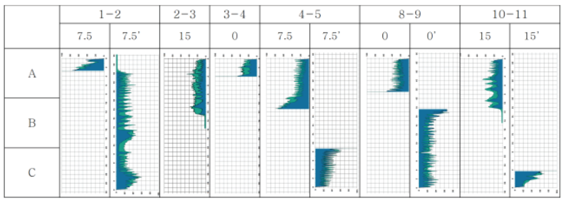

Table 5: Verification of Indirect Stress Wave Test by Drilling Resistance Measurement

	1−2	2−3	3−4	4−5	5−6	6−7	7−8	8−9	9−10	10−11
A	1988	2171	1951	2394	2508	2482	2104	2335	2524	2034
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4 – CONCLUSIONS

In this study, the coefficient (n) of Hankinson's Formula that can predict the elastic wave velocity by indirect non-destructive testing was calculated for red pine (*Pinus densiflora*). The coefficient n for Hankinson's Formula was 2.0 for ultrasonic and 1.7 for stress wave. Based on the completed Hankinson's Formula, the foundation for effectively detecting internal defects of wood was prepared.

In order to detect internal defects of red pine by non-destructive test, the area where potential deterioration was selected by indirect method test of stress wave and ultrasonic wave. This was confirmed by a drill resistance test. The threshold velocity for stress wave was 2000m/s and 3300 m/s for ultrasonic test.

As a result, the possibility of detecting internal defects by indirect methods in both stress wave and ultrasonic tests was confirmed.

This study showed that the non-destructive test method can be used as a reliable tool in the diagnosis and management of degradation of wood structures.

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