Screw Withdrawal – A Means to Evaluate Densities of *In-situ* Wood Members

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Abstract

Dynamic modulus of elasticity (MOE) of a wood member is defined as the product of its density and square of stress wave speed. The dynamic MOE, which is highly correlated to the static MOE, is commonly used to estimate the load carrying capacity and serviceability of in-situ wood members. The stress wave speed can be estimated using ultrasonic, impact, or vibration techniques. However, nondestructive evaluation of density in place is more difficult than under laboratory conditions. Screw withdrawal resistance, one of the techniques that could be used to estimate the density, was examined on wood samples salvaged from old buildings. The results show that there is a good correlation relationship between screw withdrawal strength and the density. The result of screw withdrawal test on salvaged joists indicates that there is a good relationship between the static MOE and the dynamic MOE which is calculated based on the estimated density.

Introduction

Conservation ethics and material shortages are stimulating interest in reusing wood products from demolished buildings and even reusing entire buildings. The effects of use and age on the mechanical properties of full-size timber members are not well understood and, therefore, complicate reuse (Fridley et al. 1996). A variety of nondestructive evaluation (NDE) techniques have been used to assess, in-situ, wood members (Ross and Pellerin 1994; Ross et al. 1998). The most recent use of NDE for historic structures is the repair of the USS Constitution (Ross et al. 1998). Stress wave tests were performed on various wood members in the ship to locate areas of deterioration and estimate the stiffness. The stress wave speed traveling through wood members can be used to calculate their dynamic modulus of elasticity (MOE). Dynamic MOE of a wood member, defined as the product of its density and square of stress wave speed, is highly correlated to the static MOE (Ross and Pellerin 1994). Therefore, for many years measuring dynamic MOE has been one of most commonly used NDE tools to estimate the load carrying capacity and serviceability of in-situ wood members. Two parameters, namely stress wave speed and density, need be known in order to calculate the dynamic MOE. The stress wave speed can be estimated using ultrasonic, impact, or vibration techniques. However, measuring density of a wood member in-situ is more difficult than under laboratory conditions where the standard measurement of density can be performed.

It has been known that wood specific gravity is statistically correlated to screw withdrawal strength and screw diameter since 1926 (Fairchild). The empirical equations based on Fairchild's data collected from over 10,000 tests are still the basis for designvalues for wood screws and lag screws in the 1997 National Design® Specification for Wood Construction, NDS-97. McLain (1997) did an extensive literature search on relationship between screw withdrawal and specific gravity of wood members developed by different investigators. It was found that the relationship was affected by many factors including screw geometry, depth of penetration into wood, wood grain direction, moisture content (MC), species, rate of loading, etc. Chapter 7 in the Wood Handbook (Forest Products Laboratory 1999) presented empirical relationships between withdrawal resistance and specific gravity for all kinds of fasteners (nails, screws, bolts, etc.). For wood screws the ultimate withdrawal load from side grain of wood was:

$$p = 15{,}700\ G^2\ DL \qquad [1]$$

and for lag screws the ultimate withdrawal load from side grain of wood was:

$$p = 8{,}100 G^{3/2} D^{3/4} L \qquad [2]$$

where:

- p = maximum withdrawal load (lb.),
- G = the specific gravity of the wood based on ovendry weight and volume at 12% MC,
- D = the nominal screw diameter [in.), and
- L = the length (in.) of penetration of the threaded portion of screws.

Equations [1] and [2] indicate a nonlinear regression relationship between the maximum withdrawal load and the specific gravity of the wood.

McLain (1997) reexamined the regression Equations [1] and [2] using more advanced software that could test a wide variety of alternative regression models. He compared the percentage standard error of estimates (SEE) for all regression models and found that the multiplicative model provided the best estimations. For wood screws the ultimate withdrawal load from side grain of woodwas:

$$p = 9{,}048\ G^{1.77} D^{0.82} \qquad [3]$$

For lag screws the ultimate withdrawal load from side grain of wood was:

$$p = 6{,}760\ G^{1.35} D^{0.61} \qquad [4]$$

Comparing Equations [1] and [2] with Equations [3] and [4], it is noticed that the regression coefficients and exponents are different and length of penetration is not included in the newer expression.

