VIBRATION TESTING OF TIMBER FLOOR SYSTEMS

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ABSTRACT

Inspection and evaluation of existing timber structures have been limited to individual structural members. The objective of this study was to conduct a pilot investigation on the use of transverse vibration testing techniques for inspecting timber structures by evaluating component systems such as floor systems rather than individual members. The practical considerations were 1) the effectiveness of free vibration compared with forced vibration; 2) the optimal location of forcing function input and transducers for obtaining adequate response signals; 3) the effect of superimposed dead loads on floor vibration response; and 4) the effect of joist decay on floor vibration response. We evaluated three floors, two constructed with new joists and one with salvaged joists having some deterioration, checks, and splits. Natural frequencies and damping ratios were determined for each floor. We conclude that the practical considerations involved in the inspection of floor systems could be determined through frequency and damping ratio data. Thus, transverse vibration testing holds promise as an inspection technique. Future research is needed on a range of floor spans and joist sizes.

Inspection and evaluation of existing timber structures has historically been limited to evaluating each structural member individually, which requires a time-consuming inspection. Sometimes individual members are not accessible and therefore difficult to inspect. Our overall objective was to more efficiently inspect timber structures by evaluating component systems rather than individual members. One example is the inspection of floor systems in a multi-bay building. A different floor response in one bay compared with that in the other bays would warrant a more thorough inspection of the members of that bay.

The study reported here is a continuation of several recent studies related to the overall objective of nondestructive evaluation of a timber floor system using transverse floor vibration. The first study evaluated properties of new and salvaged individual floor joists (Cai et al. 2000). The second study evaluated the responses of floor systems built in the laboratory with new and salvaged joists (Cai et al. 2002). These studies used an impact load to initially displace the structure; the free vibration characteristics of the individual joists or floor were then measured. The salvaged joists tested in these studies had seasoning checks, splits, and some edge decay, which resulted in lower stiffness values than those of the new joists. The effects of lower stiffness were difficult to detect when new and salvaged joists were used to construct a floor system. In the second study, data on the effects of magnitude and location of dead load superimposed on the floor system were limited. Nevertheless, these data suggest that superimposed loads may be an important factor in the inspection and evaluation of in-situ floor systems.

The objectives of the study reported here were as follows:

1. To compare floor system response using a rotating mass forcing function to system response using free vibration;
2. To determine if the effects of severe degrade (compared with that found in previous studies) can be detected in one or more floor joists;
3. To determine the effect of location of superimposed dead load on floor system response.

