

Floor Vibration: A Possible Assessment Method for Historic Buildings

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A new noninvasive technique has the potential to assess the in-place stiffness of timber floors.

The United States Department of Agriculture Forest Service, Forest Products Laboratory, has been developing non-destructive evaluation techniques to identify the degradation of wood in structures and the performance characteristics that remain in the structure. The work at the Forest Products Laboratory has focused on dynamic testing techniques, particularly stress-wave and ultrasonic-transmission nondestructive evaluation techniques for both laboratory and field investigations.

Our initial efforts were aimed at using stress-wave techniques. In a previous publication, we reported on an inexpensive experimental technique that was developed to observe longitudinal stress-wave behavior in small wood specimens.¹ The technique utilized a mechanical impactor to induce a wave in the specimens. Wave propagation in the specimens was observed by placing a piezo film sensor on the wood's surface. Output of the sensor was recorded and

displayed on a digital storage oscilloscope. This technique enabled us to examine fundamental wave propagation characteristics and the biological degradation of wood.

More recently we investigated the speed of sound transmission to locate degraded regions in wood material.² The test setup we developed consisted of two 84-kHz rolling transducers coupled to an ultrasonic transmitting and receiving unit. A stress wave was introduced into a specimen in the transverse direction by the transmitting transducer. The wave was then received by the opposing transducer after it traveled through the specimen. Stress-wave transmission times were displayed by the unit and recorded on a personal computer. Elevated transmission times indicated deterioration. With this technique, we were able to locate sections of deterioration in wood materials because the method was sensitive to decayed areas within the members.

Currently, the use of stress-wave techniques is limited to individual wood members. Evaluating each member of a structural system individually 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 subsystems in terms of their overall performance and serviceability. Examining the dynamic response of the structural system might provide insights 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 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

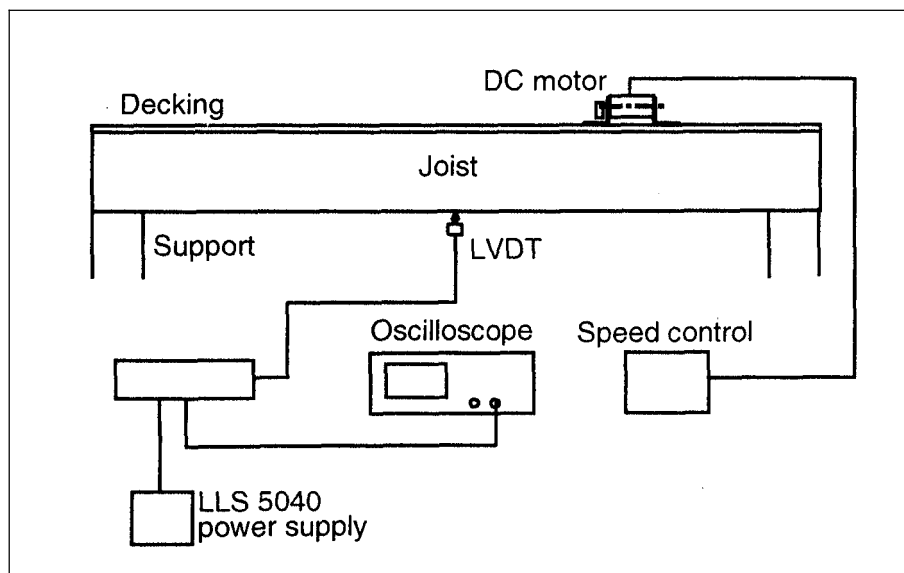


Fig. 1. Experimental setup for forced-vibration testing of wood floor systems

of that system or section would be warranted.

Based on this conceptual strategy, we began, in cooperation with Purdue University, to investigate the possibility of using a forced-vibration technique to inspect and evaluate full-sized wood floor systems. In the forced-vibration technique, the floors were set into vibration by a motor with an eccentric rotating mass attached to the floor decking. Response of the floor was monitored by an oscilloscope and used to determine the natural frequency of the floor. This article describes the testing setup that we developed for our research and the typical results obtained from its use in a historic building in Lafayette, Indiana.

