Assessment of In-Place Wood Floor Systems

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Abstract: Structural assessment of in-place wood floors is currently limited to inspection of individual members. This is costly and laborious. Consequently, the continued use or adaptive reuse of old/historic buildings is often in jeopardy because of the lack of an efficient and economical assessment method. A systems approach of assessment is the subject of this research. Floors in four old buildings and several laboratory-built floors were tested. The floor's bending stiffness was determined by static bending tests and its fundamental natural frequency was determined by transverse forced vibration. A model for one way beam action with simple support is the best predictor of floor responses. A technique for using this research to predict stiffness of existing floors is suggested.

DOI: 10.1061/(ASCE)1076-0431(2007)13:1(30)

CE Database subject headings: Nondestructive tests; Assessment; Floors; Wood; Vibration; Natural frequency; Stiffness.

Introduction

Often continued use or adaptive reuse of old/historic buildings is perceived to be unsafe and financially risky. These perceptions are frequently based on the lack of an efficient method of inspection and assessment. Inspection and evaluation of existing timber structures have historically been limited to evaluating each structural member individually, which is a time-consuming process. Sometimes individual members are not accessible and therefore difficult, even impossible, to visually inspect. When accessible, the inspector taps the member with a hard object and pricks the member to estimate the presence of and extent of deterioration of the member. Our goal was to more efficiently inspect timber structures by evaluating component systems, including complete in-place floors, rather than individual members.

Floors of interest are typically in buildings constructed in the mid-1800s through the early 20th Century. Floor construction consists of solid sawn, comparatively deep timber joists [from 51 by 305 to 51 by 406 mm (from 2 by 12 to 2 by 16 in.)] spaced 305–406 mm (12–16 in.) on center and laterally braced by lumber cross bridging and 25.4–31.8 mm (1–1.25 in.) lumber floor decking nailed to the top of the joists perpendicularly to the span direction of the joists (Fig. 1). This type of floor construction has primary strength and stiffness in the direction of the joist span. Subsequently, this type of floor construction will be referred to as a one-way action floor.

Our multiyear research project has the overall objective to use transverse floor vibration to nondestructively assess the performance of in-place wood floor systems. A series of integrated research studies have been conducted to satisfy our objective.

The first study evaluated the elastic properties of new and salvaged large [51 by 381 mm (2 by 15 in.)] individual floor joists (Cai et al. 2000). Next, floor systems of five joists and attached flooring were fabricated in the laboratory with these new and salvaged joists. Impact load initially displaced the structure and the system's damped free vibration characteristics were monitored. It was concluded that as the number of degraded (lower elasticity) joists in the floor system increased, the free vibration fundamental frequency decreased. But due to a system effect the location of degraded joists within the system could not be detected (Cai et al. 2002). Then using these same floor systems/sections (Cai et al. 2002), it was determined that (1) the transverse response of a floor system using a rotating mass forcing function was comparable to system response using free vibration; however, forced vibration provided more consistent results but eliminated the possibility to obtain damping data; (2) severe degradation of joists (produced by successively cutting three of the five joists in the floor section) produced a decrease in natural frequency, but indicated it may be difficult to detect degrade in only one or two joists; and (3) that the mass of superimposed loads should be included in frequency prediction calculations, but the location of loads has only a small effect on natural frequency (Soltis et al. 2002).

The accumulated observations of previous tests (Soltis et al. 2002) indicated that the stiffness (EI) and damped fundamental natural frequency of the floor sections were related. It was subsequently hypothesized (Ross et al. 2002) that the strongly one-way action floor systems typical of the older/historic buildings of interest could be modeled as a beam under forced transverse vibration with viscous damping. A similar finding (Wang et al. 2005a) for bridges indicated bridge decks with longitudinal stringers were modeled better using beam theory rather than plate theory.

Up to this point, the floor systems tested had a narrow range of joist depths [from 51 by 305 to 51 by 406 mm (from 2 by 12 to 2 by 16 in.)] and spans [5.6–5.9 m (220–232 in.)]. To further test

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Note. Discussion open until August 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on April 26, 2005; approved on November 29, 2005. This paper is part of the ***Journal of Architectural Engineering***, Vol. 13, No. 1, March 1, 2007. ©ASCE, ISSN 1076-0431/2007/1-30–35/$25.00.