This report is one of a series of reports coming from our research, "Nondestructive Structural Evaluation of Wood Floor Systems in Historic Buildings." This research is directed to answering technical questions that will help to make the ultimate economic decision about the fate of a building more objective. The objective of this paper is to report the results of the feasibility study of using screw withdrawal to evaluate density ofin-situ woodmembers.

Table 1. ~ The maximum screw withdrawal loads of Peirce Hall specimens.

	Length	Weight	Width	Thick-ness	SG	With-drawal load
	(mm)	(g)	---- (mm) ----			(kg)
Max	95.40	190.13	51.73	48.84	1.02	574
Min	88.42	81.30	42.41	33.78	0.48	260
Average	94.85	108.63	50.61	36.29	0.62	420
COV	2.01	25.13	4.45	9.34	20.70	18

Materials and Testing

Wood members from three different old buildings were tested in this research. They were all southern pine and were in service for about the same period of time. In order to investigate the relationship between screw withdrawal load and specific gravity, 25 small clear southern pine specimens were tested. The specimens were cut from samples salvaged from Peirce Hall on Purdue University campus which was built in 1904 and demolished in 1989. Their dimensions and specific gravity are shown in **Table 1.** The specific gravity was measured at the current moisture content which is about 7 percent. A #10 sheet metal screw (2.5 in. long) was installed in each specimen following a pilot hole (sizeof7/64). Aspacer[posi=tioningtool) wasused when the screw was turned into the lead hole, so the penetration of the screw thread for each specimen was about the same. The penetration was about 0.75 inch. Then the maximum withdrawal resistance of each screw was obtained on a universal testing machine under a constant loading rate. The maximum withdrawal loads are shown in **Table 1.**

Since the diameter and penetration of each screw were about the same, only a relationship between maximum screw withdrawal load and specific gravity was examined. Simple linear and nonlinear regression models were used. Specific gravity (G) was used as a response variable and the maximum screw withdrawal load (P) was used as a predictorvariable. The simple linear model was:

$$G = a + bP \qquad [5]$$

The nonlinear model was:

$$G = aP^b \qquad [6]$$

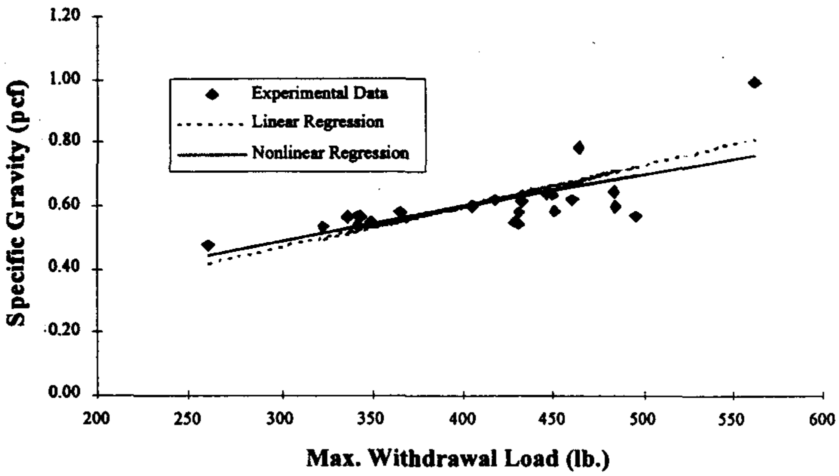

Figure 1. ~ *Regression results and experiment data.*

After regression coefficients *a* and *b* were obtained, Equations [5] and [6] were used to predict specific gravity for each specimen based on their corresponding withdrawal loads, respectively. The predicted specific gravity $(\hat{G})$ was compared with the actual specific gravity (G) in term of mean percentage deviation (*MPD*) and percentage standard error (*SEE*):

$$MPD = \frac{\sum \frac{\hat{G}-G}{G} \times 100}{n} \% \quad [7]$$

and

$$SEE = \sqrt{\frac{\sum \left(\frac{\hat{G}-G}{G} \times 100 \right)^2}{n-1}} \% \quad [8]$$

Table 2. ~ *Regression results of both Linear and nonlinear models.*

Regression method	Regression constant *a*	Regression constant *b*	*MPD* (%)	Range of *MPD*	*SEE* (%)
Linear	0.729	5.96×10^{-4}	1.2	27 to−19	12.1
Nonlinear	4.82×10^{-3}	0.711	0.63	23 to−24	11.3

The regression results are shown in **Figure 1** and **Table 2.** Based on the SEE values, the nonlinear model provides a slightly better fit to the data than the linear one. However, the SEE values of both models are less than 18.3 percent which was obtained for Equation [3] when McLain (1997) reexamined the regression models in the *Wood Handbook.* This indicates that the screw withdrawal resistance method to determine density is relatively reliable but easy to operate.