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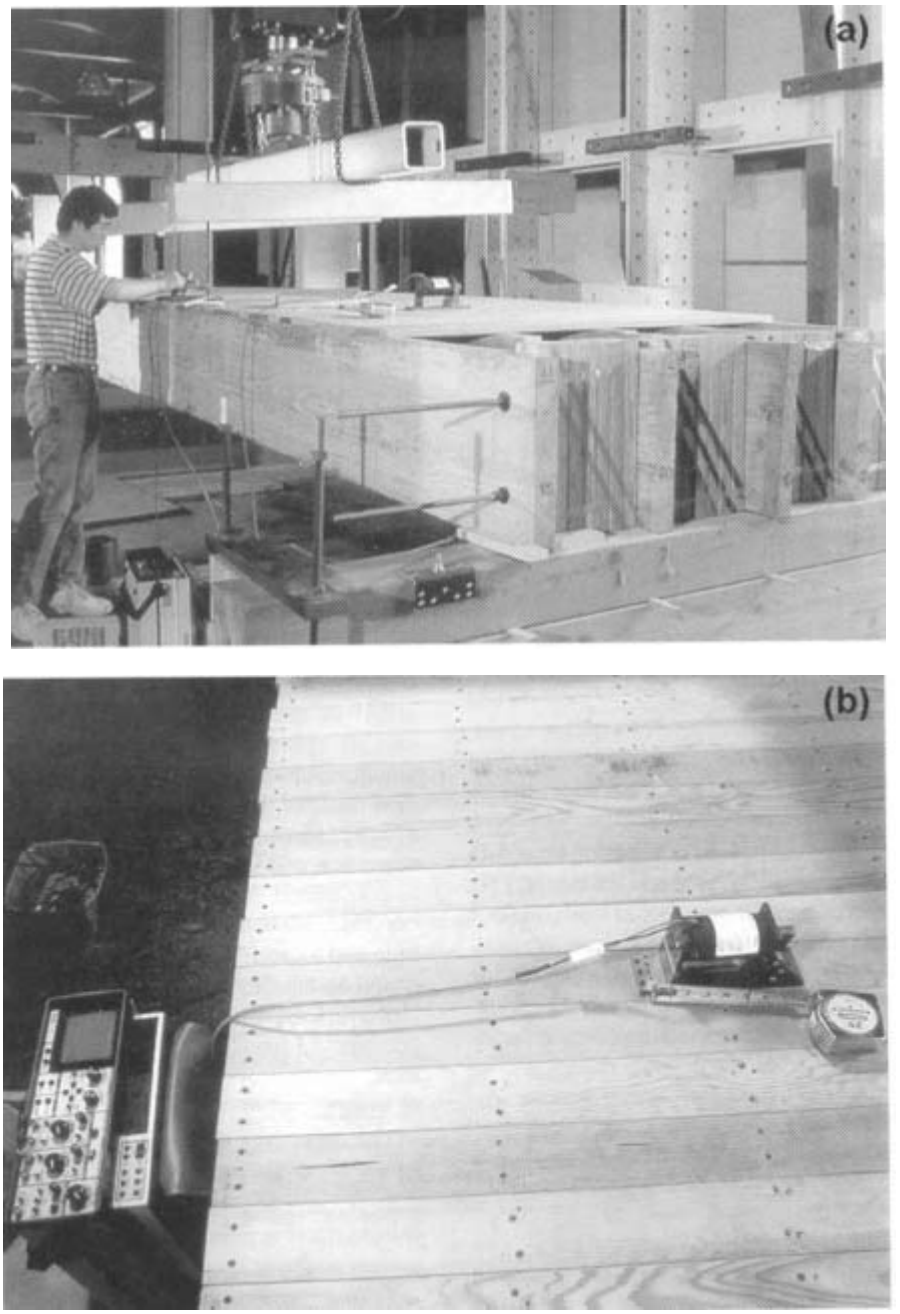

Figure 1 .—Test floor system: (a) floor test set-up; (b) floor system with motor forcing function.

Objective 1 addressed the difficulty of measuring free vibration response in a highly damped floor system. Objective 2 was motivated by the difficulty in detecting seasoning defects encountered in previous studies. Tests were conducted on the effect of dead load location on floor system response (objective 3) because the inspection of timber structures may include floor loads such as file cabinets, furniture, refrigerators, and freezers.

Background

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 (Ross and Pellerin 1994):

$$EI = \frac{f^2 W L^3}{2.46g} \qquad [1]$$

where f = fundamental natural frequency; W = beam weight (uniformly distributed); L = beam span; g = acceleration due to gravity (9.8 m/sec.^{2}); EI = stiffness (modulus of elasticity Ex moment of inertia I)

Note that Equation **[1]** represents the relationship for a simply supported idealized beam. This formula, however, is frequently used to estimate the relationship for simply supported systems as well.

The fundamental natural frequency is dependent on the characteristics of the structure E, I, W, and L and does not depend on the agent causing the motion. However, damping in the system will result in a slightly different natural frequency compared to that of an undamped system (Richart et al. 1970). For free vibration:

$$f_{\text{damped}} = f_{\text{undamped}} \sqrt{1 - D^2} \qquad [2]$$

For forced vibration, the effect of damping is dependent on the type of forcing function. If the forcing function is a harmonic force, the resonant damped frequency occurs below the undamped natural frequency:

$$f_{\text{damped}} = f_{\text{undamped}} \sqrt{1 - 2D^2} \qquad [3]$$

However, if the forcing function is a rotating mass type excitation, the resonant damped frequency occurs above the undamped natural frequency:

