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Indirect Detection of Internal Defects in Wooden Rafter with Ultrasound*1

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ABSTRACT

The purpose of this research was development of quantitative ultrasonic test methodology for detecting internal defects in members of ancient wooden building. Connection part between wooden members and/or contacted or hidden part by wall of ceiling or other construction materials make it hard to apply direct way of ultrasonic test. So indirect way of ultrasonic test needed to be applied. Test methodology with newly developed prototype of ultrasonic system was proposed. Homogeneous material with polypropylene was also tested for establishing the criterion. Results showed that TOF(time of flight)-energy and pulse length were found out to be proper ultrasonic parameters for predicting depth of defect in wood different from polypropylene. It was not possible to directly apply prediction equation derived from polypropylene. Newly established prediction equation shows coefficient of determination of 0.73 for wood. Finally, defect of replaced rafter members was predicted with the coefficient of determination of 0.32. Various aspects of ultrasound propagation in wood including anisotropy need to be carefully considered to raise up the prediction accuracy.

Keywords : rafter, polypropylene, ultrasonic test, ultrasonic parameters, TOF (time of flight)

1. INTRODUCTION

TOF (time of flight) analysis of ultrasound can provide useful information about internal status of wooden material (Ross and Pellerin, 1994; Han *et al*., 2006). Many researchers paid attention to higher possibility of internal defects in wood with lower ultrasonic wave velocity which derived from TOF data. Lee *et al*. (2004) presented a threshold of ultrasonic wave velocity to determine deterioration of wood. And most researchers agreed that velocities of transmitted ultrasonic wave which derived from TOF drops with L, R and T direction of tested wooden specimen. Lee *et al*. (2003) reported that transmitting path of ultrasound can be predicted with TOF

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of propagated ultrasound. Wave path of ultrasound was assumed to straight line in most cases, however ultrasound will be attenuated, refracted and scattered because of inhomogeneous and anisotropic property of wood as well as deterioration.

So there are several limitations to apply conventional TOF analysis of ultrasound. Normally, only initial period of arrived ultrasonic signal had been considered which makes it hard to analyze overall aspects of ultrasonic signal including shape, area and duration of the signal. Several wood scientists have been paid attention to this and focus on analysing various ultrasonic parameters such as EV (energy value) and PL (pulse length) (Berndt *et al*., 1999; Beall, 2002). Bucur and Bőhnke (1994) investigated energy value of ultrasound according to fiber orientation and reported that attenuation of ultrasound showed much higher with T, R and L directions in order. Kabir *et al*. (2002) reported that energy loss and wave length of received ultrasound is better to be considered together with conventional TOF analysis. However, many of this approaches mainly performed under controled circumstances which make it hard to applying NDE (nondestructive evaluation) of wood in field.

Recently, several wood scientists have been focused on detecting internal defects and visualization of wooden members in field. Specially, CT (computed tomography) technique was effectively applied (Kim *et al*., 2008; Lee *et al*., 2009). However, connected parts between wooden members and contacted or hidden part by wall and ceiling of the building make it hard to apply direct way of ultrasonic test. And it is not effective to apply the visualization technique of tested cross-section for rafter members which have relatively small cross-sectional area and large length (Lee *et al*., 2011). So test methodology and analyzing criterion should be carefully considered to overcome these limitations of applying ultrasonic test for NDE of wooden members.

Therefore this study was performed for establishing test methodology and analyzing criterion for wooden members which is difficult to apply direct way of ultrasonic test. Rafter members were mainly considered as the one representative example of applying indirect way of ultrasonic test. Applicability for field application was carefully considered with developing ultrasonic system and high accuracy of test was tried to be achieved with analyzing various ultrasonic parameters.

2. Materials and Methods

2.1. Materials

Wood specimens with larch (*larix leptolepis*) and rigida (*pinus rigida*) were used. And PP (*polypropylene*) was also used as the one representative example of homogeneous and isotropic material (Table 1). Size of specimens were determined with considering rafter size. All wood specimens were air-dried and moisture content was about 13%.

