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Original Article

Nondestructive and Destructive Testing of Wood Railroad Ties

Laya Khademibami

Rubin Shmulsky

Fatemeh Rezaei

Nathan Irby

Christopher Adam Senalik

Seyed Abolghasem Fatemi

The authors are, respectively, Assistant Research Professor, Department Head and Warren S. Thompson Professor, and Assistant Research Professor, Department of Sustainable Bioproducts, Mississippi State Univ., Mississippi State (lk475@msstate.edu [corresponding author], rs26@msstate.edu, and Fr280@msstate.edu); Executive Director at Railway Time Association, Vicksburg, Mississippi (nirby@rta.rog); Research General Engineer, US Forest Serv. Forest Products Lab., US Dept. of Agric., Wisconsin State, Wisconsin (christopher.a.senalik@usda.gov); and Postdoctoral Associate. Dept. of Sustainable Bioproducts, Mississippi State Univ., Mississippi State (sf1006@msstate.edu). This paper was received for publication in December 2024. Article no. 24-00059.

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Abstract

Nondestructive evaluation of wood railroad ties was previously investigated using acoustic velocity (AV). Flexural properties, however, have not been well studied among legacy ties as well as new ties of wood species and grades. Therefore, modulus of elasticity (MOE) and modulus of rupture (MOR) from two groups of wood species for three grade conditions were investigated. For similar ties, regression analysis of destructive and nondestructive data was performed. Overall, 60 new on-grade, 40 new off-grade, and 55 Grade 1 legacy ties were examined. The wood species groups were either oak/hickory or mixed hardwood. MOE and MOR of destructive evaluation were obtained, and these were compared with their companion AV value of each tie using polynomial regression analysis. All destructive evaluation data were analyzed using two-way analysis of variance. There was a statistically significant interaction between species and grade for MOR ($P < 0.0010$), in which new, on-grade oak/hickory ties had a higher MOR compared with mixed wood. Furthermore, a higher MOE ($P < 0.0001$) was observed for oak/hickory than for mixed wood ties. Additionally, the highest MOE ($P < 0.0132$) belonged to new on-grade ties, whereas legacy ties had the lowest MOE. A significant relationship was observed between AV free and fixed and with MOE and MOR. These results indicate that both wood species and grade conditions are important factors for determination of strength and stiffness of ties. Additionally, AV could be useful technology for grading new ties and for identifying legacy ties that should be removed from service.

Introduction

Wood is a long-standing structural material. It has been used in many historic buildings and transportation structures and vessels. It is also used extensively for rail ties, also known as sleepers. It is susceptible to biological degradation such as fungi and insect infestation and must be preservative treated. Although wood is a versatile and effective material for rail ties, its characteristics vary among species groupings (Lutch 2009, Rocha et al. 2021, Khademibami et al. 2024). Thus, the strength and stiffness of wood ties in various species groups requires evaluation. Despite concrete rail ties having shown promising strength and durability, most ties in the United States are wood. Concrete is heavier, more costly, and requires additional care to prevent steel rebar from shunting the signal system (Zarembski 1993) as compared with wood.