$$f_{\text{damped}} = f_{\text{undamped}} \frac{1}{\sqrt{1 - 2D^2}} \qquad [4]$$

In Equations **[2]** to **[4],** D is the damping ratio defined as the ratio of damping in the system to that critical damping where no vibratory motion occurs. The damping ratio has been studied by a number of researchers; values as high as 0.15 might be expected for buildings, depending on the nature of the material used and the friction in the connections (Rogers 1959). Corder and Jordan (I 975) tested a number of floor systems consisting of nominal 2- by 8-inch (standard 38- by 184-mm) joists and a variety of sheathing materials nailed and/or glued to the joists. Natural frequency of the floors ranged from 14 to 20 Hz, and damping ratios ranged from 0.027 to 0.083. Kermani et al. (1996) found a 0.05 damping ratio for a groove-lock flooring system using medium density fiberboard sheathing.

The log decrement □, which is the rate of decay of vibration, is related to the damping ratio (Richart et al. 1970):

$$\delta = \frac{2\pi D}{1 - 2D^2} \qquad [5]$$

Pellerin (1965) found log decrement values by both free and forced vibration for various sizes and grades of dimension lumber. Log decrements were determined from the time-amplitude response decay curve for free vibration and from the frequency-amplitude response curve for forced vibration. Pellerin found the error of measurement in the forced vibration case to be excessive and recommended the free vibration case for log decrement. Elliot (1997) found log decrement values by a dropped weight on a proprietary gymnasium floor system; values for three successive drops were 0.184, 0.218, and 0.141.

A number of studies have focused on the natural frequency of floor systems. These studies have usually been related to serviceability requirements for human response to floor vibration. An overview of floor vibration design criteria is given by Dolan et al. (1994, 1999); experimental techniques are given by Polensek (1970) and Kermani et al. (1996).

EXPERIMENTAL PROCEDURE

Three floor systems were tested for natural frequency, damping ratio, and stiffness. Each floor system was constructed of five 51- by 406-mm southern pine joists spaced 305 mm on center, with a span of 6 m (Fig. la). Two floors were constructed of new materials (called new floor 1 and new floor 2); the third floor was constructed from salvaged material recovered from a demolished warehouse built shortly after 1900 (called salvaged floor). The physical and mechanical properties of each joist were previously reported (Cai et al. 2000).

The end supports for the floor systems simulated a floor in an existing building and consisted of blocked piers. The joists were laterally braced by cross bridging 1.45 m on center. The floor decking was transverse 25- by 102-mm Douglas-fir boards fastened by 51-mm dry wall screws. Screws were used for assembly and disassembly of the decking required during the tests.

The floor systems were subjected to both free and forced vibration. Free vibration was initiated by impact from a hammer. Forced vibration was imposed by a motor with an eccentric rotating mass attached to the floor decking (Fig. **lb).** Motor speed could be manually changed to a maximum of 1,800 rpm. The rotating mass weighed 251 g with an eccentricity of 3 cm. The response to vibration was measured at the bottom of the joists using a linear variable differential transducer (LVDT). The time-deflection signal was recorded by oscilloscope. For free vibration, the damped natural frequency was determined as the inverse of the period measured from the time-deflection signal; the damping ratio was determined from the same signal using the classic log-decrement technique. 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.

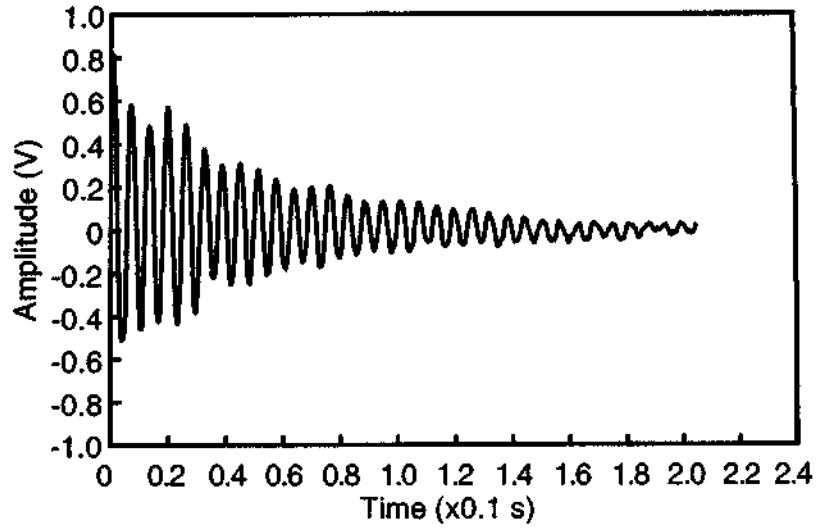

Figure2.—Example response of amplitude as a function of time for free vibration.