And replaced rafter members were also prepared for verification of derived results with sound specimens. Species of specimens were found out

Table 1. Information of tested materials

Materials	Size (mm)	No. of specimen (pieces)	Density (g/cm^3)
Polypropylene	ϕ100, 1,200	1	0.98
Wood (*larix leptolepis*)	ϕ105, 1,200	5	0.49
Wood (*pinus rigida*)	ϕ110, 1,200	5	0.58

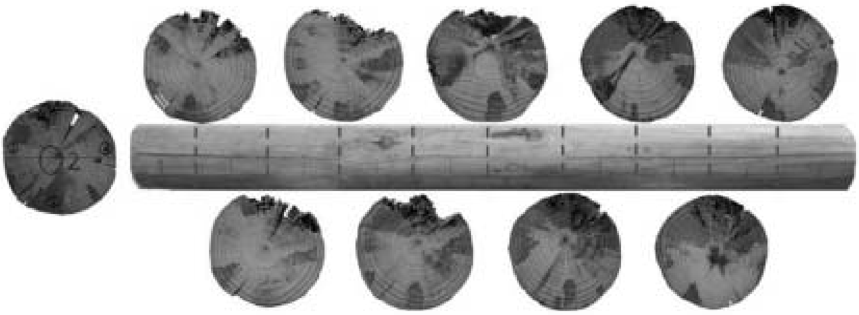


Fig. 1. Cross-sectional images of replaced rafter.

to be *pinus densiflora* and severly damaged by insects and brown-rot decay (Fig. 1). Three decayed specimens were used and average density and moisture content were about 0.4 g/cm^3 and 13 ~16% respectively.

2.2 Ultrasonic Apparatus

Ultrasonic measurement setup with indirect method was developed for prediction of internal deterioration of wooden rafter (Lee *et al*., 2011). Sensor apparatus consisted with ultrasonic transducer of 100 kHz central frequency, 40 mm in diameter and holder with spring-zig (Fig. 2). Contact pressure between transducer and test material which derived by inserted coil spring (50 mm diameter, 50 mm height) can be uniformly maintained for considering energy value of received ultrasonic signal.

Two sensor apparatus was connected to aluminum bar (35 mm in diameter and 560 mm in length). Distance between two transducers was fixed to 400 mm. Fig. 3 shows ultrasonic measurement setup including developed ultrasonic apparatus. The system was simply composed with pulser, receiver, ultrasonic transducer apparatus and notebook computer. This simple composition has advantageous for field assessment of rafter members in wooden ancient building. LabView (ver. 8.1, NI Inc., USA) was used to receive and process received ultrasonic signal.

(a) Ultrasonic transducer

(b) Transducer with holder

Fig. 2. Ultrasonic transducers used for this study.

Various ultrasonic parameters such as TOFa (amplitude), TOF-e (energy), Maximum amplitude, EV (energy value) and PL (pulse length) were derived from enveloped received ultrasonic signal. TOF-a and TOF-e are determined to the time which reaches 40% of maximum amplitude

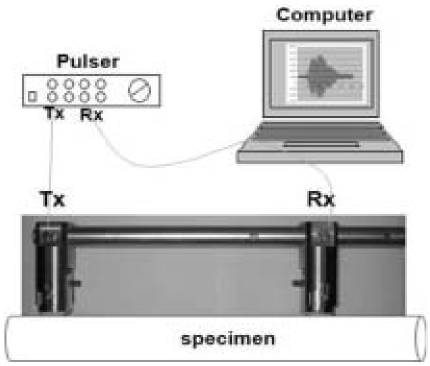


Fig. 3. Composition of ultrasonic system.

of the signal and time domain area respectively. EV divided into two cases - time and frequency domain, and only RMS voltage which indicates the time domain area of received signal was used in this research. And PL is the time duration of received signal which calculated with TOF-e at 10% and 90%.

2.3 Test Method

Five steps of test was performed for three different specimens with increasing artificial slit (10 mm in diameter) depth in seven steps (Fig. 4). Actually, deterioration in rafter shows various aspects which include fungal, insect and termite attack. It is difficult to make artificial deterioration and to quantify the amount of deterioration. So simple artificial slit was considered as the indicator of deterioration for regression analysis of received ultrasonic signal with the depth of artificial slit. Location of detection was determined to find exact effect of artificial slit on ultrasonic test results. Three times of same test was repeated and average value was used.

