LOW FREQUENCY VIBRATION APPROACH FOR ASSESSING PERFORMANCE OF WOOD FLOOR SYSTEMS[1]

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(Received February 2004)

ABSTRACT

The primary means of inspecting buildings and other structures is to evaluate each structure member individually. This is a time-consuming and expensive process, particularly if sheathing or other covering materials must be removed to access the structural members. The objective of this study was to determine if a low frequency vibration method could be used to effectively assess the structural performance of wood floors as component systems. Twelve wood floors were constructed with solid sawn wood joists in the laboratory and tested with both vibration and static load methods. The results indicated that the forced vibration method was capable of measuring the fundamental natural frequency (bending mode) of the wood floors investigated. An analytical model derived from the flexural beam theory was found to fit the physics of the floor structures and can be used to correlate natural frequency to section modulus (*EI* product) of the floor systems.

Keywords: Vibration, natural frequency, stiffness, wood floor.

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INTRODUCTION

Existing wood structures require rigorous and timely inspections to ensure their safety and structural performance. In general, structural inspection requires that some indicating parameters be monitored that are sensitive to the damage/deterioration mechanism in question. Current inspection methods for wood structures are limited to evaluating each structural member individually, which is a labor-intensive, time-consuming process. For *in situ* inspection of wood structures, a more efficient strategy would be to screen whole structural systems or subsystems in terms of their overall performance and serviceability. Examining the dynamic response of a structural system might provide an alternative way to gain insight into the ongoing performance of the system. Deterioration caused by any organism or any type of mechanical damage in structure reduces the strength and stiffness of the materials and thus could affect the dynamic behavior of the system. If, for example, one structural system or section of the system was found to respond to dynamic loads in a manner significantly different from that of other similar systems or the surrounding sections of the system, a more extensive inspection of that system or section would be warranted. Based on this conceptual strategy, we began to investigate the possibility of using a low frequency vibration approach for assessing the performance of wood structural systems by measuring the fundamental natural frequency (bending mode) and damping ratio of the entire system.

In a previous study (Soltis et al. 2002), we conducted a pilot investigation on three laboratory-constructed wood floors and addressed three practical problems on the use of vibration methods for floor inspection. 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, which could cause problems in collecting vibration data. 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 directly.

The second problem was whether vibration testing can be used to detect joist decay. The results have indicated 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 (each laboratory floor had five joists). 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 implies that the system effect of a floor with bridging and decking may make it difficult to detect decay in only one or two joists.

The third problem was to inspect a floor with superimposed loads that are not easily removed. We concluded that the additional mass of the loads should be included in frequency prediction calculations, but the locations of the loads have only a small effect on natural frequency.

The results from the previous study are limited in scope. The objectives of the study reported here were to extend the investigation of vibration methods to a series of floors that have a wide range of spans and joist sizes and to develop an analytical relationship between natural frequency and stiffness (*EI* product) of floor systems.

ANALYTICAL MODEL

An analytical model is used to relate the stiffness properties of the floor to its fundamental natural frequency for the purpose of inspection. Continuous system theory was chosen as the means for developing a theoretical vibration model based on the global physical properties of a system.

The floor systems in existing buildings are typically constructed of wood joists, cross bridging, and decking (Fig. 1). In previous studies

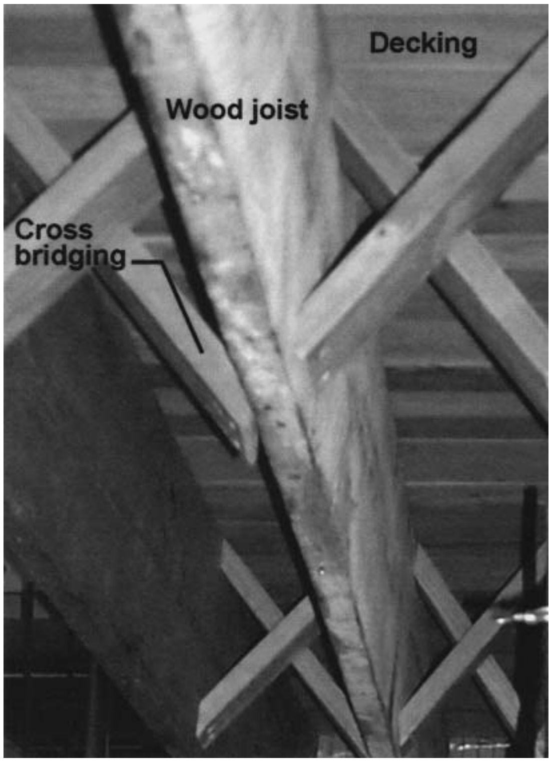

FIG. 1. Structural details of typical wood floor system.