The screw withdrawal test was then performed on nine southern pine salvaged joists following the same procedure as described previously (same screw size, same penetration depth, and same size of pilot hole). The purpose was to simulate a real case: to apply the regression results obtained previously to similar materials and to examine how the model would be used in the field. The salvaged joists were approximately 2- by 16-in. by 20 ft. and came from a demolished warehouse (built shortly after 1900 and demolished in the early 1990s) in the St. Louis, Missouri area. The overall condition of the joists was what would be expected of approximately 90 year old joists, i.e., seasoning checks, split, and some localized decay. Instead of the universal test machine, a portable screw extraction force tester (Sensor Developments, Inc. Model 90 103) was used to measure the screw withdrawal resistance. Seven measurements were taken on each edge of a joist (top edge and bottom edge) at different positions. The distance between positions was about 3.3 ft. which was about equally divided over the length of the joist (20 ft.). A large variation of measuring the screw withdrawal loads was observed partially because of the existing decay. The nonlinear regression model obtained previously on the Pierce Hall samples was then used to predict the specific gravity for each joist based on the average screw withdrawal loads on each side. Table 3 shows the actual and predicted SG. Top-SG and Bot-SG represents predicted SG using the average screw withdrawal values performed on the top and bottom edges, respectively. **Figure 2** clearly shows that predicted specific gravities are all under-estimated because of the lower screw withdrawal resistance due to the appearance of decay. It was also noted that the top edge had more decay than the bottom edge did. This observation agreed with the test result that bottom edges had higher values of the screw withdrawal.

Since the ultimate goal of the mother project was to evaluate the stiffness of in-place joists, dynamic MOE (E_d) of the nine salvaged joists were then estimated us-

Table 3. ~ Actual and predicted SG of the salvaged joists.

SG	Joist ID 1	2	3	4	5	6	7	8	9	*MPD*	SEE
										-----(%)-----	
Actual SG	0.54	0.59	0.65	0.76	0.54	0.52	0.72	0.70	0.61		
Top-SG	0.26	0.55	0.42	0.46	0.31	0.41	0.55	0.43	0.32	34.00	39.00
Bot-SG	0.41	0.48	0.49	0.56	0.52	0.44	0.51	0.46	0.41	–24.00	27.00

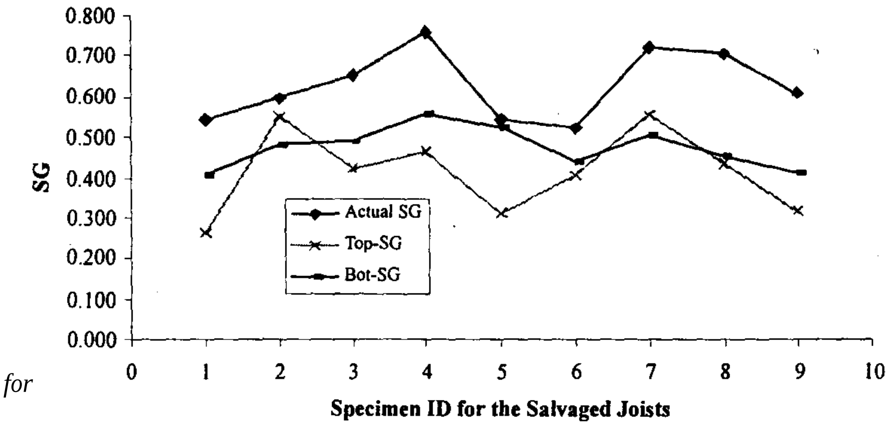

Figure 2. ~ *Actual and predicted SG for the nine salvaged joists.*

ing the following equation and correlated to their static MOE.

$$E_d = \rho v^2 \qquad 191$$

where:

ρ = density and

v = stress wave speed.

