NONDESTRUCTIVE STRUCTURAL EVALUATION OF WOOD FLOOR SYSTEMS WITH A VIBRATION TECHNIQUE

Xiping Wang, Robert J. Ross
USDA Forest Service, Forest Products Laboratory, Madison, WI 53705-2398

Michael O. Hunt
Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907-1200

Lawrence A. Soltis
USDA Forest Service, Forest Products Laboratory, Madison, WI 53705-2398

ABSTRACT

The objective of this study was to determine if transverse vibration methods could be used to effectively assess the structural integrity of wood floors as component systems. A total of 10 wood floor systems, including 3 laboratory-built floor sections and 7 in-place floors in historic buildings, were tested. A forced vibration method was applied to the floor systems to determine the natural frequency and assess the stiffness and structural integrity. The results show that deterioration in wood floor systems can be identified by measuring damped natural frequency of those floors. The forced vibration method used in this research holds promise as an inspection tool.

INTRODUCTION

Currently, inspection and evaluation of existing timber structures has been limited to evaluating each structural member individually [2], which is a labor-intensive, time consuming process. For in-place inspection of timber structures, a more efficient strategy would be to screen whole structural systems or sub-systems in terms of their overall performance. Examining the dynamic response of the structure system might provide an alternative to gain insights into the ongoing performance of the system. Deterioration caused by any organism reduces the strength and stiffness of wood components and thus could affect the dynamic behavior of the system. If, for example, one structural system or sections of the system were found to respond to dynamic loads in a manner significantly different from 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 transverse vibration techniques to inspect full-size wood floor systems by evaluating component systems. This report summaries the experimental results that we obtained from recent research activities.

ANALYTIC MODEL

The floor systems we studied are typically constructed of wood joists, cross bridging, and decking (Figure 1). In previous studies [3], 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 transverse direction. The total mass of the deck and cross bridging is distributed into the assumed mass of the joists.

Figure 1. Typical wood floor system constructed with solid-sawn wood joists, cross bridging, and deck boards

The partial differential equation (PDE) governing the transverse vibration for a simple flexure beam is given below:

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

The solution of this partial differential equation is largely dependent on the boundary conditions at each end of the beam. Bodig and Jayne (1982) have shown that a general form for the natural frequency can be derived, and given in equation (2).

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

where f is fundamental natural frequency,

ρ – mass density of the beam,
A - cross sectional area of the beam,
EI - stiffness (modulus of elasticity E H moment of inertia I).

Consider the vibration of a beam simply supported at the ends, if vibration is restricted to the first mode (8=2L), Equation (2) can be rearranged to obtain an expression for the stiffness (*EI*):

$$EI = \frac{f^2 ML^3}{2.46g} \qquad (3)$$

where M is beam mass (uniformly distributed),

L - beam span,
g - acceleration due to gravity.

EXPERIMENTAL PROCEDURE

A schematic diagram of our experimental setup is shown in Figure 2. The floor system was subjected to a forced vibration. The vibration was imposed by a motor with an eccentric rotating mass attached to the floor decking. The motor speed could be continuously changed to a maximum of 1800 rpm. The rotating mass weighed 251 g with an eccentricity of 30 mm. The response of the floor system to vibration was measured at the bottom of the center joist using a linear variable differential transducer (LVDT). Output from the LVDT was observed with a Nicolet Model 310 Digital Storage Oscilloscope. Using this setup, the damped natural frequency was observed by increasing motor speed until maximum deflection was observed. Damped natural frequency was then determined from the time-deflection data displayed by the oscilloscope.

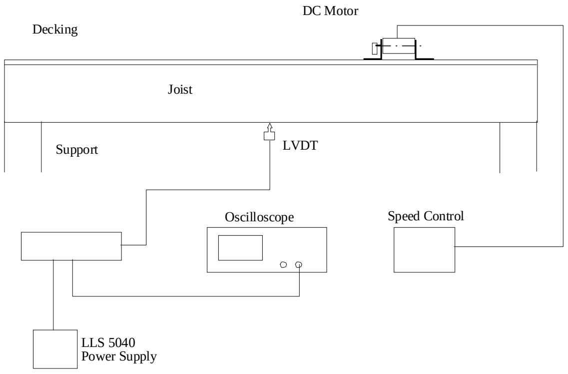

Figure 2. Experimental setup for forced-vibration testing of wood floor systems

Static bending tests were then conducted on the floor system to obtain load-deflection data by adding several hundred kilograms static load at mid-span of the joists and distributed over the width of the floor system. With the assumption of a simply supported beam, the stiffness (EI) of the floor was calculated by

$$EI = \frac{PL^3}{48\Delta} \qquad (4)$$

Where, P is static load,

Δ - Deflection,
L – Floor span.

To examine the effectiveness and sensitivity of this experimental setup, we first used it to test three wood floor sections built in the laboratory. Each floor section was constructed of five 51 x 406 mm Southern pine joists spaced 30.4 cm on center, with a span of 5.94 m. Two of the floors were constructed of new materials; the third floor was constructed from salvaged material recovered from a demolished warehouse.