(Ross et al. 2002; Soltis et al. 2002), we found that the stiffness of the joists predominates over the transverse floor sheathing because the thickness of the decking board is very small compared to the height of the joists. In addition, the deck is not continuous; and the deck boards are nailed perpendicular to the joists, reducing the stiffness that would be provided in the case of simple floor bending. The cross bridging also does not contribute to the bending stiffness of the floor because it mainly provides lateral bracing to the joists. Thus, we assumed that a floor system behaves predominately like a beam with resisting moments in the transverse direction. The total mass of the deck and cross bridging is distributed into the assumed mass of the joists.

The partial differential equation (PDE) governing the transverse vibration for a simple flexure beam is given in Eq. (1):

$$\frac{\partial^2 u}{\partial t^2} + \left(\frac{EI}{\rho A}\right)\frac{\partial^4 u}{\partial x^4} = 0 \tag{1}$$

where
EI is stiffness (modulus of elasticity $E \times$ moment of inertia of I) of the beam,
ρ mass density of the beam, and
A cross-sectional area of the beam.

The solution of this partial differential equation is generally accomplished by means of the separation of variables and is largely dependent on the boundary conditions at each end of the beam. Blevins (1993) has shown that a general form for the natural frequency for any mode (i) can be derived, as given in Eq. (2):

$$f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EI}{\rho A}\right)^{\frac{1}{2}} \tag{2}$$

where
f_i is natural frequency,
λ_i a factor dependent on the boundary conditions of the beam, and
L beam span.

Consider the vibration of a beam supported at the ends. If vibration is restricted to the first mode, Eq. (2) can be rearranged to obtain an expression for stiffness (EI):

$$EI = \frac{f^2 W L^3}{kg} \tag{3}$$

where f is the fundamental natural frequency (first bending mode), k is defined as a system parameter dependent on the boundary conditions of the beam (pin–pin support: $k = 2.46$; fix–fix support, $k = 12.68$), W is weight of the beam (uniformly distributed), and g is acceleration due to gravity.

EXPERIMENTAL PROCEDURE

Laboratory floor systems

Twelve wood floor systems were tested under laboratory conditions at Michigan Technological University (designated as MTU floors). The floors were constructed with nominal 2- by 4-in. (standard 38- by 89-mm), nominal 2- by 6-in. (standard 38- by 140-mm), and nominal 2- by 10-in. (standard 38- by 235-mm) joists. Joist materials included three wood species (jack pine, spruce–pine-fir, and white pine), and their strength properties ranged from low to high in terms of *E*-rating values. Each floor was constructed of five joists spaced 12 in. (305 mm) on center. Spans of 91, 113, and 137 in. (2.32, 2.87, and 3.48 m) were used. The jack pine solid sawn joists were cut from fresh and dead (contained decay) trees. White pine joists were from 100-year-old salvaged materials. The combinations of different joist size and floor span, plus high and low *E* materials, provided a wide range of dynamic and static performance. The joists were laterally braced by cross bridging at 1/3 and 2/3 of the span. The floor decking was transverse 1- by 4-in. (25- by 102-mm) spruce–pine–fir (SPF) boards fastened by dry wall screws.

Boundary conditions

Theoretically, a simply supported end condition provides no moment resistance, while a fixed end condition provides infinite capacity to carry moment. The true boundary conditions in real floor structures cannot be absolutely known from visual inspection of the floor or floor plans. However, laboratory floor systems can provide an opportunity to investigate how the floor response under a forcing function is affected by different end conditions, from nearly free to the condition that approximates a "real world" floor.

In this study, floors were tested at five different end conditions. First, each floor was supported by two steel pipes at the ends to approximate a simply supported boundary condition. This was necessary because the proposed analytical model needs to be validated with experimental data under an ideal boundary condition before it can be applied. Then, each floor was tested while the ends were supported with aluminum bars (simulation of hard supports), decayed jack pine boards (simulation of soft supports), and decayed jack pine boards with a layer of neoprene material on top of the boards (simulation of super-soft supports). These conditions were examined because they are often encountered in some floor structures where one end of the joists rests on a wooden or steel girder instead of a masonry wall. The soft supports were used to mimic floor joist ends resting on decayed wooden sill plates. Finally, the floors were tested with the ends of joists embedded in prefabricated masonry pockets, which simulates the end conditions of typical floor structures in existing buildings.