Forced-Vibration Technique

Forced-vibration techniques have received considerable attention for non-destructive evaluation applications in the wood industry.³ It has been shown that for a beam simply supported at its ends, the modulus of elasticity (E) of a wood member is related to the frequency of oscillation by the following equation:

$$E = \frac{f^2 WL^3}{2.46 I_g} \quad (1)$$

where E is dynamic modulus of elasticity (Pa); f , natural frequency (Hz); W , beam weight (kg); L , beam span (m); I , beam moment of inertia (m^4); and g , acceleration due to gravity (9.8 m/s^2).

The wood floor systems are typically constructed of wood joists, cross bridging, and decking. In laboratory studies, we found that the stiffness of the joists predominates over the transverse floor sheathing. Thus, we assumed that a floor system behaves predominately like a beam with resisting moments in one direction only.

In-Place Floor Tests

In this study, the forced-vibration method was used to evaluate the wood-floor systems in a two-story, old, multibay building in Lafayette. Built c. 1900, the building was adjacent to a railroad in downtown Lafayette and had been used as a warehouse for shipping and receiving products by rail. It had typical con-

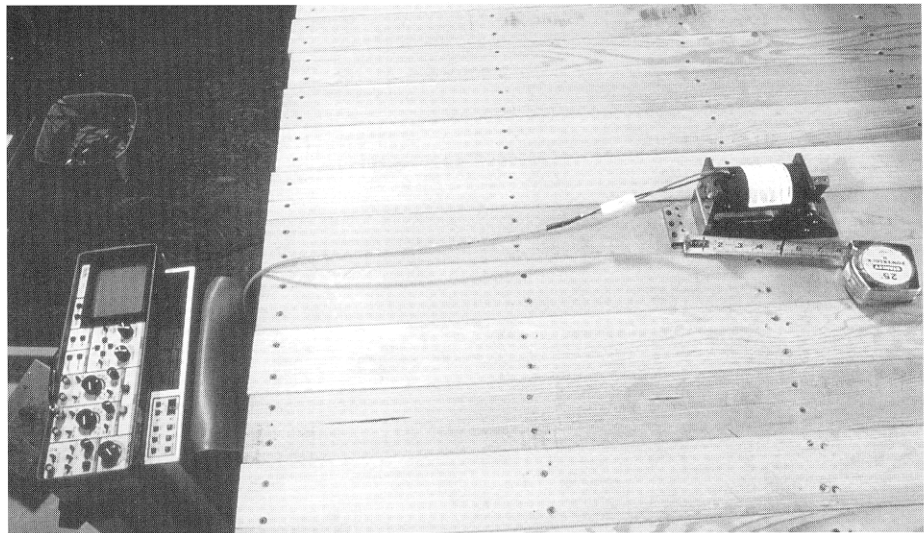


Fig. 2. The forced vibration was imposed by a motor with an eccentric rotating mass attached to the floor decking.

struction 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 that were 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 building was an excellent practical laboratory for in-place floor-evaluation research.

The floors of a total of seven bays were examined, three in the second floor and four in the third floor. These floors progress from dry and undamaged at the bottom to wet and deteriorated in the upper floors. The floor systems were tested for both natural frequency and stiffness. We then compared the measured damped natural frequency with the floorsystem’s corresponding stiffness.

Our testing setup is shown in Fig. 1. 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 (Fig. 2). The motor was at-

tached to a joist at approximately midspan. Our preliminary laboratory results revealed that the motor could be placed anywhere between quarter points to obtain comparable results. The motor speed could be continuously changed. The response of the floor system to vibration was measured at the bottom of the center joist with a linear variable differential transducer. Output from the linear variable differential transducer was observed with a Nicolet (Nicolet Instrument Corporation, Madison, Wisconsin) Model 310 digital storage oscilloscope. With this setup, the damped natural frequency was determined by increasing motor speed until maximum deflection was observed and then by measuring frequency from the time-deflection signal.

Static-bending tests were then conducted on the floor systems. To obtain load-deflection data, a static load (several hundred kilograms) was applied at midspan of the joists and distributed across the width of the floor system. The stiffness (EI) of the floor was calculated by

$$EI = \frac{PL^3}{48\Delta} \quad (2)$$

where P is static load (N); Δ , deflection (m); and L , floor span (m).