The experimental setup was then used to evaluate floor systems in an old multi-bay building in Lafayette, Indiana. Built around 1900, the building was adjacent to a railroad in downtown Lafayette and was used as a warehouse for shipping and receiving products by rail. The two story building was of typical construction for the period: masonry load bearing walls, wood joist and decking floor system and wood rafter and sheathing roof system. The floor joists were supported at one end in pockets in the masonry wall and at the other by timber girders, which were supported by a row of wood columns which was parallel and equidistant from the two outside masonry walls. During the past decade, the building underwent “demolition by neglect.” Two-thirds of the roof was totally missing except for the roof rafters; consequently, the wood floors below were in various stages of deterioration. The floors of a total of 7 bays were examined, 3 in the second floor and 4 in the third floor. These floors are in a progression of condition from dry and undamaged to wet and deteriorated. The floor systems were tested for both natural frequency and stiffness. We then compared the measured damped natural frequency with a floor system’s corresponding stiffness.

RESULTS

The location of the forcing function (motor) and LVDT measuring device is a practical concern in floor system inspection. We first examined the sensitivity of results when the motor and LVDT are at various locations in the lab-floor section. The LVDT was located at quarter and mid-span on both the center and edge joists. The motor was located at quarter and mid-span of the center joists. It was found that the location of motor and LVDT do not significantly affect the frequency. The measured frequencies were generally within 0.1 Hz of the average value that is within the experimental accuracy of measurement. This indicated that any location of either LVDT or motor was acceptable provided we could get a strong response signal.

Table 1 shows measured frequency and stiffness for both new and salvaged lab-floor sections. The measured frequency values are damped natural frequency due to a rotating mass type excitation. It is noted that salvaged floor section yielded a lower frequency (14.9 Hz) than the new floor sections (16.2 and 16.3 Hz). The lower frequency of the salvaged floor is due to its decreased stiffness (measured as 13.2 x 10^6 Nm^2), compared to the stiffness of new floor (14.9 x 10^6 Nm^2). This indicated that the effect of the deterioration in the salvaged floor was detectable by a decrease in frequency when compared to new floor sections.

Table 1. Comparison of results found from new and salvaged lab-built floor sections

Floor section	Measured natural frequency (Hz)	Floor stiffness EI (106 Nm2)
New floor I	16.2	14.94
New floor II	16.3	14.85
Salvaged floor	14.8	13.16

Figure 3 shows the relationship between stiffness and measured natural frequency of the real floor systems. The fundamental natural frequency of a structural system is dependent on the stiffness, mass, span, and boundary conditions of the system. For a continuous system that is pin supported on each end, the relationship between stiffness and natural frequency is described by equation (3). It can be seen that, given the weight and the span of floor systems, the stiffness of a floor is proportional to the square of fundamental natural frequency of the floor system. This relationship has been shown existed in real floor systems (Figure 3). Analysis revealed a strong linear relationship between floor stiffness and the square of measured natural frequency ($r^2 = 0.973$). The stiffness of inspected floor systems ranged from 8.53 to 50.87 x10^6 Nm^2. The corresponding natural frequency measured in these floors changed from 9.4 to 21.7 Hz. Based on testing results, three floor systems (f = 10.4, 10, and 9.4 Hz) had been identified as severely deteriorated and lost serviceability, one floor system (f = 12.3 Hz) was questionable and required further inspection, and three floors (f = 13.2, 16.1, and 21.7 Hz) were identified in good conditions.

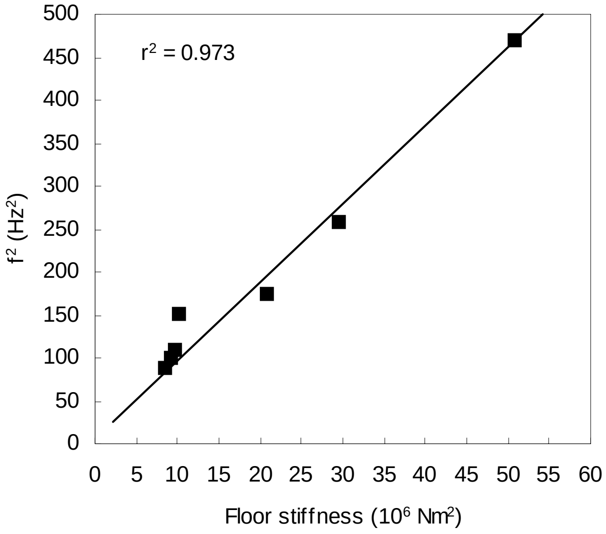

Figure 3. Relationship between measured natural frequency and floor stiffness

CONCLUSION

The preliminary data presented in this paper shows that a linear relationship exists between floor stiffness and the square of measured natural frequency. The effects of the deterioration in wood floor systems can be detected by measuring damped natural frequency of floor systems. The forced vibration technique utilized in this research holds promise as an inspection tool. Further research is necessary to see if similar results are obtained for a range of floor spans and joist sizes with different levels of deterioration.

REFERENCES

1. Bodig, Jozsef, Benjamin A. Jayne. Mechanics of Wood and Wood Composites. Van Nostrand Reinhold Company Inc. New York. 1982.

2. Ross, R.J. and R.F. Pellerin. Nondestructive testing for assessing wood members in structures: A review. GEN. TECH. REP. FPL-GTR-70 (Rev.). Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 40p. 1994.

3. Soltis, L.A., X. Wang, R.J. Ross, and M.O. Hunt. Vibration testing of timber floor systems. Forest Products Journal. 2002 (To be published).

Wang, X., R. J. Ross, M. O. Hunt and L. A. Soltis. 2002 Nondestructive structural evaluation of wood floor systems with a vibration technique. In: Proceedings of the 2002 Society of Experimental Mechanics Annual Conference and Exposition on Experimental and Applied Mechanics, June 10-12, 2002, Milwaukee, WI. pp. 260-262.