LOW FREQUENCY VIBRATION APPROACH TO ASSESS THE PERFORMANCE OF WOOD STRUCTURAL SYSTEMS

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ABSTRACT. The primary means of inspecting buildings and other structures is to evaluate each structure member individually. This is a time consuming process that is expensive, particularly if sheathing or other covering materials must be removed to access the structural members. This paper presents an effort to use a low frequency vibration method for assessing the structural performance of wood floor systems.

INTRODUCTION

Existing wood structures require rigorous and timely inspections to ensure the safety and structural performance. In general, structure inspection requires that some indicating parameter be monitored that is 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 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 systems.

In a previous study [1], we conducted a pilot investigation on three laboratory-constructed wood floors and addressed several practical problems on the use of transverse 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

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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 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. 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. A final problem was to inspect a floor with superimposed loads that are not easily removed. It was concluded that 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 results from the previous study are limited in scope. The objectives of this study were to extend the investigation of transverse 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.

ANALYTIC MODEL

An analytic model is used to relate the stiffness properties of the floor to its fundamental natural frequency for inspection purpose. Continuous system theory has been chosen as the means for developing a theoretical vibration model that is 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 (Figure 1). In previous studies [4,5], 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 provide lateral bracing

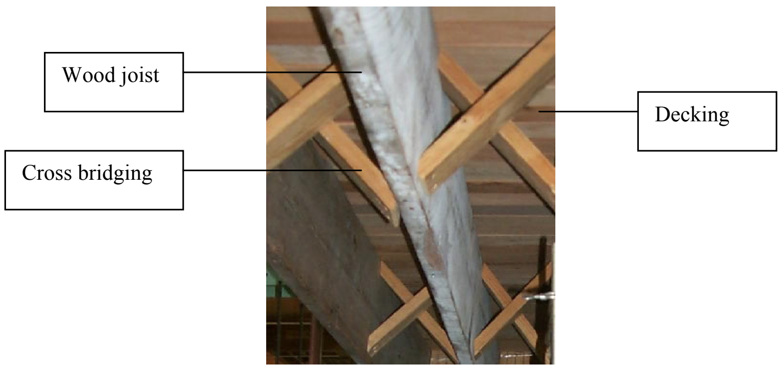

FIGURE 1. Structural details of a typical wood floor system.

to the joists. Thus, we assumed that a floor system behaves predominately like a beam with resisting moments in 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 below:

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

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. Bodig and Jayne [1] have shown that a general form for the natural frequency can be derived, and given in equation (2).

$$f = \frac{2\pi}{\lambda^2}\left(\frac{EI}{\rho A}\right)^{\frac{1}{2}} . \tag{2}$$

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

Consider the vibration of a beam supported at the ends, if vibration is restricted to the first mode (λ $2L$), Equation (2) can be rearranged to obtain an expression for the stiffness (EI):

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

where k is a system parameter dependant on the boundary conditions of the beam (pin-pin support: k = 2.46; fix-fix support, k = 12.65), M weight of the beam (uniformly distributed), and g acceleration due to gravity.

EXPERIMENTAL PROCEDURE

Laboratory Floor Systems

Twelve wood floor systems were tested in laboratory condition at Michigan Technological University (designated as MTU floors). The floors were constructed with 2 by 4 in. (51- by 102-mm), 2 by 6 in. (51- by 152-mm), and 2 by 10 in. (51- by 254-mm) joists. Joist materials included three different 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 four joists spaced 12 in. (305 mm) on center, with a span of 91, 113, or 137 in. (2.32, 2.87, and 3.48 m) respectively. 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 E and low E materials, could provide 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 carrying capacity while a fixed end condition provides infinite capability to carry moment. The true boundary conditions seen in real floor structures cannot be absolutely known from visual inspection of the floor or floor plans. However, the 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 one that is close to the real world floor. In this study, the 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), respectively. These conditions were examined because they are often occurred in some floor structures where one end of the joists sits on a wooden or steel girder instead of a masonry wall. The soft supports were used to mimic floor joist ends resting on wooden sill plates that were decayed. Finally, the floors were tested with the ends of joists imbedded in prefabricated masonry pockets. This 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 the previous paper [5]. This method was investigated as a main approach in this study 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 the real world 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. By placing the motor at midspan over the center joist, it is assured that the simple bending mode of floor vibration will be excited. The response to vibration was measured at the bottom of the center joist 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, the motor's speed was slowly increased from rest until the first local maximum response acceleration is located. The period of vibration is then estimated from ten cycles of this steady state motion.