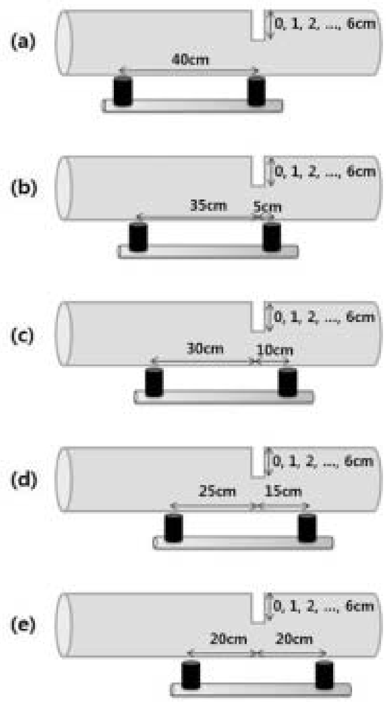


Fig. 4. Five steps of ultrasonic test.

And replaced rafter members were tested for verification. Firstly, opposite side of contacted or hidden part (damaged part) were checked and marked with every 5 cm intervals along length of specimen. Then, ultrasonic test were performed continuously with 5 cm intervals.

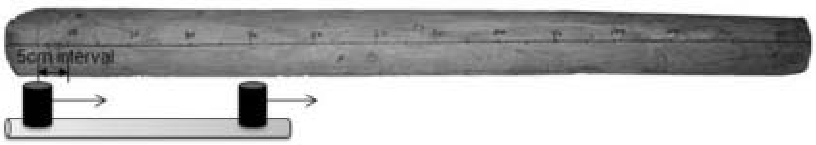


Fig. 5. Ultrasonic test method for replaced rafter member.

3. Results and Discussion

3.1 Correlation Analysis

Correlation analysis was performed on relationships between ultrasonic parameters and artificial slip depth for five steps of test cases. Following linear regression model was assumed for various ultrasonic parameters. Then, multiple linear regression analysis was performed for quantifying artificial slit depth.

$$y = ax + b \tag{1}$$

where,

y = depth of artificial slit

x = ultrasonic parameters (TOF-a, TOF-e, Max amplitude, RMS voltage, PL)

3.2 Establishment of Criterion with Homogeneous Material

Test results with polypropylene was firstly analysed for establishing criterion with homogeneous material. Ultrasonic parameters including RMS voltage and Max-amplitude show relatively high coefficient of determination specially for the case *c*, *d* and *e* (Table 2). RMS voltage shows decreasing tendency with increased depth of artificial slit (Fig. 6) same with maximum amplitude.

TOF-a and TOF-e values were measured as the most basic ultrasonic parameters of received ultrasonic signal. TOF-a shows more promising results and its coefficient of determination values show around 0.8 for case *c*, *d* and *e*.

RMS voltage, Max-amplitude and TOF-a40% show high coefficient of determination (Fig. 7) except case *a*. With these three parameters, a multiple linear regression equation for predicting artificial slit depth was proposed for case *e* (*equation 2*). And coefficient of determination for this prediction is determined to 0.94.

Table 2. Results of regression analysis between ultrasonic parameters and artificial slit depth of polypropylene

	Variables			
	Case	a	b	R^2
RMS voltage (V)	a	-22.37	785.05	0.335
	b	-54.83	804.67	0.722
	c	-84.48	916.58	0.753
	d	-89.82	906.71	0.855
	e	-91.55	871.09	0.773
Max. amplitude (V)	a	-0.0036	0.8735	0.290
	b	-0.0405	0.9241	0.574
	c	-0.0565	0.9502	0.645
	d	-0.0582	0.9401	0.734
	e	-0.0580	0.9402	0.618
TOF-a40 (μsec.)	a	1.186	330.9	0.199
	b	2.767	329.8	0.192
	c	8.638	324.0	0.789
	d	16.22	325.9	0.851
	e	14.68	336.6	0.778

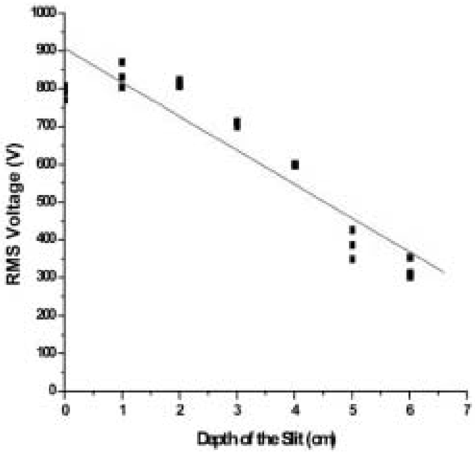


Fig. 6. Relations between artificial slit depth and RMS voltage of polypropylene (case *d*, R^2 value of 0.855).