The locations of the forcing function and LVDT were varied for the floor system made of salvaged joists. The forcing function was located over the center joist at midspan and quarter-point of span (quarter span). The LVDT was located under both the center and edge joists at midspan and quarter span. Because the results showed that LVDT location did not affect frequency (see Discussion section), for the new floor systems the LVDT was located under the center joist at midspan and the forcing function was located over the center joist at quarter span.

Floor stiffness was determined from load displacement found by adding 1.8 kN static load in eight increments at midspan of the joists and distributed over the width of the floor system.

New floor 1 was primarily tested to determine the effects of severe degrade in the ends of the joists. Since decay most often occurs at the supports, we simulated severe end degrade by sawing about 0.3 m off the ends of three joists progressively. The center joist was cut first, followed by the adjacent joists to either side. Frequency, damping ratio, and stiffness were determined for the intact floor and after each of the three joists were cut.

New floor 2 was primarily tested to determine the effect of location of superimposed dead load on floor response. The floor frequency was determined using the forcing function and placing a 222- or 445-N dead load at 0.1, 0.2, 0.3, 0.4, and 0.5 x the span length over the middle and edge joists. A load of 222 N was also superimposed after joist ends were cut.

The salvaged floor was first tested to determine the sensitivity of vibration response to the location of the LVDT and forcing function. This was considered necessary since accessibility in inspecting timber structures may limit where the LVDT and forcing function can be located. For this test, the floor decking was shimmed at all places where deterioration had occurred in the salvaged joists. The salvaged floor was then tested

without the shims to determine the effects of deterioration.

Results

Figure 2 is an example of the time-deflection signal for free vibration. The measured damped natural frequency and damping ratio were determined from this plot.

Ten replicates for the salvaged floor system were used to determine the accuracy of frequency measurements. Maximum and minimum values were ±0.1 Hz of average frequency, which represents a less than 1 percent difference from average values. The accuracy of measurements to determine damping ratio was more variable. The classic log-decrement method fits a curve to successive peaks in the time-deflection response to hammer impact. Because different hammer impacts can result in a different curve fit, we averaged the results from five replications to determine damping ratio. This resulted in about a 12 percent difference between the average and minimum or maximum value.

Table 1 indicates the sensitivity of vibration response in relationship to the location of the forcing function and the LVDT sensor on the salvaged floor. Spot checks on the other two floor systems gave similar results. The amplitude values are relative values based on the particular motor and rotating mass used as a forcing function. A different rotating mass would have resulted in different amplitude values, but the relative ratios between the values would have remained the same.

Table 2 compares frequencies found by free and forced vibration. The table shows both measured and corrected values. The measured value for free vibration was the damped natural frequency and was corrected to the undamped natural frequency using Equation **[2].** The damping ratio was found from the log decrement using Equation **[5].** The measured value for forced vibration was the damped natural frequency resulting from a rotating mass type excitation and was corrected to the undamped natural frequency using Equation **[4].**

Results for new floor 1 with simulated joist end degrade are given in **Table 3** and **Figures 3** and **4. Table 3** shows measured frequencies, relative amplitude, damping ratios, and floor stiffness. Predicted and measured frequencies for various boundary conditions are given in **Table 4.**

Tables 5 and **6** show the effect of superimposed dead load on frequency. **Table 5** gives results for loads superimposed at different locations on new floor 2 before the joist ends were cut to simulate joist end decay, and **Table 6** gives results after the joists were cut. The values in **Tables 5** and **6** are the measured frequencies for a damped forced system.

