STATIC AND VIBRATION MODULI OF ELASTICITY OF SALVAGED AND NEW JOISTS

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ABSTRACT

Conservation ethics and material shortages are stimulating interest in reusing wood products from demolished buildings and reusing entire buildings. As one of an anticipated series of reports coming from our research project titled, "Nondestructive structural evaluation of wood floor systems in historic buildings," this paper reports the results of determining the modulus of elasticity (MOE) of wood joists via static and vibration methods in both edgewise and flatwise orientations. Fifteen new southern pine joists (2-by 16- in. by 30 ft.) and nine joists (2- by 16- in. by 20 ft.) salvaged from a 90-year old warehouse were examined. For the salvaged joists, a considerable difference was observed between the edgewise MOE and flatwise MOE for both vibration and static methods. Correlative relationships were found for both new and salvaged joists for vibration edgewise MOE versus stress wave MOE; static edgewise MOE versus stress wave MOE; static edgewise MOE versus vibration edgewise MOE; and for static edgewise MOE versus static flatwise MOE. These relationships may be useful in the ongoing research of structural evaluation of in-place floor systems.

Conservation ethics and material shortages are stimulating interest in reusing wood products from demolished buildings AND reusing entire buildings. In preservation circles, the latter is often referred to as adaptive reuse of an old/historic building. Success of both ventures depends on a combination of the solution of technical questions and favorable economics. The effects of use and age on the mechanical properties of full-size timber members are not well understood and, therefore, complicate reuse (4). A variety of nondestructive evaluation (NDE) techniques have been used to assess, *in-situ*, wood members (7,8,9). The most recent use of NDE for historic structures is the repair of the USS Constitution (8).

This paper is the first in an anticipated 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 make the ultimate economic decision about the fate of a building more objective. The long-range goal of the research is to develop the means to nondestructively evaluate the structural capacity of an in-place wood floor system, which includes the flooring above and the ceiling attached to the underside of the joists. Obviously, this is a complex structural system. Our plan is to assemble floor sections in the laboratory similar in construction to the in-place floor. This will enable us to control and modify the boundary conditions and relate such to the vibration behavior of the floor section. In this way, we intend to develop basic knowledge that can be scaled-up to test the actual in-place floor system. The laboratory-built floor sections that mimic the actual in-place floor will be built of specially acquired floor joists. Three floor sections will be built using "new" joists and one built of salvaged joists.

The first phase of this ongoing research is the evaluation of modulus of elasticity (MOE) of individual floor joists. Thus, the objective of this paper is to report the results of determining the MOE of wood joists via static and vibra-

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tion methods in both edgewise and flatwise orientations.

MATERIALS

The floor system that is the "test specimen" of our research is the second floor of the Forest Products Building on the Purdue University campus. The building was constructed in 1909. The floor consists of 2- by 16-inch southern pine joists 12-in o.c. with spans of 27 feet and 30 feet.

Fifteen special order southern pine joists were produced at a Louisiana sawmill in December 1997. The joists were cut from loblolly pine (*Pinus taeda* L.) trees that were grown on high ground in the swamps near Angie, La. The joists' green dimensions were 2 by 16 inches by 30 feet. Although not graded, the joists were of high quality, with few knots, no wane, and little slope of grain. The dimensions and quality were selected to be as similar as possible to the joists in the in-place floor system. Upon receipt, the green joists were weighed and measured and their moduli of elasticity was determined using a variety of static and vibration methods, then they were stickered and stacked under restraint in the laboratory to equilibrate to the ambient moisture condition. After equilibrating, the joists were again tested using the same procedures as when green.

Nine southern pine joists (approx. 2 by 16 in. by about 20 ft.) were salvaged from a demolished warehouse near St. Louis, MO. (5). The specific southern pine species and origin of the joists were unknown. The warehouse was built shortly after 1900. The structure was referred to as a shipping warehouse. No machinery was supported by the floor. The salvaged joists came from a lower level of this six-story-high structure. The joists were spaced 16-inch o.c. and spanned about 20 feet. One end of the joist was built in a masonry pocket and the other end lapped with another joist over a support. An examination upon receipt indicated that the overall condition was what would be expected of approximately 90-year-old joists. Seasoning checks and splits were present. There was deteriorated material on the top edge of some joists where the 2-1/2-inch subfloor had been nailed. Apparently, water trapped between the joist and the subfloor contributed to this condition. Ultrasonic measurements through the thickness of the salvaged joists showed that no decay extended into the cross section beyond that which was visible and recorded.

