Changes in the dynamic modulus of elasticity and bending properties of railroad ties after 20 years of service in Taiwan

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Abstract

An ultrasonic-wave technique and transverse vibration nondestructive evaluation methods were used to evaluate the dynamic modulus of elasticity and bending properties of wood from railroad ties of creosote treated from 7 species of wood removed from service after 20 years. Two NDE techniques and static bending tests were conducted on railroad ties, and lumber and specimens subsequently cut from the ties. Regression analyses gave a reasonably useful correlation between the ultrasonic-wave-based dynamic modulus of elasticity of the ties and lumber and the corresponding flexural properties of lumber and small clear specimens determined by 2 NDE techniques and static bending techniques, respectively. The results showed that wood from the creosote-treated railroad ties removed after years of service had sufficient potential residual strength for use in exterior structural applications.

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1. Introduction

Preservative-treated wooden railroad ties are important construction materials and generally exposed to varying and frequently strict conditions. This exposure can lead to deterioration resulting from decay, insect attack, weathering, mechanical damage, etc. Therefore, railroad ties must be monitored in order to maintain structural safety in service. Ross et al. [1] indicated that it is important to periodically examine wood structural components to determine the extent of degradation so that degraded members can be replaced or reinforced to avoid structural failure.

Railroad ties have long been a major disposal problem when removed after years of service. In general, many of these retired railroad ties are no longer useful because their wood structures are damaged. However, conservation ethics and wood resource shortages have often stimulated the adaptive reuse of old (demolished, retired, or historic)

structural members. Shi et al. [2] indicated that the reuse of creosote-treated wood can greatly reduce landfill costs and is attractive both economically and environmentally. Therefore, a substantial amount of the interior sound wood can be reused for other exterior structural applications. A simple example of recycling preservative-treated wood includes the reuse of old railroad ties for landscape timbers. Thus, a concern affecting the reuse of wood resources is whether the quality of sawn timbers is sufficient for reuse. Obviously, the effective utilization of retired ties requires an understanding of their properties. Fridley et al. [3] reported that the effects of use and age on the mechanical properties of full-size timber members are not well understood and, therefore, complicate their reuse.

Wang et al. [4] indicated that a key component in determining reusability is the nondestructive evaluation (NDE) of the structural quality of the wood. During the past few decades, wood scientists have developed and used NDE tools for a wide range of applications, from wood-based materials to the evaluation of standing trees. For example, ultrasonic-wave and transverse vibration methods are two useful, nondestructive techniques for estimating the

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physical properties of a material. From these efforts evolved a hypothesis, founded on fundamental material properties, for establishing relationships among several NDE parameters and static mechanical properties and the density of wood products [5–10]. However, studies have not addressed the use of these two NDE techniques to evaluate the potential quality of preservative-treated railroad ties retired from service. In addition, little information exists concerning relationships among the two NDE parameters and important residual strength properties of the ties.

Currently, there is interest in developing and using cost-effective technologies to evaluate railroad ties removed from service. In particular, several studies have shown a good relationship between the dynamic modulus of elasticity and the static modulus of elasticity of wood members [1,2,4,11–15]. These promising results led us to hypothesize that the use of nondestructive techniques may be useful in assessing the potential quality of railroad ties removed after years of service.

Therefore, the objective of this study was to investigate the use of ultrasonic-wave and transverse vibration NDE methods, and a static bending test to assess the quality of wood (dynamic modulus of elasticity and residual strength) in retired creosote-treated wooden railroad ties.

2. Materials and methods

2.1. Materials

Total of 27 castoff creosote-treated wooden railroad ties was obtained from Taiwan Railroad Company. The dimension of these rectangular ties is approximately $14 \times 20 \times 215$ cm. These creosote-treated ties had been used as structural materials in railroad. The outer portions of the ties had been severely damaged mechanically or biologically after years of service. The major visual defects

were decay, splits, insect borer damage, etc. These 27 ties were composed of seven species of local wood (Table 1).

2.2. Experimental procedure

A schematic of the experimental procedure is shown in Fig. 1. Longitudinal ultrasonic-wave NDE methods were used to assess the railroad ties. The ties were then sawn into lumber ($4 \times 12 \times 150$ cm). Ultrasonic-wave, transverse vibration NDE methods, and static bending tests were performed on the lumber. Next, ultrasonic-wave NDE methods and static bending tests were conducted on small clear specimens. The small clear specimens ($2 \times 2 \times 32$ cm) were obtained from the lumber.