Nondestructive evaluation (NDE) technology has been widely used to determine internal or nonvisible degradation in wood materials (Ross 2015, Abadi et al. 2019, Zielińska and Rucka 2021) as well as concrete rail ties (Evani et al. 2021). NDE is used to overcome limitations of visual inspection as well as provide reasonably sensitive, accurate, efficient, labor-intensive testing material with minimal disruption in wood materials (De Groot et al. 1994, 1998; Ross et al. 1994a, 1994b, 1996, 1997, 2022; Ross and De Groot 1998) and concrete ties (Shafiei et al. 2016, Fisk 2018, Henderson and Sherrock 2018). Although the NDE of in-service rail ties is beneficial, destructive testing is required to develop meaningful correlations, and it provides accurate evaluation of strength and stiffness. Currently, the NDE method that can be representative for destructive testing is well developed for concrete ties, although this technology is not well investigated for wooden ties. There are two major variables, modulus of elasticity (MOE) and modulus of rupture (MOR), associated with destructive bending tests. MOE is related to stiffness and MOR is linked to maximum strength (Suryono and Bhakti 2019). Previous studies have shown strong correlations between ultrasonic wave speed (NDE) using railroad ties with 20 years of service in Taiwan, with MOE of 38.9 percent and MOR of 79.8 percent (Lin et al. 2005). In that study wood type was not differentiated. In the research herein, NDE evaluation among ties belonging to two wood types (oak/hickory vs. mixed hardwood), three grade conditions (new on, new off, and in service [legacy]), and two boundary conditions (free [on ballast] and fixed [packed with ballast and under static weight]; Khademibami et al. 2024) were considered. The oak/hickory are denser, on the order of 0.65 to 0.70 specific gravity, and thus considered stronger. The mixed hardwood group is generally less dense, on the order of 0.55 to 0.65 and considered less strong. The acoustic velocity (AV) was consistently higher for ties in a fixed versus free boundary condition. Additionally, higher AV was observed in new on-grade ties as compared with new off-grade or legacy ties. The effect of wood species as well as grade condition on MOE and MOR and their correlation with AV in wood ties has not yet been studied. The effects of wood types in combination with grade conditions on nondestructive and destructive strength testing when new and in-service ties were compared have not been previously investigated. AV tends to be faster in denser species and specimens with straighter grain. As such, AV should seemingly be able to separate denser species such as oak and hickory from less-dense sweet gum and other mixed hardwoods. Also, because on-grade ties have tighter restrictions on strength-reducing characteristics such as knots and bark seams, then AV should be faster in on-grade versus off-grade material. The current study investigated tie integrity in a simulated track condition, via AV, followed by destructive bending tests to determine MOE and MOR. The objectives of this work were to:

1. Evaluate MOE and MOR values between ties of two wood species groups (oak/hickory and mixed hardwood).

2. Evaluate MOE and MOR values in new on-grade versus new off-grade versus legacy ties.

3. Compare results of AV with MOE and MOR using polynomial regression.

The outcome of this study improved the understanding of the relationship between NDE and destructive testing of wood ties belonging to different wood types, grade, and new versus in-service conditions.

Materials and Methods

Experimental layout

Two species groups of wood ties (oak/hickory and mixed hardwood, which included ash, beech, sweet gum, and sycamore) were investigated. Additionally, these species groups were new freshly sawn green ties that were either new on-grade versus new off-grade or old ties that were taken out of service (legacy). The number of each category was 60 new on-grade, 40 new off-grade, and 55 legacy ties. The sample replication for each combination is presented in Table 1. Tie procurement and installation was performed according to the procedures described by Khademibami et al. (2024). After receipt, ties were installed on ballast rock and evaluated nondestructively. After NDE the new green ties were stored under a water sprinkler (Fig. 1) to prevent drying until flexural bending testing. The total time between sawing and placing the ties under the water sprinkler was 8 to 10 weeks. This protocol assured that the new ties would be at or above the fiber saturation point throughout the nondestructive and destructive testing regimes.

Destructive evaluation

The NDE procedure used herein was previously described in Khademibami et al. (2024). AV free was measured after each tie was placed on the ballast. AV fixed was measured after the ties were packed with ballast and a static weight to simulate rail loading was installed at the top of each tie. The flexural bending test was performed using an Instron 600-kN-capacity universal testing machine (Fig. 2) in accordance with a modified ASTM D-4761 (2017) standard. Modifications were required regarding span-to-depth ratio. Lengths were approximately 108 inches for on-grade, 102 to 108 inches for off-grade, and 100 to 104 inches for legacy ties. As such, spans were set for 102, 96, and 92 inches for on-grade, off-grade, and legacy ties, respectively. Tie thickness varied from approximately 6.5 to 7 inches As such, span-to-depth ratios were between 14 and 15 throughout. Both MOE and MOR were calculated:

$$MOE = PL^3/48ID \qquad (1)$$

where P is the concentrated center load (N), L is the span (m), I is moment of inertia (m^4), and D is the deflection at midspan (m).

$$MOR = PL/bh^2 \qquad (2)$$

where P is the breaking load (maximum load, N), L is the distance between supports (m), b is the width of the beam (m), and h is the depth of the beam (m).