Upon receipt, the salvaged joists were weighed and the dimensions were measured. The joists were stickered and stacked and allowed to equilibrate to the ambient conditions of the laboratory. The MOEs of the salvaged joists were determined using the same procedures as those used for the new joists.

TEST METHODS

STRESS WAVE MOE

A schematic of measuring longitudinal stress wave time is shown in **Figure 1.** As a result of an impact on the end of a wood joist, a stress wave is generated that immediately begins moving down the joist at a constant speed. Two accelerometers (Columbia model 3021) that are placed at a distance apart (L) will sense the impact pulse and send the signals to an oscilloscope (Nicolet 310). The time between the two pulses (sensed by the two accelerometers) on the scope is the time (t) during which the stress wave travels through the distance between the two accelerometers. Therefore, the stress wave speed (C) is L/t. The longitudinal stress wave MOE (SWE) can then be calculated (8) using the speed and the mass density of the wood joist (ρ):

$$SWE = C^2 \rho \quad [1]$$

STATIC EDGEWISE MOE

The static edgewise MOE (SEE) is measured with the wood joist simply supported. The support span is determined based on the specimen's size. The span was 28 feet for the new joists and 18 feet for the salvaged joists. A concentrated load was applied at the center of the span, and the loading rate was determined manually. The new joists were immediately tested when they arrived in a green condition. The load was applied by a hoist and measured by a load gage, and the deflection was measured by a dial gage. A person was responsible for keeping the joist in place (applying lateral restraint). Each joist was loaded three times and the average load/deflection slope was used to calculate the edgewise MOE. In order to improve the accuracy of collecting data, the testing method was different for the new joists (after they were air-dried) and salvaged joists. The load was applied via a hydraulic cylinder and force measured by a load cell. The deflection was measured with a linear variable differential transformer (LVDT). A computerized data-acquisition unit was used to collect load/deflection data. The specimen was tested horizontally as it lay flatwise on rollers. The weight of the joist and the

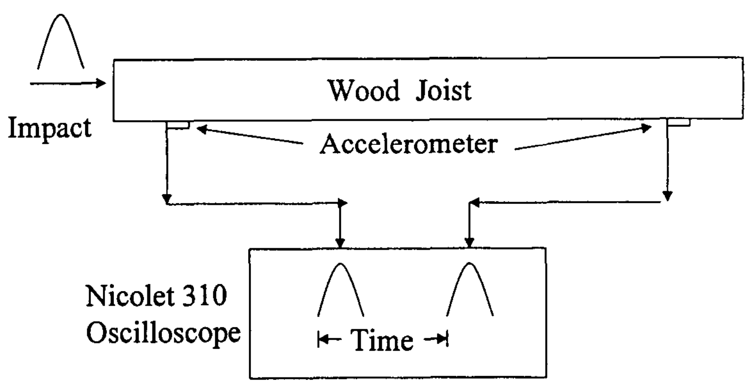

Figure 1. – Experimental set-up for measuring stress wave time.

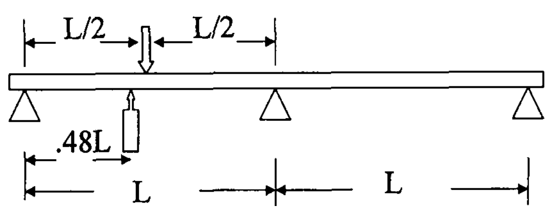

Figure 2. – Continuous beam over two equal spans.

low range of load prevented out-of-plane buckling.

STATIC FLATWISE MOE

The new joists were 30 feet long. When positioned flatwise on simple supports 28 feet apart the midspan deflection due to the weight of the joist was excessive. Therefore, to determine the static flatwise MOE (SFE) of a new joist, it was supported as a continuous beam over two equal spans (Fig. 2). Each span was 14 feet long. Left-side flatwise (LF) MOE was measured by applying concentrated load at the center of the left-side span. The load was applied manually with load increments of 25 pounds to a maximum load of 75 pounds. A dial gage was used to measure maximum deflection at 0.48L from an end support **(Fig. 2).** The flatwise MOE was then calclulated by the following equation (1):

$$MOE = 0.015\,\frac{PL^3}{I\Delta} \qquad [2]$$

where:

MOE = static flatwise MOE (psi)
P = load at the center of the span (lb.f)
L = span (in.) between two adjacent supports
I = moment of inertia of the joist (in.4)
Δ = maximum deflection (in.) at 0.48L from an end support

Similarly, right-side flatwise (RF) MOE was measured by applying concentrated load at the center of the right-side span. The average of the two was used to determine the static flatwise MOE for the joist.