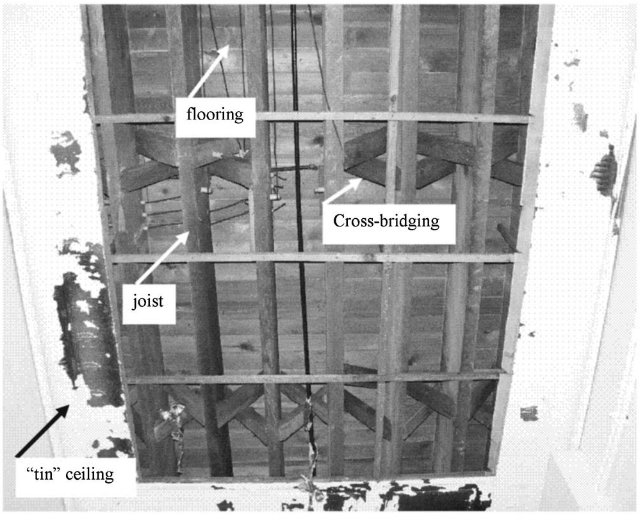

Fig. 1. Late 1800s to early 1900s in-place wood floors of interest in this research

the appropriateness of the transversely vibrated beam model, a series of lab-built floor sections were built using smaller dimension lumber joists [51 by 102, 51 by 152, and 51 by 254 mm (2 by 4, 2 by 6, and 2 by 10 in.)] and shorter spans [2.3, 2.9, and 3.5 m (90, 114, and 138 in.)] to extend the range of damped natural frequency and stiffness responses. Results supported the use of the model in correlating the damped natural frequency and EI of the lab floor sections (Wang et al. 2005a).

No literature was found related to boundary conditions. The studies referred to above tried to achieve a fixed boundary condition but deformations associated with compression perpendicular to grain precluded a fixed boundary condition. Wang et al. (2005b) also found for bridge decks that the simply supported model better predicted experimental results than the fixed end model.

The objectives of the study reported here are:

1. To present the details of transverse static and vibration testing of actual, in-place floor systems in four buildings that varied in age from a little less to a little more than 100 years as well as testing of laboratory-built floors.
2. To explore the boundary condition effects using floor sections that had been tested as a part of an in-place floor and then cut from the floor and retested as isolated systems.
3. To observe the appropriateness of modeling these floors as transversely loaded and vibrated beams and to compare the model to the experimental results.
4. Finally, to suggest an implementation technique for using our research results to assess structural quality of in-place, one-way action type, wood floor systems.

Transverse Vibration

The fundamental natural frequency of a beam is related to its stiffness. For distributed mass systems such as individual joists, this relationship is shown in the following equation (Pellerin and Ross 2002):

$$f^2 = 2.46\frac{\mathrm{EI}g}{WL^3} \tag{1}$$

where f=fundamental natural frequency (Hz); W=uniformly distributed beam weight [N (lbf)]; L=beam span [m (in.)]; g=acceleration due to gravity [9.8 m/s^2 (386 in./s^2)]; EI=stiffness (modulus of elasticity $E\times$ moment of inertia I) [N m^2 (lbF in.^{2})]. Note that Eq. (1) represents the relationship for a simply supported idealized beam. Based on accumulated experimental experience and considering that the in-place floors were one-way action type systems, it was hypothesized that the in-place floors in this study could be modeled as a simply supported, continuous system under transverse vibration (either free or forced) with viscous damping. In other words, Eq. (1) is appropriate for describing the vibration performance of the in-place floors in this study. This agrees with the conclusions of Wang et al. (2005b) for bridge decks with longitudinal stringers.

Experimental Procedure

Test Materials

Floor systems in four buildings of similar construction and age were subjected to transverse vibration and static load. The general construction type common to all buildings is referred to as masonry load bearing walls with floors of timber joists and decking. Details of the floor system in each of the four buildings are given separately.

Railroad Building

This industrial style brick building was constructed in 1900 in downtown Lafayette, Ind. Among other uses it had been a rail freight storage facility. It had two full stories and a partial third story. Testing was done on three bays of the second floor and four bays of the third floor. The three bays on the second floor were directly beneath three of the tested bays on the third floor. Bays were approximately 4 by 5.6 m (157 by 220 in.) in area. Distinguishing characteristics for floor constructions on the two levels follows.