Statistical analysis

The experimental design was completely randomized, considering each railroad tie as an experimental unit. A two-way analysis of variance with three by two factorial arrangements of treatments to test for the main and interactive effects of the three grade condition treatments (new on grade, new off grade, and legacy) and two wood species group treatments used. All data were examined for normal distribution using the Shapiro–Wilk test at $\alpha = 0.05$. General linear mixed models (PROC GLIMMIX) of SAS 9.4© (SAS Institute Inc, Cary, NC) were used to analyze the mean treatment difference for MOE and MOR variables; treatment differences were considered significant at $P \leq 0.05$. Additionally, Fisher's protected least significant difference for determination of mean separation (Steel and Torrie 1980) was used. The following statistical model was used for all data:

$$Y_{ijk} = \mu + G_j + S_i + (GS)_{ij} + E_{ij} \qquad (3)$$

where μ is the population means; G_i is the effect of grade condition treatments ($i = 1$ to 3); S_j is the effect of wood species treatment ($i = 1$ to 2); $(SG)_{ij}$ is the interaction of each wood species treatment with grade condition treatment; and E_{ij} is the residual error.

The linear and polynomial regression between AV of free and fixed boundaries and MOR and MOE were determined using PROC REG of SAS 9.4© (SAS Institute):

$$y_i = ß_0 + \Sigma_{ijk}\, ß_i X_i + ß_j X^2{}_j + ß_k X^3{}_k + e_{ijk} \qquad (4)$$

where y_i is the AV of free and fixed boundaries or MOE and MOR in the i, j, kth sample; X_i is the value related to input variable in the ith sample; $X^2{}_i$ is the value related to input compositions in the jth sample; $X^3{}_k$ is the value related to input variable in the kth sample (assumed to be a known constant measured without error); β_0 is the overall intercept; β_i is the linear coefficient for input variables; β_j is the quadratic coefficient for input variables; β_k is the cubic coefficient for input variables; and e_{ijk} is the residual error assumed to be normal ($N \sim [0, \sigma^2]$). Probability was deemed significant at $P \leq 0.05$.

Results

The summary statistics of MOE and MOR for different wood species in combination with grade condition are shown in Table 1. The coefficient of variation between MOE and MOR was relatively close between treatment combinations except in those ties belonging to oak/hickory new off grade. In addition, the variation between observations was relatively high for both MOE (37.9%) and MOR (46.2%) in oak/hickory legacy ties, whereas this combination also had more replications. The results for mean differences between two wood species groups and three grade conditions for MOE and MOR variables are shown in Table 2. There was significant interaction between wood species group and grade condition for MOR ($P = 0.0010$) in which new on-grade oak/hickory ties exhibited higher MOR in comparison with the mixed wood (Fig. 3). There was no significant difference between new off and legacy ties in both wood species groups. There was no significant interactive difference between wood species group and grade conditions for MOE (Table 2). However, greater MOE was observed for oak/hickory relative to mixed wood (Fig. 4). In addition, MOE was highest in new on ties and lowest in legacy ties, whereas MOE was intermediate for new off ties (Fig. 5). The relationship between different combinations of AV with MOE and MOR is presented in Table 3 and the individual comparison is also demonstrated in Figure 6a–f. Results showed that all regression comparisons have become significant for linear polynomial (quadratic and cubic) models. In addition, higher R^2 was observed between AV free and AV fixed (0.67) or between MOE and MOR (0.69), indicating promising correlation for the abovementioned comparison. Furthermore, R^2 for comparison between AV fixed and MOR was lowest (0.11), whereas between AV free and MOE (0.34), AV free and MOR (0.21), and AV fixed, and MOE (0.19) were intermediate.