Discussion

Inspection and evaluation of existing timber structures is often complicated by lack of accessibility. It is sometimes impossible to inspect or test at all locations. The strongest response would be detected if both the measuring device and forcing function were located at points of maximum displacement, which is generally midspan for beams and floors. In our study, the LVDT was located at quarter span and midspan on

TABLE 1. — Effect of location of LVDT and forcing function on vibration response of salvaged floor system.

Location[a]		Relative amplitude	Measured frequency
LVDT	Forcing function		
			(Hz)
Center joist (0.5L)	Center joist (0.25L)	1.3	15.4
Center joist (0.25L)	Center joist (0.25L)	0.4	15.5
Center joist (0.5L)	Center joist (0.5L)	1.5	15.3
Center joist (0.25L)	Center joist (0.5L)	1.3	15.3
Edge joist (0.5L)	Center joist (0.25L)	2.5	15.5
Edge joist (0.25L)	Center joist (0.25L)	1.4	15.6

[a] L designates floor span.

TABLE 2. — Results of free and forced vibration.

Floor system	Measured frequency		Log decrement	Avg. damping ratio	Undamped natural frequency	
	Free	Forced			Free	Forced
	(Hz)				(Hz)	
New floor 1	16.3	16.2	0.164	0.0261	16.3	16.2
New floor 2	15.9	16.3	0.140	0.0223	15.9	16.3
Salvaged floor	14.8	14.9	0.182	0.0290	14.8	14.9

TABLE 3. — Effect of simulated joist end decay on floor response for new floor 1.

No. of joists with cut ends	Measured frequency		Relative amplitude	Log decrement	Avg. damping ratio	Floor stiffness
	Free	Forced				
	(Hz)					($\times 10^6$ N m^2)
0	16.3	16.2	2.7	0.164	0.0261	14.90
1	16.1	16.0	2.6	0.188	0.0299	13.85
2	15.1	15.0	2.8	0.188	0.0299	1 1.20
3	12.0	12.4	2.6	0.239	0.0380	8.65

both the center and edge joists. The motor was located at quarter span and midspan of the center joists. The measured forced damped frequencies were generally within 0.1 Hz of the average value (15.4 Hz), which is within the experimental accuracy of measurement. The only exception occurred for the LVDT at its most extreme location, the quarter span of the edge joist, where the frequency was 0.2 Hz different from the average value. We decided that any location of the LVDT or motor was acceptable provided the response signal was strong. For convenience, we located the LVDT at midspan of the center joist and the motor at quarter span of the middle joist for the remaining tests.

The undamped natural frequency is dependent on the stiffness, mass, span, and boundary conditions of the floor system. In theory, it is independent of the method of vibration. Comparison of free and forced measured frequencies indicated small discrepancies **(Table 2).** The undamped natural frequency shown in **Table 2** is the measured damped frequency corrected for damping. Obviously this correction is negligible to one decimal place; for the remainder of this discussion, the natural and resonant frequencies are considered equal. Note that although the damping corrections (Eqs. **[2]** and **[4])** are based on a lumped mass system, we applied them to a distributed mass system.

The log decrement values for the floor systems varied from 0.140 to 0.182 **(Table 2).** Pellerin (1965) found that values for individual dimension lumber ranged from approximately 0.2 to 0.6; Corder and Jordan (1975) found values ranging from approximately 0.17 to 0.5. Elliot (1997) found values for the same floor in successive impacts to vary from 0.14 to 0.22. These studies suggest that log decrement values are difficult to measure and hence variable.

Comparison of the floors constructed of new and salvaged joists reinforced the findings of a previous study (Cai 2000). The lower frequency of the salvaged floor was due to its decreased stiffness (measured as 13.2×10^6 N m^2), compared with the stiffness of new floor 1 (14.9×10^6 N m^2) **(Table 3).** For the salvage floor, decking shims had an effect on frequency. When the shims were removed, frequency decreased from 15.4 to 14.9 Hz **(Tables 1** and **2).**

Joist decay usually occurs at the supports, where water often accumulates. We simulated joist end decay by sawing off the ends of three joists. This created a discontinuous member as part of the floor system still interconnected by bridging and floor decking. Concerned about this discontinuity, we initially sawed the joists one-half their depth and determined floor response and stiffness. The values fell between those of an uncut and cut joist; these values are not reported but are shown on **Figure 3.** We believe the effect of discontinuity is overcome by the system effect of the entire floor.