However, for the salvaged joist (which was obtained air-dried), the static flatwise MOE was measured when it was simply supported over a span of 18 feet. A concentrated load was applied at the midspan with load increments of 25 pounds to a maximum load of 75 pounds.

VIBRATION FLATWISE MOE

Transverse flatwise vibration was stimulated by impacting the joist at the midspan while the joist was simply supported flatwise **(Fig. 3).** A LVDT (Lucas/Schaevitz GCD- 121-500) was used to measure the vibration and the signal was shown on the oscilloscope (Nicolet 310). The frequency of the vibration could be obtained from the signal. The vibration flatwise MOE (VFE) was then calculated by the following equation (8):

$$MOE = \frac{f^2 \rho L^3 V}{2.46 Ig} \qquad [3]$$

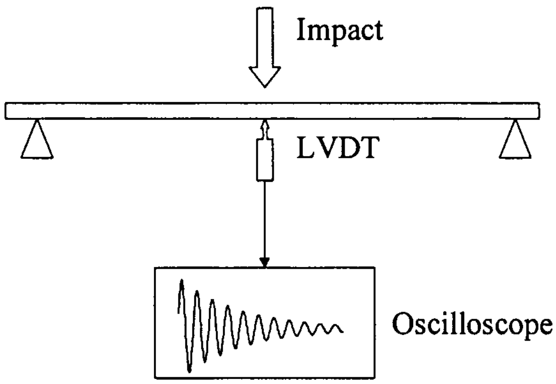

Figure 3. – Schematic of measuring transverse vibration.

TABLE 1. – Properties of new joists when green.

ID	MC	Length	Width	Thickness	Density[a]	SFE[b]	SEE[b]	VFE[b]	VEE[b]	SWE[b]
	(%)		(in.)[c]		(pcf)[c]			(10^6psi)[c]		
NJ01	30.2	362.0	15.9	1.860	40.6	1.35	1.39	1.55	n/a	1.95
NJ02	57.7	365.0	16.0	1.984	46.8	1.59	1.55	1.71	n/a	1.95
NJ03	78.5	366.5	16.0	2.043	55.5	2.13	1.80	2.20	n/a	2.60
NJ04	97.0	365.0	16.0	1.902	62.7	2.24	1.79	2.49	n/a	2.52
NJ05	49.9	363.3	15.9	1.846	47.7	1.91	1.68	1.96	n/a	2.04
NJ06	51.8	365.5	15.9	1.887	48.7	2.24	1.69	1.85	n/a	2.30
NJ07	45.3	362.6	15.9	1.925	48.2	1.90	1.56	1.93	n/a	2.14
NJ08	51.9	364.5	16.0	2.086	44.5	1.52	1.62	1.84	n/a	2.03
NJ09	80.4	366.0	16.0	2.061	53.7	1.55	1.57	1.65	n/a	1.93
NJ10	34.3	361.5	15.9	1.957	43.7	1.78	1.42	1.84	n/a	1.68
NJ11	40.4	361.5	15.9	1.928	48.2	1.92	1.47	2.27	n/a	1.89
NJ12	51.9	361.5	15.9	1.976	48.3	1.66	1.14	1.47	n/a	1.86
NJ13	35.5	361.5	16.0	2.002	39.5	1.26	1.32	1.44	n/a	1.50
NJ14	76.6	371.5	15.9	2.011	50.4	1.41	1.28	1.27	n/a	2.00
NJ15	63.4	363.5	16.0	1.905	48.7	2.03	1.79	2.14	n/a	2.14
MIN	30.2	361.5	15.9	1.846	39.5	1.26	1.14	1.27		1.50
MAX	97.0	371.5	16.0	2.086	62.7	2.24	1.80	2.49		2.60
Mean	56.3	364.1	16.0	1.958	48.5	1.77	1.54	1.84		2.04
COV	34.4	0.7	0.2	3.7	11.9	18.0	13.0	18.4		14.0

[a] Weight and volume at indicated moisture content.
[b] SFE = static flatwise MOE; SEE = static edgewise MOE; VFE = vibration flatwise MOE; VEE = vibration edgewise MOE; SWE = stress wave MOE.
[c] 1 inch = 0.0254 m; 1 pcf = 16.03 kg/m^3; psi = 6894.78 pa.