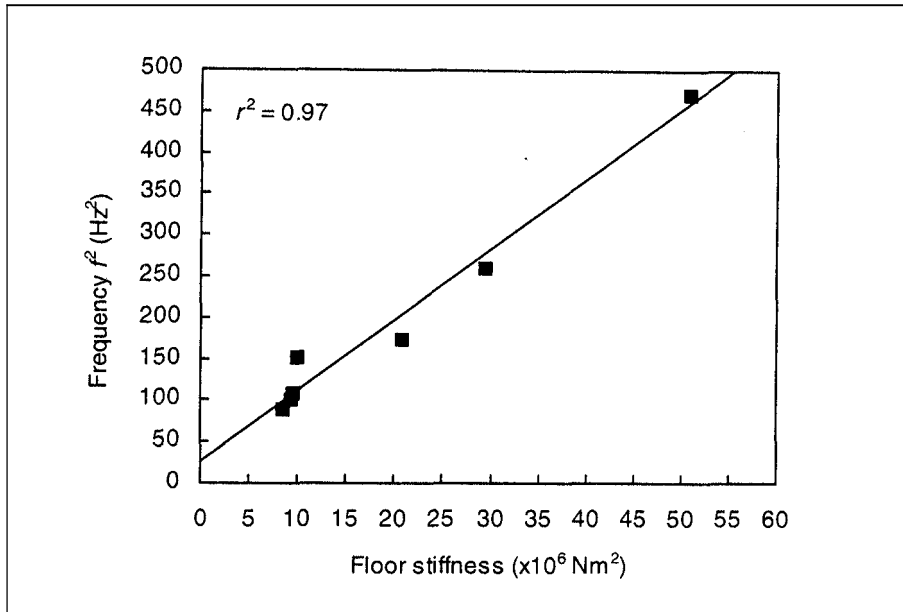


Fig. 3. Relationship between floor stiffness and measured natural frequency.

Results

The relationship between stiffness and measured natural frequency of the building floor systems is shown by Fig. 3. 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 can be expressed as

$$EI = \frac{f^2 W L^3}{2.46g} \quad (3)$$

where EI is the stiffness of the system. 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 to exist in the building floor systems (Fig. 3). Analysis revealed a strong linear correlation between floor stiffness and the square of measured natural frequency ($r^2 = 0.97$). The stiffness of inspected floor systems ranged from 8.53 to $50.87 \times 10^6 \text{ N}\cdot\text{m}^2$. The corresponding natural frequency measured in these floors ranged from 9.4 to 21.7 Hz . Based on testing results, three floor

systems ($f = 10.4$, 10 , and 9.4 Hz) were identified as severely deteriorated and had lost serviceability, one floor system ($f = 12.3 \text{ Hz}$) was questionable and required further inspection, and three floors ($f = 13.2$, 16.1 , and 21.7 Hz) were identified as being in good condition.

Potential Use

We believe that the forced-vibration technique has the potential to be used in older timber-framed structures that are being considered for adaptive reuse. In such structures, it is important to have a good estimate of the remaining stiffness of the floor sections. This technique may provide for a noninvasive method of estimating the stiffness of such floors. We feel that it will be a strong complement to visual and other inspection methods.

Conclusion

The preliminary data presented in this paper show that deterioration in wood floor systems can be detected by measuring damped natural frequency of those floor systems using a forced-vibration technique. The forced-vibration tech-

nique used 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 real deterioration.

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Notes

1. R. J. Ross, R. C. DeGroot, and W. J. Nelson, "Technique for Nondestructive Evaluation of Biologically Degraded Wood," *Experimental Techniques* 18 (1994 Sept./Oct.): 29-32.
2. R. J. Ross and R. C. DeGroot, "Scanning Technique to Identify Biologically Degraded Wood," *Experimental Techniques* 22 (1998 May/June): 32-33.
3. R. J. Ross and R.F. Pellerin, 1994. *Nondestructive Testing for Assessing Wood Members in Structures: A Review*. General Technical Report FPL-GTR-70 (Rev.). Madison, Wis.: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

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