1. Third floor: Each bay consisted of nine 51 by 292 mm (2 by 11.5 in.) deep joists spaced 406 mm (16 in.) on center and with span of 5.8 m (228 in.). One end of the joists was supported on a wood ledger strip anchored to the outside brick wall and the other end was supported by a nail laminated girder. The girder was supported by timber columns spaced 4 m apart. The end of the joist supported on the girder was lapped and nailed to the end of a joist from an adjacent bay that was also supported by the common girder. Southern pine flooring [22 by 133 mm (7/8 by 3 in.)] was nailed to the top edge of each joist and perpendicular to the joist span direction.
2. Second floor: Each bay consisted of ten 51 by 356 mm deep joists 356 mm on center and span of 5.7 m. One end of the joist was encased in a pocket in the outside brick wall and the other end was supported on a nail laminated girder. The girder was supported by heavy timber columns spaced 4 m on center. The joist end bearing on the girder was overlapped and nailed to the end of a joist from an adjacent bay that was also supported by the common girder. Hard maple flooring (22 by 82 mm) was nailed to the top edge of each joist and perpendicular to the joist span direction.

The floors on both levels had two lines of cross bracing across the width of the floors at the third points of the floor span. All joists, girders, cross bracing, and columns were southern pine. Visual observation indicated the joists to be a high quality grade as few knots were observed.

The railroad building was a victim of demolition by neglect and was scheduled for demolition when floor assessment was initiated. The situation provided a unique opportunity in that the roof over three adjacent bays varied in weather tightness from complete to partial to none. Consequently, the floors on the levels below varied similarly from dry and sound to partially rotted floor decking and wet joists to extensive wet and rotten flooring and joists. Thus there were three identical and adjacent floor systems subjected to three different aging conditions; three bays each on the second and third floors.

Forest Products Building

In 1909 a two story building was constructed on the Purdue University, West Lafayette, Ind., campus to initially house the Agricultural Engineering Department. Later it was renamed the Forest Products Building. The floor assessed in this study consisted of ten 51 by 399 mm (2 by 15.7 in.) joists 330 mm (13 in.) on center and span of 8.7 m (342 in.). Both ends of the joists were encased in pockets in brick walls. There were three lines of 51 by 102 mm (2 by 4 in.) cross bridging between joists that extended across the width of the floor at quarter points of the joist span. The joists and cross bracing were high grade southern pine. The structural decking was two layered. Nailed to the top of the joists and perpendicular to the span were 21 mm (13/16 in.) southern pine boards. Then 19 by 38 mm (3/4 by 1.5 in.) strips were nailed perpendicularly to the flooring and on 406 mm (16 in.) centers. A 22 mm (7/8 in.) layer of hard maple flooring was nailed to these strips and was oriented perpendicular to the joist span. The structural floor decking was covered with 3 mm (1/8 in.) thick vinyl floor tile which in turn was covered with the current wear surface of carpeting.

Agricultural Hall

Built in 1901, the building underwent major updating and renovation including a large addition in 2001. In preparation for the addition, the original south wing was removed. Prior to its demolition the research team tested the wood floor system that originally was the floor of the Assembly Hall. Two large bays of the second floor were tested. One bay, hereinafter referred to as Bay A, had eight 51 by 399 mm (2 by 15.7 in.) joists 305 mm (12 in.) on center and span of 6.3 m (248 in.). In the second and larger bay, referred to hereinafter as Bay DE, there were 13 joists of the same size, span, and spacing. There were four lines of 51 by 102 mm (2 by 4 in.) cross bracing between joists that extended across the width of the floor. The locations of the lines of cross bracing relative to the south end of the 6.3 m (248 in.) span were 1.3, 2.5, 4.7, and 6.0 m (51, 98, 185, and 236 in.). The joists and cross bracing were of high grade southern pine. The floor decking was oriented perpendicularly to the joist span and its overall construction was similar to the previously described Forest Products Building floor, but with the following differences. The top wear surface of the two layered floor decking system was 22 mm (7/8 in.) southern pine tongue and groove boards. Similarities in the floor decking construction may have been due to the fact that the same architect designed both buildings.

Salvaged floor sections: Just before the wing was demolished three intact floor sections were removed from the Assembly Hall floor. Included was Bay A and a portion of Bay DE. A chain saw was used to isolate the ends and sides of the sections from the surrounding floor. The intact sections were then hoisted to the ground (Fig. 2). Salvaged Bay A was as described previously except its span was now 6.2 m (244 in.), not 6.3 m (248 in.). The difference resulted from cutting the joists at the face of the end supports. Salvaged Bay DE consisted of an eight joist section that was cut from the in-place 13 joist wide floor. The length of salvaged Bay DE was 6.1 m (240 in.). The shortened length of the bay was due to cutting the joists at the face of the supports.