TABLE 2. — Properties for new joists when air-dried.

ID	MC	Length	Width	Thickness	Density[a]	SFE[b]	SEE[b]	VFE[b]	VEE[b]	SWE[b]
	(%)		(in.)[c]		(pcf)[c]			(10^6psi)[c]		
NJ01	10.0	362.0	15.3	1.699	39.1	1.94	2.19	2.13	2.36	3.39
NJ02	10.5	365.0	15.5	1.894	35.6	1.95	2.36	2.00	2.25	2.19
NJ03	9.9	366.0	15.3	1.942	37.8	2.23	2.56	2.54	2.05	2.70
NJ04	10.0	365.0	15.2	1.807	38.8	2.61	2.68	3.16	2.84	2.91
NJ05	10.3	363.0	15.5	1.758	37.9	2.21	2.36	2.47	2.08	2.45
NJ06	10.2	365.5	15.3	1.780	39.0	2.54	2.59	2.55	2.37	2.74
NJ07	10.2	362.5	15.2	1.826	40.4	2.42	2.47	2.61	3.00	2.92
NJ08	10.1	364.0	15.3	1.997	35.2	1.71	2.37	2.13	1.86	2.43
NJ09	10.6	366.0	15.4	1.970	35.7	2.00	2.28	2.19	1.83	2.30
NJ10	10.3	361.5	15.5	1.886	38.3	1.85	2.15	2.14	1.74	2.01
NJ11	10.0	361.5	15.4	1.875	40.3	2.21	2.20	2.40	1.98	2.28
NJ12	9.9	360.5	15.4	1.907	37.6	1.83	1.88	2.14	1.51	2.22
NJ13	9.9	361.0	15.5	1.915	34.7	1.43	1.99	1.49	1.71	1.79
NJ14	10.5	371.0	15.3	1.923	34.5	1.66	1.78	1.93	1.62	2.12
NJ15	10.0	363.5	15.3	1.818	36.0	2.05	2.54	2.57	1.89	2.57
MIN	9.9	360.5	15.2	1.699	34.5	1.43	1.78	1.49	1.51	1.79
MAX	10.6	371.0	15.5	1.997	40.4	2.61	2.68	3.16	3.00	3.39
Mean	10.2	363.9	15.3	1.866	37.4	2.04	2.29	2.30	2.07	2.47
COV	2.3	0.7	0.7	4.5	5.3	16.2	11.5	16.8	20.7	16.7

[a] Weight and volume at indicated moisture content.
[b] SFE = static flatwise MOE; SEE = static edgewise MOE; VFE = vibration flatwise MOE; VEE = vibration edgewise MOE; SWE = stress wave MOE,
[c] 1 inch = 0.0254 m; 1 pcf = 16.03 kg/m^3; psi = 6894.78 pa.

TABLE 3. — Properties for salvaged joists.

ID	MC	Length	Width	Thickness	Density[a]	SFE[b]	SEE[b]	VFE[b]	VEE[b]	SWE[b]
	(%)		(in.)[c]		(pcf)[c]			(10^6psi)[c]		
OJ01	10.0	240.0	15.1	1.759	33.9	1.55	1.05	1.69	1.34	1.99
OJ02	9.7	254.0	15.5	1.895	37.1	1.48	0.92	1.42	0.98	1.62
0J03		242.0	15.5	1.864	40.8	2.35	1.46	2.07	1.60	2.46
OJ04		240.0	15.8	2.025	47.3	2.81	1.69	2.82	1.50	2.71
OJ05		273.5	15.0	2.313	33.7	1.23	1.16	1.21	1.14	1.77
OJ06		277.5	15.6	1.837	32.6	1.61	1.22	1.50	1.16	1.84
OJ07		272.0	15.7	1.926	45.2	2.27	1.51	2.12	1.40	2.60
OJ08		273.0	15.8	1.913	44.0	1.29	1.05	1.25	1.09	1.61
OJ09	9.4	252.0	15.3	1.774	37.9	1.18	0.86	1.18	1.00	1.58
MIN	9.4	240.0	15.0	1.759	32.6	1.18	0.86	1.18	0.98	1.58
MAX	10.0	277.5	15.8	2.313	47.3	2.81	1.69	2.82	1.60	2.71
Mean	9.7	258.2	15.5	1.923	39.1	1.75	1.21	1.70	1.25	2.02
COV	3.2	6.1	1.9	8.7	13.8	33.1	23.4	32.4	17.8	22.3