The drawback of this forced vibration approach is the assumption that must be made: the first maximum acceleration found corresponds to the simple bending mode of the structure. A parallel research on timber bridges by Morison et al. [2,3] showed that the frequency measured by 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.

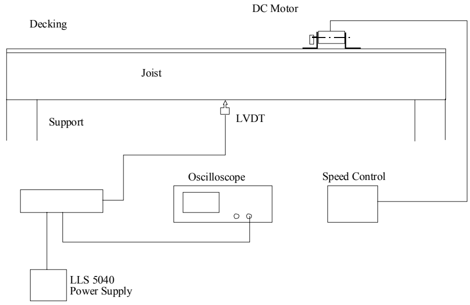

FIGURE 2. Experimental setup for forced vibration testing of a wood floor system.

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's stiffness, *EI* product. The static load testing was done by placing 236 pounds 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 a floor's width, the *EI* product was therefore estimated directly from the load-deflection data based on the beam bending equation:

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

where P is static load (lbs), 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 4 was not obtained due to its possible high frequency and the speed limitation of the motor. Floor 4 was therefore excluded from data analysis.

A comparison of measured natural frequencies from free vibration and forced vibration showed that the results from two methods matched quite closely, differing less than 3% for the simple support condition and less than 7% for the masonry support condition. This indicates that the lowest bending mode of each floor's vibration was properly captured by 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. It appeared that the hardness of end supporting materials had little or no effect on floor's natural frequency. In contrast, the masonry pocket end supports yielded a higher frequency than pinned end supports due to 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 percent for the most floor systems tested except for floor 2 and 7, which had an increase

TABLE 1. Physical characteristics and measured natural frequencies of the floor systems.

Floor No.	Joist size (in.)	Span (in.)	Weight (lb)	Measured natural frequency (Hz)					
				Pinned support			Masonry pocket support		
				Forced	Free	Percent Difference (%)	Forced	Free	Percent Difference (%)
1	2 by 4	91.25	108	21	21.2	-0.94	26.7	28.7	-6.97
2	2 by 4	91.25	110	20	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	-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	113	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	8.1	-1.23	10	10.5	-4.76

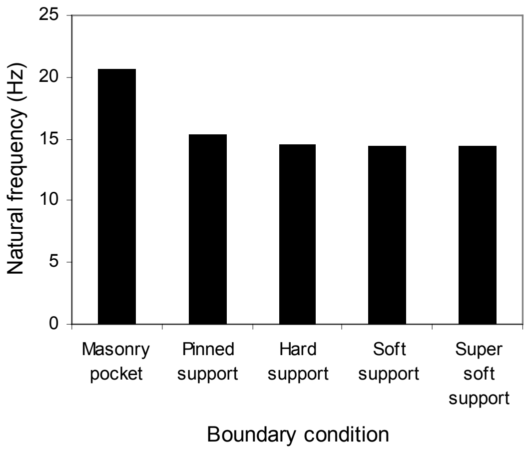

FIGURE 3. Measured natural frequencies of a floor system at various end support conditions.

in frequency less than 10 percent. The difference in this frequency increase was mainly due to the different constraint forces existed 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.

The proposed model (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 experimental data and boundary predictions. Here, EI/ML^3 was treated as the independent variable, and natural frequency as the dependent one. The natural frequency was predicted over a range of EI/WL^3 assuming both simply supported and fixed boundary conditions. The measured results under masonry pocket end conditions were then superimposed onto the same set of axes. It can be seen from Figure 4 that measured results lie close to the simple support boundary predictions. A more close examination of this figure indicated that the

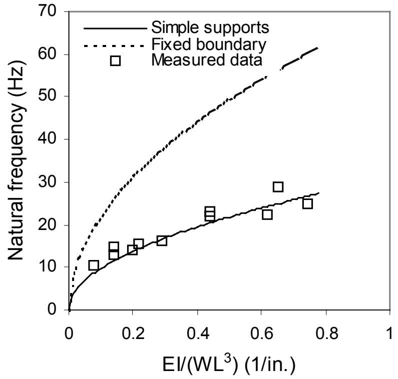

FIGURE 4. Measured data and boundary predictions.