The effects of simulated joist end deterioration in new floor l **(Table 3, Fig. 3)** were a decrease in floor stiffness, a corresponding decrease in frequency, and an increase in the damping ratio as the joists were cut progressively. In new floor 1, the effects of the loss of one or two joists were small compared with those of the loss of all three joists **(Fig. 4);** similar results were found for new

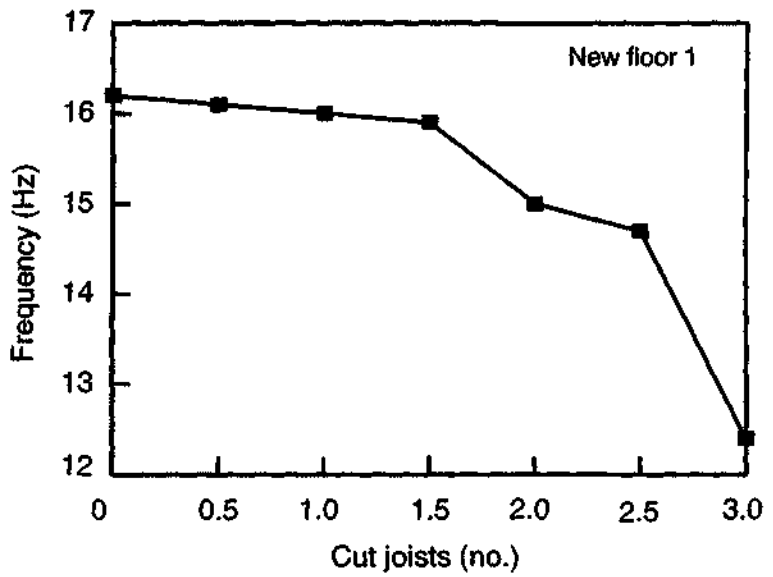

Figure 3. - Effect of simulated joist end deterioration in new floor 1.

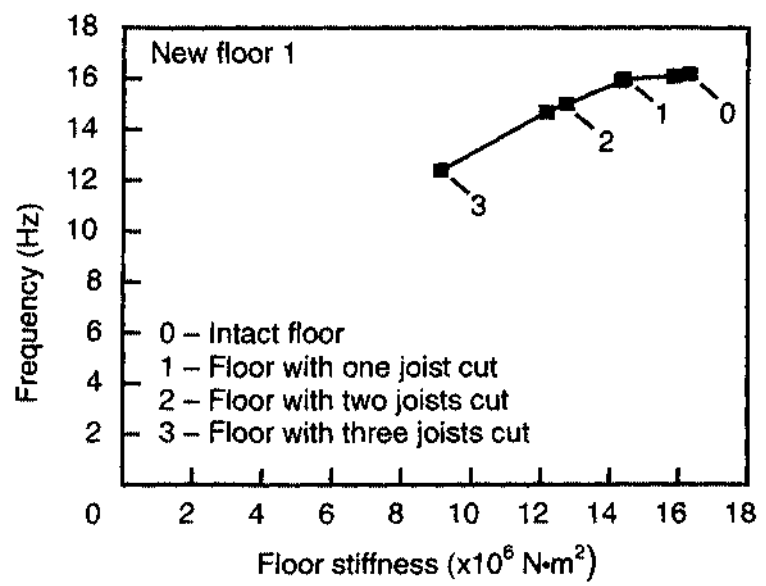

Figure 4. - Relationship of frequency and stiffness for new floor 1 with simulated deterioration.

TABLE 4. — Comparison of predicted and measured frequencies for new floor 1.