Discussion

The aim of the current study was to determine the strength of new railroad ties and in-service ties from two combinations of wood species using destructive test variables. Additionally, the relationship between nondestructive and destructive evaluations of ties was investigated. The results of the current study showed that there is a significant difference in stiffness between wood species groups, as oak/hickory had a higher MOE than mixed hardwood species. Additionally, MOR was higher in new on-grade oak/hickory wood, but there was no difference for MOR between the grade conditions in the mixed hardwood species. The physical and mechanical properties of samples of red and white oak lumber have been previously determined using MOE and MOR values (Uzcategui et al. 2020), but their mechanical performance has not been compared with other mixed hardwood species. Furthermore, although MOE and MOR associated with red and white oak have not been top ranked among various species (Hiziroglu 2016), the findings herein indicate that ties made from oak/hickory can perform better on deflection and bending than those from mixed hardwood species. Lower MOE was found for old ties in this study. Similar to destructive testing, lower AV was observed for old ties as compared with new ties in the companion study conducted by Khademibami et al. (2024). For AV, however, no significant difference was observed between oak/hickory and mixed wood (Khademibami et al. 2024). The basis for inconsistent results between nondestructive and destructive evaluations and of railroad ties could be linked to relatively low correlation between AV free and AV fixed with MOR and MOE. The results herein showed that higher relationships were observed within AV response (AV free vs. AV fixed) by 67 percent and within destructive variables (MOE vs. MOR) by approximately 69 percent, whereas a relatively low R^2, between 11 and 37 percent, was observed between NDE and destructive testing variables. Previous studies that compare NDE with destructive testing have shown relatively low R^2; 20 percent correlation was observed between NDE and destructive testing for woodcrete (Fadiel et al. 2022) and 5 to 50 percent correlation was found for concrete ties (Qurashi et al. 2019) when other factors such as moisture content and temperature were not included. The work reported here revealed a significant correlation between

NDE and destructive evaluation for wooden ties. Other factors such as wood type, moisture content, and grade conditions can be included as predictors to increase the accuracy of the abovementioned comparison. Ross (2015) showed that NDE wooden tie integrity is dependent on several factors including moisture content, temperature, and wood species.

Conclusions

In conclusion, the effect of oak/hickory and mixed hardwood species combined with new on-grade, new off-grade, and legacy tie grade condition on the MOE and MOR were investigated. NDE and destructive evaluations of railroad ties were compared using polynomial regression. Findings revealed that MOE was only individually affected by wood species group and grade conditions; oak/hickory had greater MOE value than mixed hardwood species. New on-grade ties exhibited a greater MOE in comparison with new off-grade or legacy ties, and legacy ties were the lowest. Furthermore, MOR for new on-grade ties was lower in mixed wood as compared with oak/hickory, whereas no differences were observed between new off-grade and legacy ties in different wood species. Moreover, significant correlations were observed between AV responses and MOE and MOR, particularly between AV free and AV fixed responses and between MOE and MOR. These findings suggest that tie integrity might have been different among wood species groups as well as grade conditions.

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Figure 1.—New ties stored under a water sprinkler after nondestructive evaluation in the ballast rock bed and before destructive flexural testing.

Figure 2.—Demonstration of static bending test.

Figure 3.—Interaction effects of species and boundary effects on modulus of rupture (MOR) of railroad ties. [a–c] Treatment means within the same column within effect without common superscripts are significantly different ($P \leq 0.05$*). Number of replications per treatment combination is 154; SEM = 65,274.*

Figure 4.—Main effect of oak/hickory species and mixed hardwood species on modulus of elasticity (MOE) of railroad ties. Number of replications per treatment combination is 148; SEM = 52,005.