$$y = -0.0071 \times x1 + 3.0387 \times x2 + 0.0289 \times x3 - 5.8935 \tag{2}$$

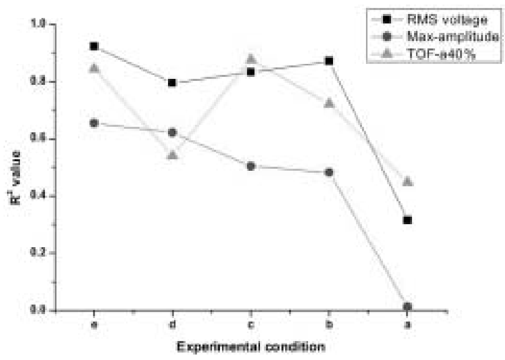


Fig. 7. Coefficients of determination values of five experimental conditions for polypropylene.

where,

y = depth of artificial slit (case *e*) of polypropylene

x1 = RMS voltage

x2 = Max-amplitude

x3 = TOF-a40

3.3 Application on Wooden Material

Same analysing method was applied for wooden specimens with larch and rigida. Different with previous results, coefficients of determination showed not high values compared with polypropylene specimen (Table 3, 4; Fig. 9). Coefficients of determination of the TOF-a40 were very low including other ultrasonic parameters except RMS voltage and Max-amplitude of case *d* and *e*.

Fig. 8 shows schematic diagram of ultrasonic propagation in PP (polypropylene) and wood which is to be expected. Because wood is anisotropic material, wave velocity on L direction is faster than R and T directions. So ultrasonic parameters of case *c*, *d* and *e* for PP can be affected while parameters of case *d* and *e* of wooden material is softly affected by artificial slit. Predicting model (*equation 2*) for PP specimen was applied and its correlation showed also not high (Fig. 9) for wood.

Table 3. Results of regression analysis between ultrasonic parameters and artificial slit depth for larch

	Variables			
	Case	a	b	R^2
RMS voltage (V)	a	-2.540	464.26	0.002
	b	-13.77	483.38	0.181
	c	-8.560	418.66	0.036
	d	-23.16	504.50	0.352
	e	-22.65	441.96	0.288
Max. amplitude (V)	a	0.0133	0.7371	0.125
	b	-0.0285	0.8256	0.303
	c	-0.0124	0.6739	0.037
	d	-0.0276	0.8086	0.174
	e	-0.0441	0.8078	0.530
TOF-a40 (µsec.)	a	4.660	281.9	0.273
	b	2.223	303.4	0.066
	c	10.10	280.1	0.134
	d	8.687	283.6	0.085
	e	7.929	307.5	0.261

Table 4. Results of regression analysis between ultrasonic parameters and artificial slit depth for rigida

	Variables			
	Case	a	b	R^2
RMS voltage (V)	a	-3.784	347.12	0.007
	b	10.21	315.25	0.058
	c	-19.30	433.40	0.139
	d	-28.39	486.56	0.345
	e	-15.80	299.34	0.368
Max. amplitude (V)	a	-0.0051	0.6384	0.006
	b	0.0078	0.6015	0.014
	c	-0.022	0.7637	0.110
	d	-0.0325	0.7555	0.324
	e	-0.0357	0.6227	0.317
TOF-a40 (µsec.)	a	-2.852	337.39	0.019
	b	3.383	310.65	0.013
	c	1.995	290.35	0.042
	d	-2.288	298.01	0.021
	e	5.039	300.16	0.077

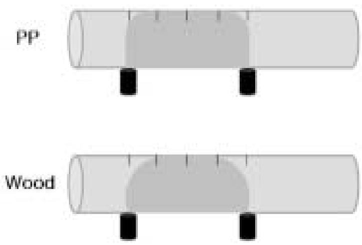
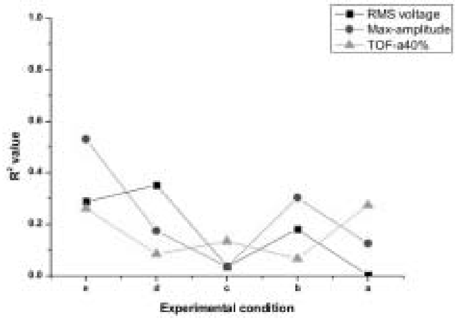
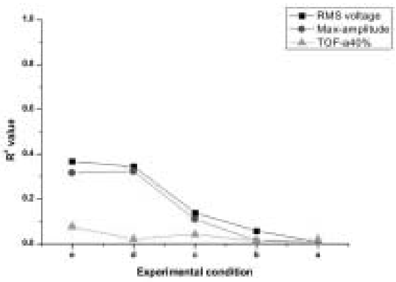


Fig. 8. Schematic diagram of expected propagation of ultrasound in test material.