Vibration tests

All laboratory-constructed floor systems were subjected to forced vibration testing. The forced vibration approach employed is a purely time domain method as described in previous work (Soltis et al. 2002). We used this method as our main approach because it could enable a stronger response by use of a larger forcing function, which is desired when real floor structures are inspected. The other advantage of this forced vibration method is that it eliminates the need for modal analysis and is easy to perform in realworld applications.

Figure 2 shows the experimental setup for conducting forced vibration testing on laboratory floor systems. The vibration was imposed by a motor with an eccentric rotating mass attached to the floor decking. Placing the motor at the quarter-point of span over the center joist ensured that the simple bending mode of floor vibration would be excited. The response to vibration was measured under the center joist at midspan using a linear variable differential transducer (LVDT). The time–deflection signal was recorded by an oscilloscope. To locate the fundamental natural frequency in bending mode,

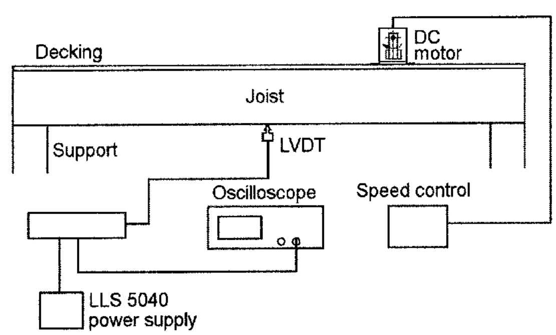

FIG. 2. Experimental setup for forced vibration testing of wood floor system.

the motor speed was slowly increased from rest until the first local maximum displacement response was located. The period of vibration was then estimated from 10 cycles of this steady-state motion.

The drawback of the forced vibration approach is the assumption that the first maximum acceleration found corresponds to the simple bending mode of the structure. A parallel research on timber bridges by Morison et al. (2002, 2003) showed that the frequency measured by the forced vibration method might correspond to a mode other than the bending mode in some cases. An error could occur when other modes (typically torsion) were misidentified as the bending mode. To verify the results from forced vibration testing, free vibration testing was also performed on each floor system to measure the fundamental natural frequency in bending mode. Free vibration was initiated by impact from a hammer, and the fundamental natural frequency was determined as the inverse of the period measured from the time-domain signal.

Load–deflection analysis

To correlate the natural frequency of floor systems to a measure of structural performance, the floors were also evaluated by load–deflection analysis, which provided a more direct measure of floor stiffness, the *EI* product. The static load testing was done by placing 236 lb (107 kg) of line load in five increments across the structure at midspan and measuring the deflection response of the center joist, again at midspan, with a dial indicator. Since the load was distributed evenly across the width of the floor, the *EI* product was therefore estimated directly from the load–deflection data based on the beam bending equation

$$EI = \left(\frac{P}{\Delta}\right)\left(\frac{L^3}{48}\right) \tag{4}$$

where P is static load (lb), Δ midspan deflection (in.), and L floor span (in.).

RESULTS AND DISCUSSION

Table 1 summarizes the physical characteristics and measured natural frequencies of the floor systems. The frequency data of floor 5 were not obtained because of the possible high frequency of this floor and the speed limitation of the motor. Floor 5 was therefore excluded from data analysis.

A comparison of measured natural frequencies from free vibration and forced vibration showed that the results from the two methods

TABLE 1. *Physical characteristics and measured natural frequencies of laboratory floor systems.*[a]

				Measured natural frequency (Hz)					
				Pinned support			Masonry pocket support		
Floor no.	Joist size[b] (in.)	Span (in.)	Weight (lb)	Forced	Free	Difference (%)	Forced	Free	Difference (%)
1	2 by 4	91.25	108	21.0	21.2	−0.94	26.7	28.7	−6.97
2	2 by 4	91.25	110	20.0	20.5	−2.44	21.3	22.3	−4.48
3	2 by 4	91.25	111	16.2	16.5	−1.82	21.7	22.7	−4.41
4	2 by 4	113	140	15.3	15.6	−1.92	20.7	22.0	−5.91
5	2 by 10	113	223	—	—	—	—	—	—
6	2 by 4	113	146	13.8	14.0	−1.43	15.5	16.4	−5.49
7	2 by 4	11.3	126	11.6	11.8	−1.69	14.5	15.4	−5.84
8	2 by 6	113	163	23.8	24.5	−2.86	24.2	24.8	−2.42
9	2 by 4	113	136	11.3	11.4	−0.88	13.8	14.1	−2.13
10	2 by 4	137	171	10.6	10.7	−0.93	14.1	14.9	−5.37
11	2 by 4	137	168	10.3	10.4	−0.96	12.7	12.9	−1.55
12	2 by 4	137	157	8.0	8.1	−1.23	10.0	10.5	−4.76

[a] One inch = 25.4 mm. 1 lb = 0.454 kg.
[b] Nominal dimensions.

matched quite closely, differing less than 3% for the simple support condition and less than 7% for the masonry support condition. This indicated that the lowest bending mode of each floor's vibration was properly captured by the forced vibration method.