2.2.1. Ultrasonic-wave measurements

The railroad ties, lumber, and specimens were analyzed using an ultrasonic-wave technique for longitudinal transmission; the ultrasonic-wave apparatus (Sylvatest, frequency 22 kHz; Swiss Products) used transmitting and receiving transducers.

The ultrasonic-wave velocity (V) and the dynamic modulus of elasticity (MOEt_u [tie], MOEl_u [lumber], and

Fig. 1. Schematic of experimental materials procedure.

Table 1

Physical characteristics and dynamic modulus of elasticity (MOEt_u) of creosote-treated railroad ties removed after 20 years of service

Species	Code	Bulk density (kg/m ³)	Moisture content (%)	Vt (m/s)	MOEt _u (MPa)	Number of railroad ties
<i>Cyclobalanopsis longinix</i>	CL	775.2 (50)	29.0 (1.5)	4213 (603)	13756.1 (4747.7)	4
<i>Schima superba</i>	SS	559.3 (80)	32.3 (4.5)	3934 (492)	86537.0 (2747.5)	7
<i>Castanopsis carlesii</i>	CC	577.8 (50)	31.0 (3.7)	4097 (166)	9700.6 (1546.1)	3
<i>Pasania harlandii</i>	PH	620.0 (35)	31.3 (1.0)	4690 (270)	13638.4 (1685.5)	3
<i>Koompassia melaccensis</i>	KM	692.2 (47)	32.9 (1.0)	4501 (105)	14022.5 (1751.8)	3
<i>Litsea acuminata</i>	LA	434.0 (298)	36.4 (6.1)	3325 (901)	4796.7 (4297.5)	4
<i>Cyclobalanopsis gilvs</i>	CG	561.6 (176)	37.1 (1.9)	3788 (395)	8058.2 (3222.5)	3

Vt, Ultrasonic-wave velocity of railroad tie; MOEt_u, dynamic modulus of elasticity of tie by the ultrasonic-wave technique (at a moisture content of 12%). Values in parentheses represent the standard deviation.

MOE_{su} [specimen]) were calculated from the following formulas:

$$V = \frac{L}{T}, \quad \text{and}$$

$$\text{MOE}_{\text{tu}}, \text{MOE}_{\text{lu}}, \text{or MOE}_{\text{su}} = V^2 \times \rho;$$

where V is the ultrasonic-wave velocity in the direction parallel to the grain of the sample, L is the distance between the two transducers, T is the propagation time of the pulse from the transmitting transducer to the receiving transducer, MOE_{tu}, MOE_{lu}, or MOE_{su} is dynamic modulus of elasticity in the direction parallel to the grain of the sample, and ρ is the bulk density of the sample.

2.2.2. Transverse vibration tests

The transverse vibration technique was used to estimate the dynamic modulus of elasticity (MOE_{lv}) of the lumber obtained from the ties, using a Metriguard Model 340 E-computer. The test lumber was supported at one end by a knife-edge support and at the opposite end by a load-cell transducer. The dimensions of the lumber were physically measured, and then the load-cell transducer that was interfaced with the computer automatically determined its weight and natural frequency. The MOE_{lv} of the lumber was determined by the following equation [4,12]:

$$\text{MOE}_{\text{lv}} = \frac{\text{fr}^2 \times W \times L^3}{2.46 \times I \times g},$$

where MOE_{lv} is the modulus of elasticity determined by transverse vibration, fr is the natural frequency (Hz), W is the weight of the lumber (g), L is the span of lumber between supports (cm), I is the moment of inertia (cm⁴) and g is the gravitational constant (9.8 m/s²).

2.2.3. Static bending tests

The static bending tests were conducted in accordance with ASTM D198 [16] (third-point loading method for lumber) and ASTM D143 [17] (center loading method for specimens), using a Shimadzu (Japan) UH-10A universal-type testing machine. All specimens were positioned flat (edgewise loading) for the bending tests. The proportional limit, ultimate load, and deflection were obtained from load-deflection curves, and the modulus of elasticity (MOE_l [lumber], MOE_s [specimen]) and modulus of rupture (MOR_l [lumber], MOR_s [specimen]) were calculated.

In this study, each sample's dynamic modulus of elasticity and bending property data were adjusted to single moisture content of 12 % according to Wang et al [18] and Wang [19].