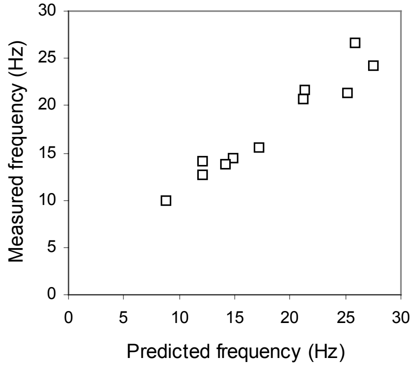

FIGURE 5. Relationship between predicted and measured frequencies.

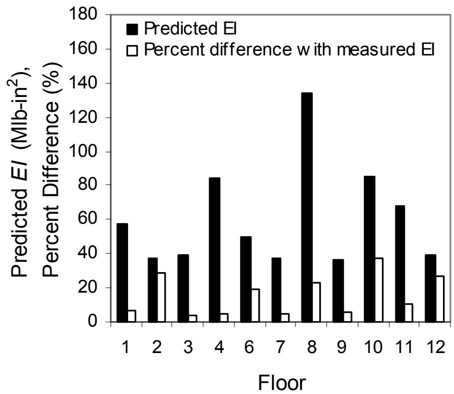

FIGURE 6. Predicted EI product and percent difference with measured EI.

measured data of the most floor systems were actually fall between simple support and rigidly fixed boundary conditions, with a distinct bias toward the simply supported prediction. Only two floors (Floor 2 and 8) fall a little bellow 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 therefore is a valid representation of the relationship between natural frequency and *EI* product of floor systems. However, in order 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 analytic model in equation (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 equation (3) can be used to predict floor's natural frequency using measured EI product. Figure 5 illustrated 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 conclusion that the theoretical model is appropriate to the wood floor structures.

From the perspective of in-place inspection, a possible implementation scheme was 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 frequency and the overall system parameter and made a comparison against the measured EI product. The result (Figure 6) shows quite a bit of variation, from 4 percent as a minimum, to 37 percent maximum difference (in absolute value). It is believed that the natural variation of floor construction is the main error source. The second contributing factor could be the small sample size. If more floors had been available, more representative averages could have been obtained.

CONCLUSION

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

1. Forced vibration method is capable of measuring the natural frequency (bending mode) of wood floor structures investigated.

2. The hardness of end supporting materials had little or no effect on floor's natural frequency. In contrast, the masonry pocket end supports, which simulated the end conditions of typical floor structures in existing buildings, yielded a higher frequency than pinned end supports.

3. The analytical model generated from the simple beam theory fits the physics of the floor structures investigated and can be used to correlate the natural frequency to EI product. However, in order for the model to be applied to floor inspection, it needs to be calibrated with field data from in-place floor systems.

REFERENCES

1. Bodig, J. and Jayne, B. A. *Mechanics of Wood and Wood Composites*. Van Nostrand Reinhold Company Inc. New York, 1982, pp.263-264.
2. Morison, A.M., Van Karsen, C.D., Evensen, H.A., Ligon, J.B., Erickson, J.R., Forsman, J.W., and Ross, R.J. "Nondestructive evaluation of timber bridges: a global approach using impact generated FRFs," In: Proceedings, Twentieth International Modal Analysis Conference and Exposition on Structural Dynamics, Los Angeles, CO. February 4-7, 2002. pp. 1567-1573.
3. Morison, A.M., Van Karsen, C.D., Evensen, H.A. and Ligon, J.B. Dynamic response of timber bridges as a tool to measure structural integrity. *Experimental Techniques.* **27(3)**, 25-28 (2003).
4. Ross, R.J., Wang, X., Hunt, M.O. and Soltis, L.A. Transverse vibration technique to identify deteriorated wood floor systems. *Experimental Techniques* **26(4)**, 28-30 (2002)
5. Soltis, L.A., Wang, X., Ross, R.J. and Hunt, M.O. Vibration testing of timber floor systems. *Forest Prod. J.* **52(10)**, 75-81(2002).