Figure 3 shows the results of a floor system (floor 4) tested at various end support conditions. Examination of this figure revealed that the natural frequency from forced vibration was about the same for the pinned, hard, soft, and super-soft end support conditions. The hardness of end-supporting materials apparently had little or no effect on the natural frequency of the floor. In contrast, the masonry pocket end supports yielded a higher frequency than did the pinned end supports because of the possible constraints added to the ends of the joists. The increase in measured frequency for the masonry pocket supports was from 20% to 35% for most floor systems tested except floors 2 and 7, which had an increase in frequency of less than 10%. This difference in frequency increase was mainly a result of the different constraint forces existing on each floor. This indicated that, even with the same end support structure, the end conditions could vary from floor to floor as a result of construction variability.

It should be mentioned that the end support conditions simulated in this experimental study are still limited compared to the situations that might occur in real-world floor structures. For example, in contemporary floor systems, one support condition that could affect the vibrational response of the structure is when one end of the floor joists is supported on a flexural beam or girder. This beam support could cause a significant drop in the fundamental frequency of the floor system. The use of soft or super-soft support will not simulate the flexible condition that a beam would provide. The effect of flexible support conditions on the vibrational response of floor systems should be carefully examined in future studies.

The proposed model (Eq. (3)) represents a possible relationship between natural frequency and section modulus (*EI* product) of a floor structure. This model needs to be examined with experimental data for its validity. Figure 4 shows theoretical predictions for two extreme supporting conditions (free–free and fixed–fixed) and experimental data obtained under masonry pocket end conditions. Here, EI/WL^3 was treated as the independent variable and natural frequency as the dependent variable. The natural frequency was predicted over a range of EI/WL^3 assuming both simply supported and fixed boundary conditions. The measured results un-

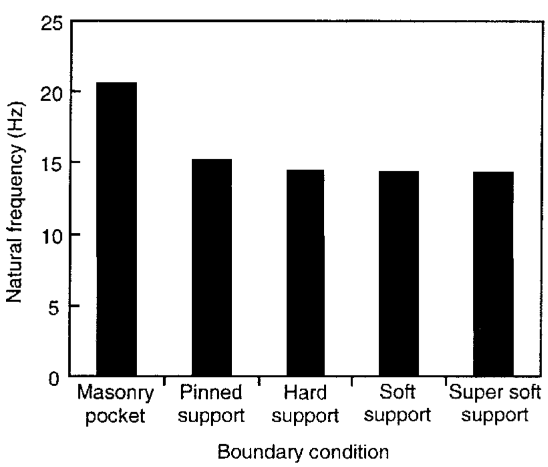

FIG. 3. Natural frequency of floor system (floor 4) measured at various end support conditions.

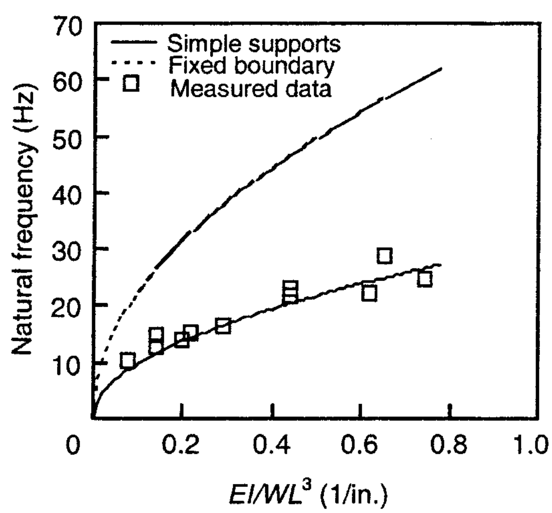

FIG. 4. Theoretical predictions for simple support and fixed boundary conditions and experimental data obtained under masonry pocket end conditions.

der masonry pocket end conditions were then superimposed on the same set of axes. We observed that measured results lie close to the simple support boundary predictions. A closer examination of Fig. 4 indicated that the measured data of most floor systems actually fell between simple support and rigidly fixed boundary conditions, with a distinct bias toward the simply supported prediction. Only two floors (floors 2 and 8) fell a little below the simple supported prediction.