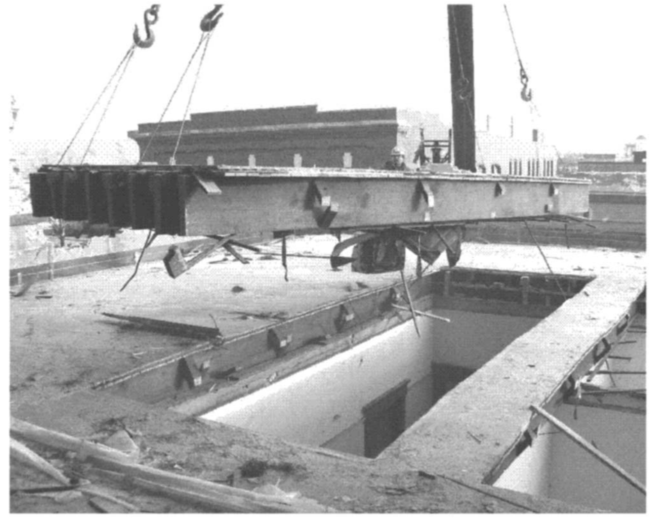

Fig. 2. Salvaged floor section being hoisted from Agricultural Hall

IWU Administration Building

The Administration Building for Indiana Wesleyan University (IWU) in Marion, Ind., was built in 1894. In October 2002, the university planned extensive renovation and updating of the building. As a part of construction planning, the university asked our research team to assist their structural engineering consultant in assessing four in-place wood floors comprising the main level of the building. The four floors were identified as the northwest corner room, northeast corner room, advancement office, and the southeast corner room.

The floor construction, in general, consisted of full 51 mm (2 in.) thick joists with nominal 25.4 mm (1 in.) thick pine subfloor and nominal 25.4 mm (1 in.) thick tongue and groove southern pine finish flooring. The flooring was oriented perpendicularly to the joist span. The joists were bearing in masonry pockets on both ends. There was a line of 51 by 102 mm (2 by 4 in.) cross bracing of the joists at midspan. The joists and cross bracing were southern pine. Distinguishing characteristics for the four floors were as follows.

- Northeast corner and northwest corner rooms: The southern pine joists were 51 by 330 mm (2 by 13 in.) cross section and spaced 406 mm (16 in.) on center. The span of the 18 joists was 7 m (275 in.).
- Advancement room: The eleven 51 by 330 mm (2 by 13 in.) southern pine joists were spaced 406 mm (16 in.) on center and had a span of 5.1 m (201 in.). One joist had termite damage along two-thirds of its bottom edge. Four other joists had spotty termite damage. A 1920s vintage safe estimated to weigh 4,450 N (1,000 lbf) was situated over three joists toward an outside edge of the floor at about quarter span.
- Southeast corner room: There were sixteen 51 by 279 mm (2 by 11 in.) southern pine joists in this floor. They were

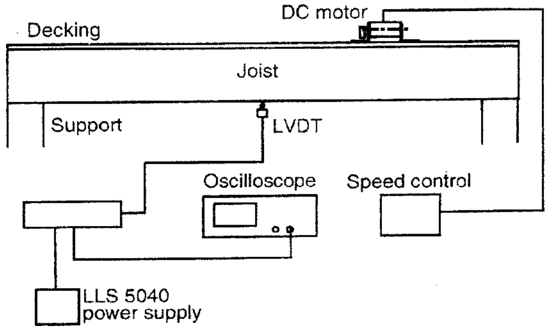

Fig. 3. Schematic diagram of experimental transverse vibration test setup

spaced 406 mm (16 in.) on center and had a span of 5.2 m (205 in.). Five joists toward one side of the floor were charred. Records showed that this area of the building was damaged by a 1916 fire.