3. Results and discussion

3.1. Physical properties

Table 1 summarizes the physical characteristics of the creosote-treated railroad ties used in this study. Average

moisture content values of the ties ranged from 29.0% to 37.1% and were close to or exceeded the fiber saturation point (about 30%). In this experiment, according to the information provided by the Taiwan Railroad Company, all railroad ties had been in service for approximately 20 years. The small differences in moisture contents from tie to tie may imply similar service conditions or service histories. Wang et al. [4] indicated that older piles had higher moisture contents than newer piles and also exhibited greater moisture content changes in the radial direction than the newer piles. Comparisons of average moisture contents of the ties and the lumber obtained from them are shown in Tables 1 and 2. Average moisture contents of the lumber ranged from 28.6% to 37.7%. This result indicated that the average moisture content values of ties were similar to those of the lumber. In other words, the outer layer, middle layer, and center of the ties all had similar mean moisture content values.

Bulk density is one of the most-common properties used to evaluate wood and is generally regarded as the most-important property of the wood, i.e., the property to which most other properties are strongly related. Bulk density values ranged from 434.0 to 775.2 kg/m³ for the railroad ties, from 545.3 to 763.3 kg/m³ for the lumber, and from 584 to 855.4 kg/m³ for the small clear specimens (Tables 1–3). These results indicate that the mean bulk density values of ties were similar to those of the lumber. However, the small clear specimens had higher mean bulk density values than the ties and lumber. Moreover, the mean bulk density values of the ties and lumber were similar to that reported (Table 4) by Wang [20] and smaller than those of the specimens.

This may have been caused by creosote-treated performance and defect characteristics. This supports the hypothesis that creosote increases the bulk density, but defects (splits, seasoning checks, decay, and insect damage) decrease the density of the wood. The increasing effect was dependent on the depth and distribution of creosote penetration in the ties. Shi et al. [2] indicated that the measured densities of creosote-treated wood (Douglas fir and Southern pine) exceeded the values provided in the *Timber Construction Manual* (reference value). This result is reasonable because incorporating creosote preservative increases the wood weight.

The average bulk density values of the specimens were higher than those of the ties and lumber, because the specimens were clear and the ties/lumber contained defects. Therefore, the average bulk density values of specimens were mainly influenced (increased) by the creosote treatment; however, the ties and lumber were affected by the defects (decreases) and creosote (increases).

3.2. Ultrasonic-wave propagation

Average ultrasonic-wave speeds ranged from 3324.5 to 4690.1 m/s for railroad ties, from 3547.5 to 4815.2 m/s for the lumber, and from 4212.3 to 4982.8 m/s for the small

Table 2
Dynamic modulus of elasticity (MOE) and static bending properties of the lumber

Code	Bulk density (kg/m ³)	MC (%)	VI (m/s)	MOElu (MPa)	MOElv (MPa)	MOEI (MPa)	MORI (MPa)	Number of tested lumbers
CL	763.3 (56)	29.7 (1.8)	4551 (110)	15 811.0 (1650.9)	17 778.6 (3254.0)	125 893.7 (1116.3)	67.2 (11.5)	12
SS	552.2 (83)	34.0 (3.4)	4097 (448)	9270.5 (2423.5)	10 138.7 (1755.0)	9258.8 (1116.3)	47.2 (7.0)	28
CC	577.8 (57)	35.0 (7.8)	4207 (126)	10 224.2 (1173.1)	14 049.8 (1087.9)	9803.4 (1323.6)	67.6 (6.2)	9
PH	591.5 (39)	42.0 (2.5)	4815 (080)	13 714.6 (1064.6)	18 988.5 (717.8)	13 758.9 (314.8)	91.7 (1.2)	9
KM	715.4 (38)	28.6 (2.2)	4569 (147)	14 937.8 (1730.1)	20 262.5 (2933.6)	13 995.0 (445.8)	103.9 (3.4)	9
LA	545.3 (123)	30.2 (2.5)	3548 (358)	6862.4 (2116.0)	9912.0 (4400.2)	6035.4 (1811.7)	32.3 (11.1)	16
CG	551.9 (161)	37.7 (1.7)	4121 (470)	9373.5 (2316.2)	12 353.9 (205.8)	14 318.9 (579.2)	130.4 (4.8)	9

VI, Ultrasonic-wave velocity of the lumber; MOElu, dynamic modulus of elasticity of the lumber by the ultrasonic-wave technique; MOElv, dynamic modulus of elasticity of the lumber by the transverse vibration technique; MOEI, modulus of elasticity of the lumber by the static bending test; MORI, modulus of rupture of the lumber by the static bending test (at a moisture content of 12%).