Figure 5.—Main effect of new freshly sawn green ties (new on), either on grade or off grade (new off) or legacy, that were taken out of service on modulus of elasticity (MOE) of railroad ties. [a–c] *Treatment means within the same column within effect without common superscripts are significantly different (*P *≤ 0.05). Number of replications per treatment combination is 148; SEM = 60,474.*

Figure 6.—Regressed relationship of acoustic velocity (AV) between AV free versus AV fixed boundary conditions with modulus of elasticity (MOE) versus modulus of rupture (MOR) for all ties. (a) Polynomial regression between AV free and AV fixed; (b) polynomial regression between MOE and MOR; (c) polynomial regression between AV free and MOE; (d) polynomial regression between AV free and MOR; (e) polynomial regression between AV fixed and MOE; (f) polynomial regression between AV fixed and MOR.

Table 1.—Experimental layout indicating replicates, type of railroad ties used in this study, and summary statistics of modulus of elasticity (MOE) and modulus of rupture (MOR) in different railroad ties including two boundaries, two sets of wood species, and three grade conditions.

	New on ties				New off ties				Old (legacy) ties			
	Oak/hickory		Mixed wood		Oak/hickory		Mixed wood		Oak/hickory		Mixed wood	
	MOE (milli	MOR (psi)	MOE	MO	MOE	MO	MOE	MO	MOE	MO	MOE	MO

	on psi)		(million psi)	R (psi)	(million psi)	R (psi)	(million psi)	R (psi)	(million psi)	R (psi)	(million psi)0	R (psi)
Mean	1,410,648	7,142	1,130,653	4,922	1,176,695	5,220	1,066,660	4980	967,990	3,499	966,702	3,388
Median	1,453,489	7,121	1,095,532	4,983	1,209,520	5,613	1,089,589	5,061	911,009	3,566	907,821	3,662
SD	324,183	1,826	228,992	1,130	158,374	1,441	228,425	1,384	366,672	1,615	225,429	895
Coefficient of variation (%)	23.0	25.6	20.3	23.0	13.5	27.6	21.4	27.8	37.9	46.2	23.3	26.4
Minimum	736,240	3,003	766,826	2,877	765,825	1,175	738,219	2,365	290,620	681	561,717	1,924
Maximum	1,972,861	10,442	1,584,761	7454	1,345,121	6,906	1,527,176	7111	2,023,045	6,799	1,273,694	4,470
Replicates	38	38	22	22	20	20	20	20	43	43	11	11

Table 2.—Effects of different species and grade conditions of railroad ties on modulus of elasticity (MOE) and modulus of rupture (MOR).

Treatments		MOE (million psi)	MOR (psi)
Species			
	Oak/hickory	1,185,142^{a}	5,287
	Mixed wood	1,054,665^{b}	4,430
	SEM	52,005	271.6
Grades			
	New on	1,270,605^{a}	6,032
	New off	1,121,755^{b}	5,100
	Legacy	967,351^{c}	3,443
	SEM	60,474	328.5
Species by grades			
	New on	1,410,813	7,143^{a}
Oak/hickory	New off	1,176,656	5,220^{b}
	Legacy	967,958	3,499^{c}
	New on	1,130,397	4,922^{b}
Mixed wood	New off	1,066,853	4,980^{b}
	Legacy	966,744	3,388^{c}
	SEM	65,274	421.0
		P-value	
Species		**<0.0001**	<0.0001

Grades	**0.0132**	0.0019
Species by grades	0.0757	**0.0010**

[a–c] Treatment means within the same column within effect without common superscripts are significantly different ($P \leq 0.05$).

Table 3.—Relationship between nondestructive (acoustic velocity [AV]) and destructive (modulus of elasticity [MOE] and modulus of rupture [MOR]) evaluations of railroad ties.

P-value	AV free[a] vs. AV fixed[b]	AV free vs. MOE	AV free vs. MOR	AV fixed vs. MOE	AV MOR
Linear	<0.0001	<0.0001	<0.0001	<0.0001	0.0010
Quadratic (x^2)	<0.0001	<0.0001	<0.0001	<0.0001	<0.000
Cubic (x^3)	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.000**
R^2	0.67	0.34	0.21	0.19	0.11

[a] AV was measured after each tie was placed on the ballast.

[b] AV was measured after the ties were packed with ballast and with a static weight installed atop each tie.