[a] Weight and volume at indicated moisture content.
[b] SFE = static flatwise MOE; SEE = static edgewise MOE; VFE = vibration flatwise MOE; VEE = vibration edgewise MOE; SWE = stress wave MOE,
[c] 1 inch = 0.0254 m; 1 pcf = 16.03 kg/m^3; psi = 6894.78 pa.

where:

MOE = dynamic MOE (psi)
f = natural frequency (Hz)
ρ = the mass density (lb./in.^{3})
L = joist span (in.)
V = volume of joist
I = moment of inertia (in.^{4})
g = acceleration due to gravity (386 in./sec^2).

VIBRATION EDGEWISE MOE

Transverse vibration edgewise MOE (VEE) was measured similarly to the vibration flatwise MOE except the joist was simply supported edgewise. Since the frequency of edgewise vibration was higher than the frequency of flatwise vibration, the higher energy of impact was needed in order to obtain a high quality vibration curve on the scope.

RESULTS AND DISCUSSION

Fifteen new joists and nine salvaged joists were tested. **Table 1** shows the properties of the new joists when green. **Table 2** presents the properties of the new joists when air-dried. **Table 3** shows the properties of the salvaged joists. After air-drying, a small specimen moisture content (MC) sample was cut at least 2 inches from an end of each new joist. This small specimen was ovendried to obtain the MC representative of the joist. The MC (air-dried) and the joist weight (when green) were used to determine the MC of the joist when green. Three small specimens (one from each of three different salvaged joists) were used to determine the average MC of all salvaged joists. Only three of the salvaged joists were sampled because they had sufficient length beyond that needed for subsequent full span testing; the others were too short.

The specific gravity of the new joists was about 6 percent greater than that reported by the *Wood Handbook* (3). The corresponding static MOE for the new material was about 10 percent greater in the green condition and 28 percent greater in the air-dried state than the comparable *Handbook* values.

The average MC of the new joists decreased about 46 percent from the green as-delivered state to the air-dried condition. Corresponding to the decrease in MC was an expected associated increase in MOEs. Average SFE, VFE, and SWE increased from about 15 to 25 percent. Average SEE increased about 49 percent; however, some of this difference may be due to test procedure differences. It has been noted earlier that different test techniques were used in evaluating this property in the green and air-dried conditions.

Radial shrinkage was somewhat higher and tangential shrinkage somewhat lower than expected for the new joists. Radial shrinkage and tangential shrinkage from green to the average air-dry MC of 10.2 percent were 3.9 and 4.3 percent, respectively. The corresponding values for loblolly pine based on *Wood Handbook* calculations were 3.2 and 4.9 percent.

The specific gravity of the salvaged joists was about 12 percent greater than reported in the *Wood Handbook,* assuming the species to be loblolly. However, the SEE was 32 percent less than the *Wood Handbook* value. It should be noted that the general appearance of the salvaged joists was good, considering the presence of expected seasoning cracks and splits. There was no apparent visual indication that the stiffness of this high-density material would be so unexpectedly low.