For codes, see Table 1.

Table 3
Dynamic modulus of elasticity (MOE) and static bending properties of specimens

Code	Bulk density (kg/m ³)	Vs (m/s)	MOEsu (MPa)	MOEs (MPa)	MORs (MPa)	Number of specimens
CL	855.4 (45)	4868 (175)	20 269.9 (2168.5)	14 927.6 (2134.5)	135.3 (29.7)	56
SS	634.4 (56)	4304 (457)	11 753.2 (2688.7)	8629.8 (2406.0)	87.7 (31.8)	126
CC	651.4 (48)	4826 (216)	15 168.7 (1260.3)	12 143.2 (1232.7)	110.0 (24.0)	48
PH	694.6 (47)	4983 (106)	17 245.5 (1139.5)	13 778.9 (1041.2)	129.9 (20.7)	36
KM	755.2 (56)	4627 (304)	16 168.3 (2223.2)	12 549.3 (2150.3)	124.1 (24.8)	36
LA	584.1 (83)	4212 (321)	10 364.2 (1893.4)	7818.2 (1807.0)	81.9 (22.2)	64
CG	788.8 (101)	4872 (207)	18 725.6 (3523.3)	14 139.9 (4250.3)	122.3 (51.2)	36

Vs, Ultrasonic-wave velocity of specimens; MOEsu, dynamic modulus of elasticity of specimens by the ultrasonic-wave technique; MOEs, modulus of elasticity of specimens by the static bending test; MORs, modulus of rupture of specimens by the static bending test (at a moisture content of 12%).

For codes, see Table 1.

clear specimens (Tables 1–3). Ultrasonic-wave speeds measured in the lumber increased about 1.5–8.1% and increased 2.7–22.3% in specimens compared to those measured in the railroad ties. In other words, ultrasonic-wave speed showed the following trend: specimens > lumber > ties. Wang et al. [4] indicated that creosote attenuates stress-wave propagation and the attenuation effect is dependent on the depth of creosote penetration in the wood. Moreover, various defects such as splits, decay, and insect borer damage decrease ultrasonic wave speed in ties. Therefore, the average ultrasonic wave speed values were mainly influenced by the creosote and defect factors.

Table 4
Modulus of elasticity and modulus of rupture of 7 solid wood species published by Wang [20]

Code	Bulk density (kg/m ³)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)
CL	767	14 896	127.3
SS	491–514	10 339–13 739.6	98.8–104.1
CC	607–749	11 760–14 288.4	54.7–59.8
PH	531–598	11 965.8–16 317	133.1–150.3
KM	930	2087.4	133.4
LA	441	8575–12348	96.6–102.6
CG	774	18 228	191.5

For codes, see Table 1.

3.3. Modulus of elasticity and modulus of rupture

The average dynamic modulus of elasticity values (MOEtu) of railroad ties using ultrasonic-wave techniques are shown in Table 1. The MOEtu of ties ranged from 4796.7 to 14,022.5 MPa. The average dynamic modulus of elasticity values (MOElu and MOElv) of the lumber obtained from railroad ties using ultrasonic-wave and transverse vibration techniques are shown in Table 2. The MOElu of the lumber ranged from 6862.4 to 15,811.0 MPa and the MOElv ranged from 7042.2 to 15,212.1 MPa. Static bending tests conducted on the lumber supported these results. The static modulus of elastic (MOEI) values for the lumber ranged from 6035.4 to 14,318.9 MPa. Values for the modulus of rupture (MORl) ranged from 32.3 to 130.4 MPa for the lumber. The average dynamic modulus of elasticity values (MOEsu) of specimens obtained from the lumber using ultrasonic-wave techniques are shown in Table 3. The MOEsu of specimens ranged from 10,364.2 to 20,269.9 MPa. Static bending tests conducted on specimens supported these results. The static modulus of elastic (MOEs) values for the lumber ranged from 7818.2 to 14,927.6 MPa. Values for the modulus of rupture (MORs) ranged from 81.9 to 135.3 MPa for the lumber.

In this experiment, the modulus of elasticity and modulus of rupture values of samples were below average reference values (Table 4) for 7 species of wood [20]. Some of the specimen property data showed that the wood quality was similar to reference values. This result was similar to that in the report of Leichti et al. [15], who indicated that the mean modulus of elasticity of specimens was approximately 85% of the *Wood Handbook* (reference value) stiffness value for green coastal Douglas fir. In other

words, preservative-treated Douglas fir wood plies retain good wood quality.