The densities were estimated from the previous screw withdrawal testing and stress wave speeds were determined using Metriguard Stress Wave Timer. The following exercise was performed to examine regressions between static MOE (E) and product of screw withdrawal load (p) and the square of stress wave speed. The regression equation is:

$$E = a + b\rho v^2 \qquad [10]$$

where a and b are regression coefficients. The results are shown in **Table 4** and **Figure 3.** It is observed that the predicted MOE based on the average screw withdrawal loads on the less-decayed bottom edges is highly correlated to the static MOE. The SEE is 11.2 percent.

Finally, screw withdrawal test was performed on the joists in the Forest Product Building on the Purdue University campus following the same procedure as described previously [same screw size, same penetration depth, and same size of pilot hole]. The Forest Product Building constructed in 1909 is the sixth oldest extant building on campus. It is a typical building built in that period which consists of load bearing masonry walls, southern pine timber floor, and roof support system. The portable screw extraction force tester was used to measure the screw withdrawal resistances. Six measurements were taken on the bottom edge of a joist (the top edge is inaccessible) at different positions. A total of sixteen joists in the existing building were tested and their SGs were estimated using the regression model developed on the Peirce Hall samples (**Table 5**). The estimated densities of the joists would provide valuable information to evaluate the structural integrity of the existing wood floor system. A relative small variation of measurements was observed partially because the joists were in a uniform condition.

Summary and Conclusion

Wood specimens from three different historical buildings were tested to investigate screw withdrawal as a mean to estimate specific gravities of in-situ wood members. Twenty-five southern pine specimens from the first building demolished in 1989 were tested to examine the relationship between screw withdrawal resistance and specific gravity. The result of less standard percentage error than McLain's indicated there is a high correlation between the screw withdrawal resistance and specific gravity. This coincided with results found in McLain's work (1997) and Wood Handbook. The regression model developed from the specimens in the first building was then applied to data for nine old joists salvaged from the second building. The model underestimated the specific gravities of the salvaged joists and

Table 4. ~ Actual and predicted MOE of the nine salvaged joists.

E	Joist ID 1	2	3	4	5	6	7	8	9	MPD	SEE
										-----(%)-----	
Static E (10^9 pa)	7.27	6.34	10.07	11.65	8.01	8.44	10.39	7.24	5.91		
v (10^3 m/s)	5.03	4.34	5.10	4.96	4.75	4.93	4.97	3.96	4.24		
Top-E	6.87	9.14	9.19	9.49	7.20	8.69	10.71	7.36	6.66	2.40	18.4
Bot-E	7.93	7.29	9.90	10.83	9.34	8.29	9.85	5.92	5.96	0.86	11.2

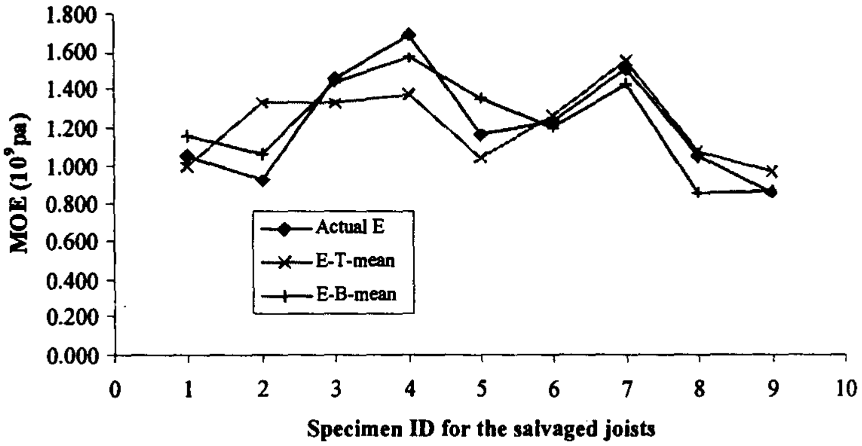

Figure 3. ~ *Actual and predicted MOE for the nine salvaged joists.*

Table 5. ~ *Estimated SG of joists in the Forest Product Building.*

	JoistID 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Estimated SG	0.52	0.56	0.60	0.54	0.57	0.58	0.58	0.60	0.61	0.55	0.68	0.56	0.53	0.56	0.62	0.49

resulted in larger standard percentage error due to appearance of decay. However, the predicted specific gravity along with stress wave time produced a good correlation with the static MOE. Finally, the model was performed on the sixteen joists in the third building which is still in service on Purdue University campus. The estimated densities of the joists would provide valuable information to evaluate the structural integrity of the existing wood floor system.

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