In **Figures 4, 5,** and **6,** the static and vibration MOEs are plotted against the

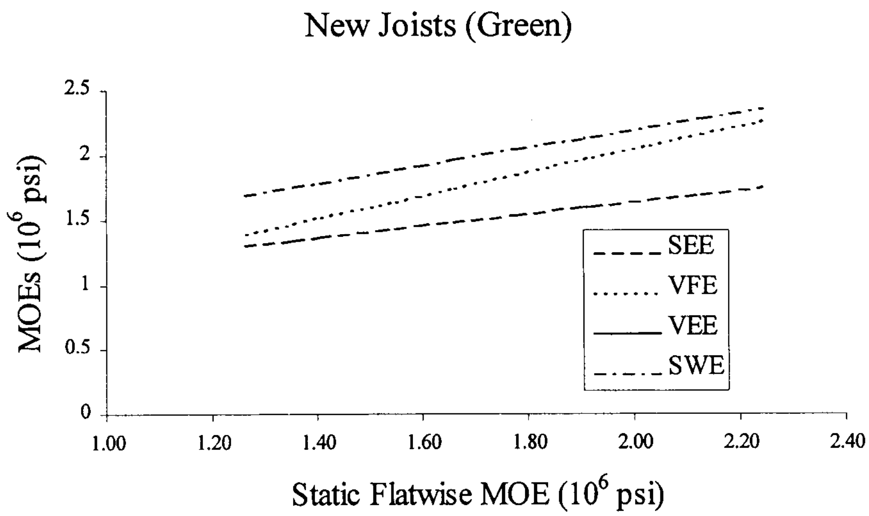

Figure 4. – Regression relationships between MOEs for new joists when green.

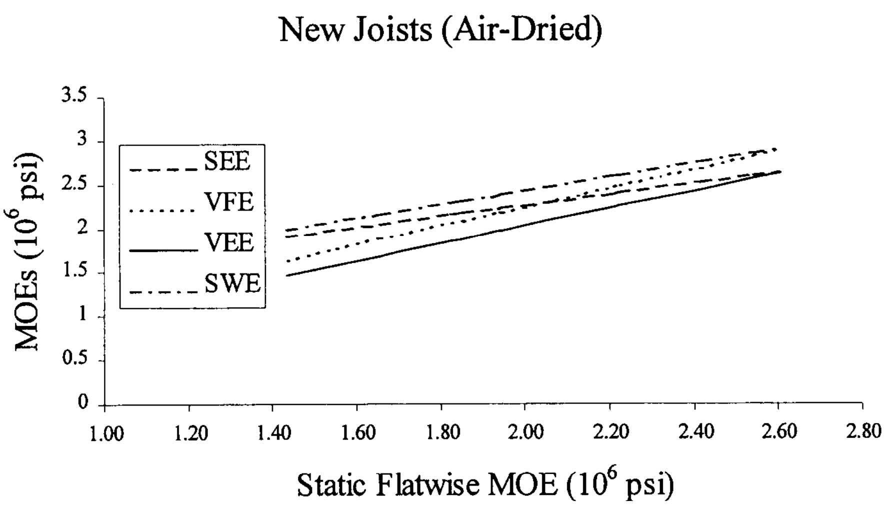

Figure 5. – Regression relationships between MOEs for new joists when air-dried.

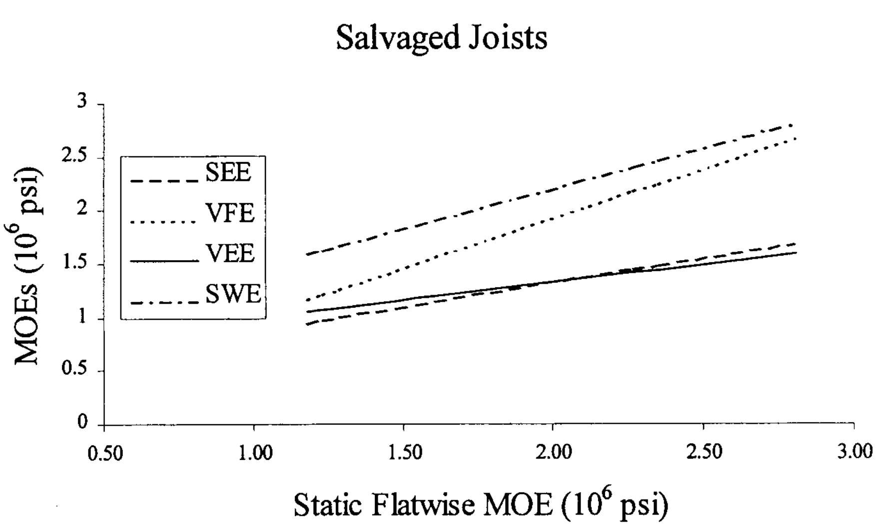

Figure 6. – Regression relationships between MOEs for salvaged joists.

TABLE 4. — Regression coefficients among MOEs regressed against SFE.