No. of joists with cut ends	Measured frequency		Predicted frequency for different support conditions		
	Free	Forced	Pinned/pinned	Fixed/cantilever	Weighted average
	(Hz)				
0	16.3	16.2	21.1	7.5	--
1	16.1	16.0	20.3	7.3	18.4
2	15.1	15.0	18.2	6.5	14.7
3	12.0	12.4	16.0	5.7	11.0

TABLE 5. — Effect of loud locution on response of intact new floor 2. [a]

Load	Loaded joist	Measured frequency for load at various locations along joists					
		0	0.1L	0.2L	0.3L	0.4L	0.5L
(N)		(Hz)					
222	Center	16.3	16.3	16.0	15.9	15.8	15.8
	Edge	16.3	16.2	16.1	15.9	15.8	15.8
445	Center	16.3	16.1	15.8	15.5	15.4	15.2
	Edge	16.3	16.2	15.9	15.3	15.0	15.0

[a] L designates floor span. Floor frequency was measured by forced vibration.

TABLE 6. — Effect of load location on response of new floor 2 with simulated joist end decay.[a]

No. of joists with cut ends	Measured frequency for 222-N load at various locations along joists					
	0	0.1L	0.2L	0.3L	0.4L	0.5L
	(Hz)					
0	16.3	16.3	16.0	15.9	15.8	15.8
1	15.9	15.8	15.7	15.6	15.5	15.3
2	15.0	14.7	14.6	14.6	14.6	14.4
3	13.3	11.7	11.7	12.5	11.9	11.9

[a] L designates floor span. Floor frequency was measured by forced vibration.

floor 2 **(Table 6).** These results indicate that the systems effect of the floor will mask the effect of decay if it is limited to only one or two joists. The question is whether repair is needed if only one or two joists are deteriorated.

Either frequency or damping ratio could be used as an indicator of joist end decay. Changes in both frequency and damping ratio were small for floors with one or two cut joists and greater for floors with three cut joists. Relative amplitude is not a good indicator of changes resulting from damaged joists. Amplitude is a relative value, dependent on the forcing function; thus, applying a constant forcing function masked the effect of change in stiffness on amplitude.

Equation **[1]** relates frequency to stiffness for a continuous system that is pin supported on each end. Using the floor stiffness values of **Table 3** and Equation **[1]** resulted in higher predicted frequencies for the pinned/pinned end case, compared with measured frequencies **(Table 4).** There are two possible explanations for this. First, Equation **[1]** is for an idealized spring-dashpot system with viscous damping. This may not be a good predictor of an actual floor system with friction damping. A second explanation may be related to boundary conditions. When joist ends are cut, the cut joist acts as a cantilever beam interacting with the floor system. For a fixed end cantilever beam, the constant of 2.46 in Equation **[1]** becomes 0.314. Using this constant value predicts smaller frequencies for the fixed/cantilever case compared with the measured values **(Table 4).** The boundary conditions for the floor systems with cut joist ends were not determined but fell within the two cases used for prediction. A better prediction of floor system frequency is made by taking a weighted average of the constants, 2.46 and 0.314. For example, when one of the five joists is cut, the weighted average constant is $(4 \times 2.46 + 1 \times 0.314)/5 = 2.03$. Using this constant results in a predicted frequency of 18.4 Hz **(Table 4).**

A practical problem of inspecting floor systems is the effect of superimposed loads that are not easily removed during inspection, such as equipment, file cabinets, and large appliances. The effects of a 222- and 445-N load at various locations along the center and edge joists are shown in **Table 5.** The 445-N load increased the mass of the floor system by about 5 percent, which, in a worst case scenario, would result in an approximate 3 percent decrease in frequency, based on Equation **[1].** We observed an approximate 7 percent decrease in frequency for the 445-N load located at midspan of the center joist **(Table 5).** We believe that the difference between the 3 and 7 percent decrease in frequency is the result of combining lumped mass and distributed mass sys-

tems, whereas Equation **[1]** is based on distributed mass.

The effect of superimposed loads was relatively small. The results of loading the edge joists were somewhat more variable than those for center joists; we may have introduced a torsional vibration component to the floor responses. The effect of superimposed load was more pronounced for joists with cut ends. For the case of three cut joists, we observed an approximate 12 percent decrease in frequency **(Table 6)** for the 222-N load located at midspan of the center joist; whereas the increase in mass alone (Eq. **[1])** would predict an approximate 1 percent decrease. The results indicate the location of a superimposed load has no practical effect if the load is located in the first quarter of the span; a small effect occurs if the load is located between one- and three-quarters of the span.