Test Procedures

In-Place Floors

The floor systems were subjected to both free and forced vibration. Free vibration was initiated by impact from a large hammer. Forced vibration was imposed by an electric motor with an eccentric rotating mass. This unit was attached at four points with lag screws to two adjacent floor joists. Motor speed could be manually changed from rest to a maximum of 2,500 rpm. The rotating mass weighed 1,404 g (3.1 lb) with an eccentricity of 2.54 cm (1 in.). A schematic diagram of the experimental setup is shown in Fig. 3. The response to vibration was measured at the bottom of the joists using a linear variable differential transducer (LVDT). The LVDT was placed at midspan of the floors. The time–deflection signal was recorded by storage oscilloscope. For free vibration, the damped natural frequency was determined as the inverse of the period measured from the time-deflection signal. For forced vibration, the damped resonant frequency was determined by increasing motor speed until maximum deflection resonance was observed and then measuring frequency from the time–deflection signal.

In addition to natural frequency, each floor's EI was determined by static loading. A line load of layers of 178 N (40 lb) bags of water conditioner salt was placed along the midspan of the floor's joists. Load-deflection data for the floor was recorded for increasing increments of line load. Four layers were used. Deflection was monitored by the same LVDT and in the same location as was used for the previously described dynamic test. A simple beam model was used to calculate the EI of the floor as

$$\mathrm{EI} = \frac{PL^3}{48\Delta} \tag{2}$$

where P=total load [N (lbf)]; L=floor span [m (in.)]; and Δ=deflection [m (in.)].

Salvaged Floor Sections

Sections removed from Agricultural Hall (Fig. 2) were tested similarly to the lab-built floor sections (Cai et al. 2002; Soltis et al. 2002). The dynamic and static load testing were similar to that described earlier for in-place floors. The purpose of using the salvaged sections was to explore the effects of boundary conditions on the performance of in-place floors.

The testing protocol consisted of combinations of restraint of the ends of the section and edge support. For end restraint the ends of the floor sections were wrapped with a system of cable tightened with a come along. The cable was anchored to the railroad tie end supports. The cable restraint system was to resist as much as possible the rotation of the section ends when the sections were tested. To study the possible effect of lateral stiffness across the width of the in-place floors, the salvaged sections were supported fully along each edge from $L/4$ to $3L/4$ by stacks of railroad ties. The stack of railroad ties were banded together and the edges of the floor sections were in turn banded to the edge supporting ties. The latter was to prevent the floor section from bouncing on the ties during dynamic testing.

In contrast to the in-place floors previously tested, a more direct estimate of floor weight was possible. Partial floor sections were salvaged along with the complete sections that were subsequently tested. Samples that could be handled were cut from the partial floor sections and weighed. Hence a better estimate of the unit weight of the salvaged floor sections and consequently the in-place weight of Agricultural Hall floors was available.

Results

A total of 14 in-place floors and four configurations of two salvaged floor sections were tested. The results of the dynamic and static testing are summarized in Table 1. Only forced natural frequency is listed in Table 1 as earlier reported by Cai et al. (2002) forced vibration was more consistent than free vibration results. Note the factor EI/WL^3 shown in the last column of Table 1 where EI was determined by the static load test; W=estimated weight of the floor/section; and L=measured floor span. This factor and the measured forced damped natural frequency for each floor are the coordinates of data points plotted in Fig. 4. The solid curve in Fig. 4 is a plot of the hypothesized response, Eq. (1). Also included in Fig. 4 are data points for all prior tested laboratory built floor sections (Forsman and Erickson 2001; Soltis et al. 2002; Wang et al. 2005a). Twelve special laboratory floor sections were built and tested by Michigan Technological University (Forsman and Erickson 2001). The purpose of these tests was to extend the range of floor construction beyond the large joist sizes experienced in the in-place floors discussed earlier. Thus, Fig. 4 is a summary plot for all testing in this multiyear project. The data point (19.6, 0.076) for a bay in the Railroad Building is an outlier in Fig. 4. Unfortunately, this floor could not be retested before the building was demolished. A least squares analysis yields a coefficient of determination (r^2) of 0.85 for comparing the empirical data versus theory. Based on these favorable results, the hypothesis that in-place wood floors, such as those tested in this project, can be modeled as a simply supported, one-way beam system under transverse vibration with viscous damping [Eq. (1)] was accepted.