	New joists (green)			New joists (air-dried)			Salvaged joists		
	Slope	Intercept	r[a]	Slope	Intercept	r[a]	Slope	Intercept	r[a]
SEE	0.455	0.734	0.722	0.621	1.026	0.777	0.454	0.419	0.928
VFE	0.883	0.281	0.827	1.058	0.134	0.911	0.927	0.070	0.981
VEE				0.992	0.046	0.768	0.330	0.667	0.864
SWE	0.672	0.848	0.749	0.784	0.867	0.629	0.744	0.716	0.959

[a] r = correlation coefficient.

TABLE 5. — Regression coefficients for edgewise MOEs.

	New joists (air-dried)			Salvaged joists		
Regression[a]	Slope	Intercept	r[b]	Slope	Intercept	r[b]
VEE-SWE	0.751	0.220	0.724	0.453	0.329	0.922
SEE-SWE	0.366	1.390	0.571	0.594	0.014	0.943
SEE-VEE	0.428	1.407	0.692	1.102	-0.158	0.861

[a] First variable used as dependent and second used as independent.
[b] r = correlation coefficient.

SFE for the new joists (green), new joists (air-dried), and salvaged joists, respectively. The regression curves for the various MOEs are plotted in the figures using the regression coefficients given in **Table 4.** It is observed that in all cases strong correlations exist between the MOEs and SFE. This observation is consistent with what other investigators have found (6,7,8). However, a dramatic difference is noted between the graphs of the behaviors of the new and salvaged joists. For the new joists in both the green **(Fig. 4)** and air-dried **(Fig. 5)** condition, the graphs of the static and dynamic MOEs versus SFE indicate a combined or grouped behavior over their full range of values. In contrast, the corresponding plot **(Fig. 6)** of salvaged joists data indicates two separate groupings: edgewise performance (SEE and VEE) and flatwise performance (VFE and SWE). Clearly, flatwise MOEs are higher than edgewise MOEs.

Recently, the machine stress lumber (MSR) industry received American Lumber Standards Committee permission (2) to increase the flatwise MOE relative to the edgewise MOE of MSR lumber. The increase for flatwise MOE ranges from 50,000 psi to 100,000 psi depending upon the assigned edgewise MOE.

In our study of the new joists, there was a mixed response. When tested green, the average horizontal MOE was greater than the average edgewise MOE. However, in the air-dried state, the condition was reversed: edgewise MOE was greater than flatwise MOE. For the salvaged joists, the average flatwise MOE exceeded the average edge MOE by over 500,000 psi, a much greater margin than that observed by the MSR industry.

A detailed examination of the salvaged joists will be done in an attempt to explain their unexpectedly low edgewise resistance. One possible explanation that will be examined is that the cross-sectional properties of the joists deteriorated more than has been accounted for to date. For example, the longitudinal stress wave modulus for the salvaged joists, which is relatively high (2.02×10^6 psi) does not include the section modulus or moment of inertia in its calculation. Similarly, flatwise MOEs are unaffected by splits through the thickness of the joist. However, both SEE and VEE are dependent upon the split-affected moment of inertia of the section in a joist orientation. In the extreme case when a split completely through the thickness is located at the neutral axis, the moment of inertia is but one-fourth of a solid section. We will examine the salvaged joists to determine if the aggregate of smaller splits that do not extend completely through the thickness of the joist may effect a lesser decrease in the joist's moment of inertia, and hence its edgewise MOE.

Table 5 presents regression relations for a combination of edgewise and stress wave MOEs. It is noted again that these analyses are based on small samples: 15 new joists and 9 salvaged joists. If these favorable results are substantiated by more extensive testing, these relations could be very beneficial in our in-place floor evaluation research.

CONCLUSIONS

Correlative relationships were found for VEE versus SWE, SEE versus SWE, and SEE versus VEE for both new and salvaged joists. These relationships may be useful in the ongoing research of structural evaluation of in-place floor systems.

For the salvaged joists, a significant difference was observed between the SWE and both the SEE and VEE. The SWE was over 60 percent greater than either edgewise MOE.

Also for the salvaged joists, the SEE and VEE were at least 30 percent less than their horizontal counterparts. This is especially noteworthy as floor joists are loaded in the edgewise configuration. Ongoing research will try to explain this difference.

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