Conclusions

This report is a continuation of research related to the overall objective of nondestructive inspection of a timber floor system using transverse floor vibration. In the study reported here, we addressed several practical problems.

The first problem was related to the best way to obtain a good signal response when inspecting a floor with limited accessibility. We found that the location of the response measuring device and forcing function do not significantly affect frequency. Both free and forced vibration gave acceptable results. Free vibration has the advantages of being easy to apply and giving both frequency and damping data. Its disadvantage is that the response is sometimes weak. Forced vibration enables a stronger response by use of a larger forcing function. It also appears to give more consistent results. Its disadvantage is that no damping data can be obtained.

The second problem was whether vibration testing can be used to detect joist decay. The results indicate a decrease in natural frequency and increase in damping ratio proportionate to the amount of decay, as simulated by progressively cutting the ends of three joists. Either frequency or damping ratio is a good indicator of decay, but frequency can be measured more accurately than damping ratio. Small changes in frequency and damping ratio were observed with the loss of one or two joist ends, but greater change was observed with the loss of three joist ends. This indicates that the systems effect of a floor with bridging and decking may make it difficult to detect decay in only one or two joists. Decay should be easy to detect in a floor with many deteriorated joists. The question is whether deterioration limited to one or two joists in a floor system has a significant effect on structural integrity, warranting repair of the floor. The effects of deterioration in the salvaged floor were detected by a decrease in frequency and/or increase in damping ratio compared to that of a new floor.

A final problem was to inspect a floor with superimposed loads that are not easily removed. The additional mass of the loads should be included in frequency prediction calculations, but the location of the loads has only a small effect on natural frequency. The effect of a superimposed load was larger for the floor system with cut joists than for the undamaged floor.

In summary, vibration testing holds promise as a technique for inspecting timber floor systems. Future research is necessary to determine whether similar results can be obtained for a range of floor spans and joist sizes.

Literature Cited

Cai, Z., M.O. Hunt, R.J. Ross, and L.A. Soltis. 2000. Static and vibration moduli of elasticity of salvaged and new joists. Forest Prod. J. 50(2):35-40.

_____, R.J. Ross, M.O. Hunt, and L.A. Soltis. 2002. Pilot study to examine use of transverse vibration nondestructive evaluation for assessing floor systems. Forest Prod. J. 52(1):89-93.

Corder, S.E. and D.E. Jordan. 1975. Some performance characteristics of wood joist floor panels. Forest Prod. J. 25(2):38-44.

Dolan, J.D. and R.E. Kalkert. 1994. Overview of proposed wood floor vibration design criteria. Wood Design Focus, Fall:12-15. Forest Prod. Soc., Madison, WI.

_____, T.M. Murray, J.R. Johnson, D. Runte, and B.C. Shue. 1999. Preventing annoying wood floor vibrations. ASCE J. Struct. Eng. 125(1):19-24.

Elliot, P.W. 1997. Dynamic evaluation and simulation of safety, performance, and uniformity of hardwood sports surfaces. A thesis in partial fulfillment for the Degree of Doctor of Philosophy in Engineering, Purdue Univ., West Lafayette, IN.

Kermani, A., W. McKenzie, and A. Bensalem. 1996. The static and dynamic response of a MDF groove-lock flooring system. J. Inst. Wood Sci. 14(1):27-33.

Pellerin, R.F. 1965. A vibrational approach to nondestructive testing of structural lumber. Forest Prod. J. 15(3):93-101.

Polensek, A. 1970. Human response to vibration of wood-joist floor systems. Wood Sci. 3(2):111-119.

Richart, F.E., J.R. Hall, and R.D. Woods. 1970. Vibrations of Soils and Foundations. Prentice-Hall, Inc., Englewood Cliffs, NJ. 414 pp.

Rogers, G.L. 1959. Dynamics of Framed Structures. John Wiley & Sons, Inc., New York. 355 pp.

Ross, R.J. and R.F. Pellerin. 1994. Nondestructive testing for assessing wood members in structures: A review. Gen. Tech. Rept. FPL-GTR-70. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 40 pp.