In Tables 1–3, it was found that the MOEtu, MOElu, MOElv, MOEI, MORl, MOEsu, MOEs, and MORs values showed the following trend: specimens > lumber > ties. Furthermore, the MOElu (by the ultrasonic wave method) values were higher than those for MOElv (by the transverse vibration method). We consider that creosote and the defect characteristics are the most-important factors affecting the properties of the railroad ties. This is similar to the results of Shi et al. [2], who indicated that the outer layer of creosote-treated wood has a higher creosote concentration than the inner layers. In addition, the outer layers of the used wood may be damaged as a result of having been in service. Removal of both the outer layer and the defects should contribute to a larger strength in the sawn timber.

Therefore, it should be possible to remove part of the damaged outer layer of the ties and reuse the center or middle layers for exterior applications. Similar results have been reported for creosote-treated Douglas fir and Southern pine piles [4].

3.4. Correlations among bulk density, ultrasonic wave speed, dynamic and static bending properties

Correlations among several selected properties of railroad ties, lumber, and specimens could be represented by positive linear regression formulas and the coefficients of correlation (r) obtained from these analyses are summarized in Table 5. Good correlations ($r = 0.69–0.96$, $p < 0.01$) were found between NDE parameters and the static mechanical properties of ties, lumber and specimens. These results indicate that reasonably useful relationships exist

Table 5
Coefficients of relationships among the wood variables

		Railroad tie			Lumber						Specimen				
		BDt	Vt	MOEtu	BDl	VI	MOElu	MOElv	MOEI	MORl	BDs	Vs	MOEsu	MOEs	MORs
Railroad tie	BDt	1	0.52*	0.80**	0.95**	0.57**	0.88**	0.79**	0.39	0.51	0.81**	0.56*	0.75**	0.60**	0.61**
	Vt		1	0.90**	0.42	0.81**	0.71**	0.73**	0.84**	0.66**	0.41	0.62**	0.63**	0.65**	0.68**
	MOEtu			1	0.71**	0.79**	0.88**	0.88**	0.73**	0.66**	0.63**	0.66**	0.74**	0.74**	0.76**
Lumber	BDl				1	0.44	0.80**	0.72**	0.22	0.28	0.78**	0.44	0.67**	0.61**	0.61**
	VI					1	0.78**	0.79**	0.95**	0.73**	0.79**	0.79**	0.83**	0.79**	0.79**
	MOElu						1	0.91**	0.80**	0.69**	0.78**	0.71**	0.84**	0.82**	0.82**
	MOElv							1	0.70**	0.74**	0.66**	0.73**	0.78**	0.79**	0.78**
	MOEI								1	0.76**	0.66*	0.89**	0.83**	0.87**	0.92**
	MORl									1	0.52	0.84**	0.73*	0.77**	0.80**
Specimen	BDs										1	0.72**	0.94**	0.79**	0.75**
	Vs											1	0.91**	0.90**	0.83**
	MOEsu												1	0.97**	0.91**
	MOEs													1	0.96**
	MORs														1

BDt, bulk density of railroad ties, BDl: bulk density of lumber, BDs: Bulk density of small clear specimens.

For other codes, see Tables 1–3.

** $p < 0.01$.

among ultrasonic wave properties of ties, lumber, and specimens, the transverse vibration properties of the lumber, and corresponding flexural properties of the lumber and specimens. This observation of strong correlations is consistent with what other investigators have found for various wood materials using several NDE techniques. [4,11–12].

Schad et al. [11] reported that density is known to be the critical factor in railroad tie performance and durability. In this experiment, values of the MOR for the lumber and specimens increased with increasing bulk density, and the coefficients of correlation are summarized in Table 5. Good coefficients of correlation ($r = 0.67\text{--}0.94$, $p < 0.01$) existed among the dynamic MOE and density values of ties, lumber, and specimens. However, lower coefficients of correlation ($r = 0.22\text{--}0.79$) were found between the static mechanical properties and density values of ties, lumber and specimens. Although, density is an important parameter for defining the strength and dynamic force, the effect of density on bending properties (MOE and MOR) and dynamic MOE in this study may have been caused by the creosote treatment and defect characteristics. Therefore, the bulk density values were weakly related to the static bending properties in samples.