This result essentially suggests that the theoretical model generated from the simple beam theory fits the physics of wood floor structures and is therefore a valid representation of the relationship between natural frequency and *EI* product of floor systems. However, for this model to be useful, an overall system parameter (k) that best describes the boundary conditions of the floor systems investigated should be determined from experimental data.

The analytical model in Eq. (3) was applied to the measured *EI* product and natural frequency for the floors tested under masonry pocket end conditions. A system parameter (k) was therefore estimated for each floor. These results were then averaged to provide an overall system parameter that best describes the entire population. The average system parameter was determined to be $k = 2.65$, with a standard deviation of 0.533.

With newly developed system parameter k, the model in Eq. (3) could be used to predict the natural frequency of a floor using measured *EI* product. Figure 5 illustrates the relationship between predicted frequency from the model and measured frequency from forced vibration. Regression analysis of data revealed a strong linear correlation ($R^2 = 0.93$) between predicted frequencies and measured values. This again supports the previous observation that the theoretical model is applicable to wood floor structures.

From the perspective of in-place inspection, a possible implementation scheme is to use the measured natural frequency to predict *EI* product for each floor system. To investigate the error of the model on stiffness prediction, we calculated *EI* product for each floor using measured

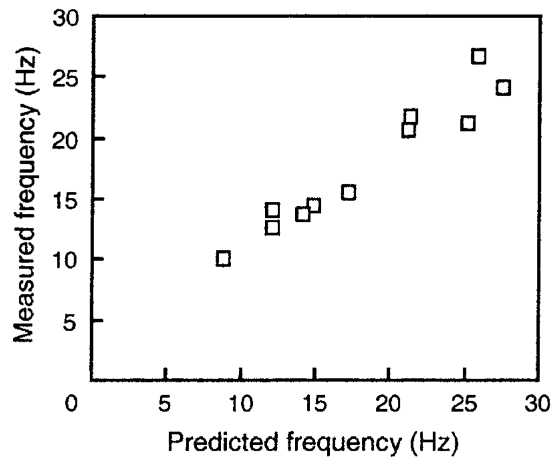

FIG. 5. Relationship between predicted and measured frequencies of floor systems under masonry pocket end conditions.

frequency and the overall system parameter ($k = 2.65$) and made a comparison against the measured *EI* product. The result (Fig. 6) shows quite a bit of variation, from 4% minimum to 37% maximum difference (in absolute value). We speculate that this variation is primarily caused by the composite action in floor systems and the natural variation of floor construction. For example, the composite action between the sheathing and the joists (both across the width of

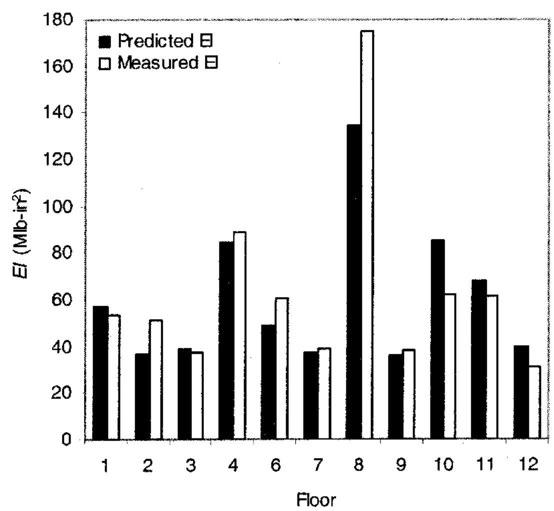

FIG. 6. Predicted *EI* product and percentage of difference with measured *EI* products of floor systems.

the floor and along the length of a single joist) is very variable due to the discontinuity of lumber sheathing and the type of connection used. The fixity or the constraint of end supports, on the other hand, may also vary from floor to floor due to construction variability. Another contributing factor could be the small sample size. If more floors had been available, more representative average system parameters could have been obtained.

CONCLUSIONS

The forced vibration method was used to measure the fundamental natural frequency of laboratory-constructed floor systems at various end support conditions. An analytical model based on beam theory was proposed to represent the relationship between natural frequency and *EI* product of the floors. From the results of this laboratory investigation, the following conclusions can be drawn:

- The forced vibration method is capable of measuring the natural frequency (bending mode) of wood floor structures.
- The hardness of end-supporting materials has little or no effect on the natural frequency of a floor. In contrast, the masonry pocket end supports, which simulate the end conditions of typical floor structures in existing buildings, yield a higher frequency than do pinned end supports.
- The analytical model generated from the simple beam theory fits the physics of the floor structures investigated and has a potential to be used to correlate the natural frequency to *EI* product. However, for the model to be applied to floor inspection, it needs to be calibrated with field data from in-place floor systems.

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