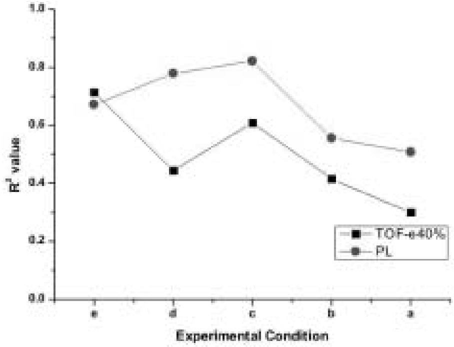


(a) Larch

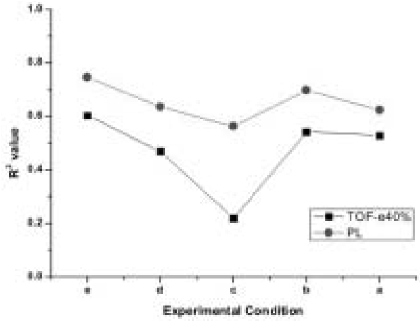


(b) Rigida

Fig. 9. Coefficients of determination values of five experimental conditions for wood.



(a) Larch



(b) Rigida

Fig. 10. Coefficients of determination values of TOF-e40% and PL of five experimental conditions for wood.

Different propagation phenomena of ultrasound on wood seems to be cause of this different results. So ultrasonic parameters were checked again to find appropriate parameters which can be applied for detection of artificial slit and hence TOF-e40% and PL (pulse length) showed relatively high coefficient of determination (Fig. 10).

With these two parameters, multiple linear regression analysis was performed to develop a predicting equation for artificial defect (*equation 3*) and the coefficient of determination was 0.73.

$$y = 0.013205 \times x1 + 0.001354 \times x2 - 1.92077 \quad (3)$$

where,

y = depth of artificial slit (case *e*) of wood
x1 = TOF-e40
x2 = PL

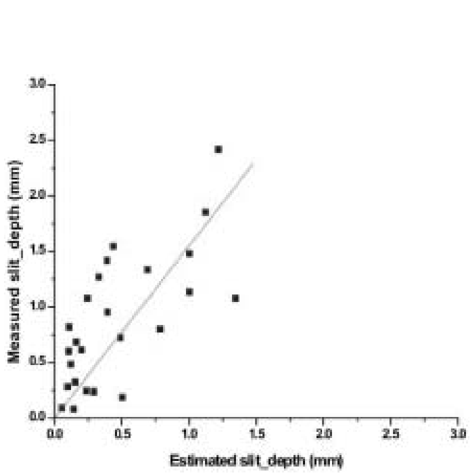


Fig. 11. Prediction results of deterioration.

3.4 Verification with Replaced Rafter Members

Three replaced rafter members were used for verification. Prediction model for wood (*equation 3*) was applied because it was not possible to use prediction equation with homogeneous material (*equation 2*). Deteriorated depth can be estimated with coefficient of determination of 0.32. Depth of the deteriorated part (measured_ depth) was rather underestimated and coefficient of determination was not high (Fig. 11). Mixed effects of anisotropic, inhomogeneous properties and deterioration with insect and brown-rot decay is considered to be reason for this result.

4. Conclusions

Ultrasonic apparatus with careful consideration on applicability and accuracy was developed for indirect defect detection of rafter members. For homogeneous material with polypropylene, RMS voltage which is the area of received ultrasonic signal, maximum amplitude and TOF-amplitude were found out to be proper ultrasonic parameters for predicting defects. Prediction equation of defect was established for application to wooden material. However, anisotropic property of wood was confirmed with comparison with homogeneous material. TOF-energy and pulse length were found out to be proper ultrasonic parameters for predicting depth of defect in wood. Newly established prediction equation shows coefficient of determination of 0.73 for wood. Finally, the defect of replaced rafter members was predicted with the coefficient of determination of 0.32. Various aspects of ultrasound propagation in wood including anisotropy need to be carefully considered to raise up the prediction accuracy.

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