Values of the dynamic MOE and bending properties of ties, lumber, and specimens increased with increasing ultrasonic wave velocity, and the relationships could be represented by positive linear regression formulas ($r = 0.66\text{--}0.95$, $p < 0.01$, as shown in Table 5), respectively. On the other hand, the relationships between ultrasonic velocity and bulk density are shown in Table 5. The ultrasonic velocity tended to increase with increasing density, but the coefficients of correlation ($r = 0.44\text{--}0.72$) were lower. Hence, the ultrasonic velocity and bulk density values were weakly correlated in the samples.

The creosote increased the density and attenuated the ultrasonic wave/transverse vibration propagation in the wood, and the enlargement and attenuation effects were dependent on the depth and distribution of creosote penetration in the ties, respectively. In addition, the various defect traits decreased and weakened the density and ultrasonic wave/transverse vibration propagation in the wood.

Based on the above analyses and results, some of the variations in results may have been due to the creosote treatment and defect characteristics that had various degrees of impact on the ultrasonic-wave or transverse vibration properties of the wood.

3.5. Residual strength rate

In this paper, the actual values of MOEt and MORT of ties were not recorded in 20 years ago. Hence, the MOEt and MORT values were estimated by the credible regression formulas. The values of the MOE and MOR could be obtained by dynamic modulus properties, because the values of the MOEl and MORl increased linearly with

Table 6

Residual modulus of elasticity and modulus rupture rate (%) of railroad ties

Code	Residual modulus of elasticity rate (%)	Residual modulus of rupture rate (%)
CL	77.8	60.9
SS	75.7	54.0
CC	72.6	56.9
PH	79.8	58.9
KM	71.5	79.3
LA	64.0	39.6
CG	38.9	25.4

For codes, see Table 1.

increasing MOElu values and their relationships could be represented by the following positive linear regression formulas:

$$\text{MOEl} = 0.04\text{MOElu} + 94.8, \quad r = 0.69^{**} \text{ and} \quad (1)$$

$$\text{MORl} = 0.65\text{MOElu} + 9944.7, \quad r = 0.80^{**} (p < 0.01). \quad (2)$$

The values of MOEt and MORT could be obtained from the values of MOElu, measured and calculated from railroad ties, substituted into Eqs. (1) and (2).

The residual modulus of elasticity rate (RMOE, %) was calculated as

$$\text{RMOE}(\%) = \frac{\text{MOEt}}{\text{MOEr}} \times 100,$$

where MOEr is the referential (reference) modulus of elasticity [20], and MOEt is the calculated modulus of elasticity (from Eq. (1)).

The residual modulus of rupture rate (RMOR, %) was calculated as

$$\text{RMOR}(\%) = \frac{\text{MORT}}{\text{MORr}} \times 100,$$

where MORr is the referential modulus of rupture [20], and MORT is the calculated modulus of rupture (from Eq. (2)).

In this experiment, the average RMOE values of ties ranged 38.9–79.8% and average RMOR values ranged 25.4–79.3% (Table 6). It was found that the modulus of elasticity and modulus of rupture values of samples were below average reference values [20]. Compared to the average reference values, the average residual modulus of elasticity rate of the lumber was 69% and that of specimens was 89%. Moreover, the average residual strength rate of the lumber was 63% and specimen was 96%. In other words, the MOEl, MOEs, MORl, and MORs values were about 31%, 11%, 37%, and 4% lower than reference values [20].

4. Conclusions

Conservation ethics and wood resource shortages are generating increasing interest in reusing railroad ties

removed after years of service. This study investigated the dynamic modulus of elasticity and residual strength of railroad ties removed after years of service by ultrasonic-wave and transverse vibration methods, and static bending test, with the following results.

1. For these railroad ties removed after years of service, ultrasonic-wave speed showed the following trend: specimens > lumber > ties, and there was a good relationship existed between ultrasonic wave speed and bending properties in ties, lumbers and specimens.
2. There was a reasonably useful correlation between ultrasonic-wave- and transverse vibration-based modulus of elasticity values in ties and the corresponding static bending properties in the lumber and specimens. ($r = 0.69\text{--}0.96$, $p < 0.01$)
3. In these 2 NDE technologies, it was found that the dynamic modulus of elasticity calculated by ultrasonic-wave method (MOElu) was higher than that for MOElv (calculated by the transverse vibration method).
4. The residual MOE and MOR rate values of ties were ranged from 38.9 to 79.8% and 25.4 to 79.3%, respectively, and it was found that the values of RMOE and RMOR for lumbers and specimens were higher than those of ties.
5. The railroad ties removed after years of service retained good quality wood in their inner layers. Therefore, lumber and specimens from these ties have the potential for use in exterior structural applications.

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