Discussion and Implementation

For the salvaged sections (AGs), the simple beam model is appropriate whether or not ends are restrained and free edges supported. The changes in boundary conditions of these sections do not stiffen their performance to near the level observed when the

Table 1. Characteristics and Test Results of In-Place Timber Floors

Floor location	Floor code	Joist size (mm)	Spacing (mm)	Span (m)	Forced frequency (Hz)	EI (10^6 N m^2)	EI/WL^3 (1/cm)
Purdue	FPRD	51 by 397	336	8.79	12	59.4	0.035
Railroad	Bay 2-2	51 by 356	305	5.75	19.6	24.8	0.076
	Bay 4-2	51 by 356	305	5.75	14.5	19.8	0.07
	Bay 6-2	51 by 356	305	5.75	13.5	17.4	0.061
	Bay 1-3	51 by 292	406	5.55	9.9	9.3	0.046
	Bay 2-3	51 by 292	406	5.55	12	9.9	0.049
	Bay 4-3	51 by 292	406	5.55	9.6	9.6	0.048
	Bay 6-3	51 by 292	406	5.55	9.4	8.4	0.042
AG	A	51 by 381	305	6.31	17.6	43.2	0.12
	DE	51 by 381	305	6.31	15.6	59.6	0.107
AGs[a]	Au	51 by 381	305	6.25	13.5	22.8	0.072
	Ar	51 by 381	305	6.25	13.9	29.2	0.076
	DEr	51 by 381	305	6.07	13.5	22.2	0.068
	DEr/es	51 by 381	305	6.07	13.7	23.2	0.071
IWU	SE	51 by 279	406	5.23	14.2	14.4	0.076
	NW	51 by 330	406	7.05	11.6	31.1	0.036
	NE	51 by 330	406	7.04	12.3	37.5	0.043
	Advance	51 by 330	406	5.08	17.9	26.3	0.131

Note: mm=25.4 in.; N m^2=348 lb in.^{2}; and 1/cm=2.54 1/in.

[a]Au=unrestrained ends; Ar=ends restrained; DEr=ends restrained; DEr/es=ends restrained and edges supported.

sections were a part of the in-place continuous floor (AG). The additional stiffness of the in-place floor bays is unexplainable. One possibility is that cross walls stiffen the in-place floor system.

With the acceptance of the hypothesis that Eq. (1) explains the behavior of the in-place timber floors examined in this project, attention was directed to how to use this information in the assessment of the structural capability of in-place floors. It is recognized that strongly one-way action wood floors are customarily deflection limited. Most floor joist design is governed by deflection criteria based on stiffness whereas bending stresses are usually less than bending strength criteria. So if the floor's EI can be predicted then, coupled with building code imposed deflection limit, e.g., $L/360$, the allowable floor load can be backcalculated.

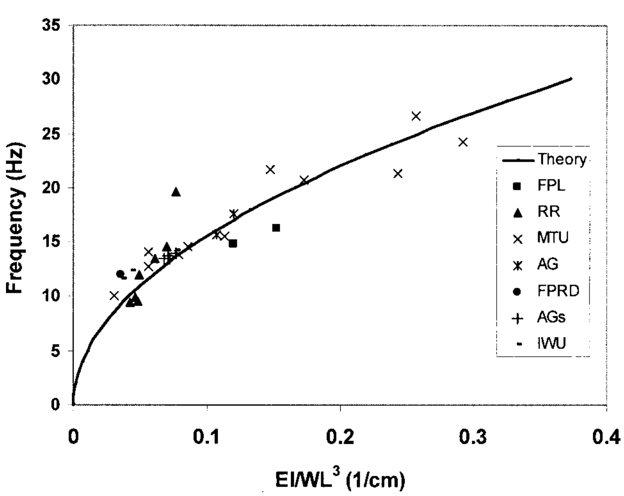

Fig. 4. A scatter plot of the in-place floor test data and previously tested lab-built floor sections (FPL and MTU). Solid curve is plot of theory [Eq. (1)]. Note: 1/cm=2.54 1/in.

Using the calculated allowable floor load, the bending stress and induced shear stress in the joists can be calculated and compared to allowable stresses. In the case of bending stress, for the size of joists encountered in this study, current allowable stresses range from 3,970 KN/m^2 (575 psi) (No. 3 and stud grade) to 14,150 kN/m^2 (2,050 psi) (dense select structural grade) (American Forest and Paper Association 2005). Therefore, for the quality and size of southern pine joists involved in this study, good engineering judgment indicates an allowable bending stress of 10,350 kN/m^2 (1,500 psi).

The goal of the implementation phase was to develop a methodology of using the measured damped natural frequency of a floor to safely predict the floor's EI. To safely predict means that variability must be accommodated. Although theory fits experimental data extremely well (r^2=0.85) there is obvious scatter about the theoretical curve (Fig. 4). For implementation, Fig. 4 is replotted so that frequency is now the independent (measured) variable and EI/WL^3 is the dependent variable to be predicted (Fig. 5). The form of the theoretical curve suggested a natural log regression to best fit the data. The natural log regression of EI/WL^3 versus frequency and the theoretical curve are shown in Fig. 5. The natural log regression curve conforms to the theoretical curve and fits the data well especially in the practical range of low and medium frequencies. A coefficient of determination (r^2) of 0.85 was obtained when actual test values of EI/WL^3 were compared with values predicted by the natural log regression. To establish allowable bending stress for lumber, the fifth percentile exclusion limit of the distribution is used to account for variability. Similarly, creation of the lower bound of the 90% prediction band (Neter et al. 1996) in effect establishes the 5% exclusion limit for the stiffness (EI/WL^3) variable. The 5% exclusion limit curve is also shown in Fig. 5. It is noted that the experimental data are above the 5% exclusion limit with the exception of the previously identified outlier.

This experience suggested that the 5% exclusion limit could be the control curve. In practice, (1) an in-place floor would be trans-

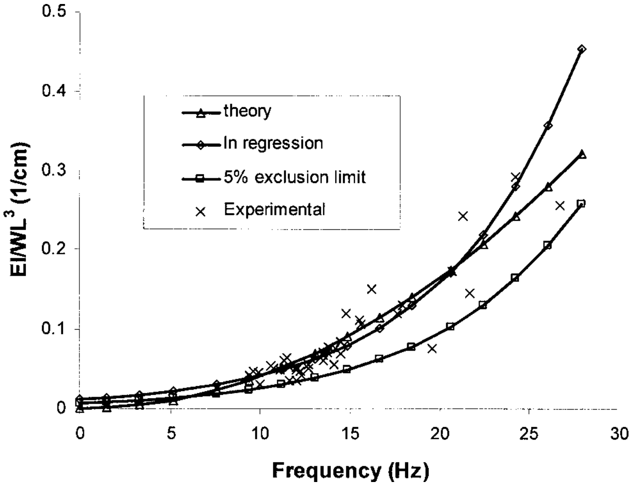

Fig. 5. Plots of theory, natural log (ln) regression, 5% exclusion limit and experimental data. Note: 1/cm=2.54 1/in.

versely resonated to determine its damped natural frequency; (2) the frequency value would be used to trace vertically to the intersection with the control curve; and (3) then from the intersection point trace horizontally to the ordinate axis to obtain the associated value of EI/WL^3. The EI of the floor can be isolated from this value by measuring the floor span and estimating the weight of the system. Currently, the weight (W) of the floor of interest would be estimated by calculating the volume of the components of the floor and multiplying these volumetric values by respective handbook density values for the wood species involved. This method does not recognize the variation of density in the components; hence it needs to be improved.

To avoid direct measurement of system weight, Australian researchers assessing timber bridges measured the system's natural frequencies at two levels of mass, thus eliminating the mass parameter from the calculation of the system's stiffness (Crews et al. 2004). However, the senior writer in 2001 had attempted a similar technique and experienced highly variable results for the floor being tested. The technique was discontinued at that time.

As outlined previously, with the EI of the test floor now determined the allowable floor load would be calculated and a check of the bending and shear strength capacities calculated.

Conclusion

Transverse vibration test results for in-place floors in four buildings and several lab-built floors are given. The boundary conditions for some of the lab-built floors were varied to approximate end fixity. Test results indicate end fixity could not be achieved; a model for one way beam action with simple supports is the best predictor for lab and existing floor responses. We feel the deformation associated with compression perpendicular-to-grain stresses precluded achieving a fixed boundary condition.

A methodology for using this research to predict stiffness of existing floors is suggested. The method relies on estimating the weight of the floor system. Further research is needed to more accurately estimate this weight.

Acknowledgments

The writers gratefully acknowledge research funding provided by the National Center for Preservation Technology and Training of the National Park Service, the USDA Forest Products Laboratory, and Purdue University. Appreciation is also expressed to Everette Mills, former student assistant, for instrumentation assistance and general support and Alexander Lipka of the Purdue University Statistical Consulting Service for formulation of regressions and associated prediction interval curves.

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