PILOT STUDY TO EXAMINE USE OF TRANSVERSE VIBRATION NONDESTRUCTIVE EVALUATION FOR ASSESSING FLOOR SYSTEMS

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ABSTRACT

Evaluation of existing timber structures requires procedures to evaluate *in situ* structural members and components. This report evaluates the transverse vibration response of laboratory-built floor systems with new and salvaged joists. The objectives were to 1) compare floor system response to individual member response; 2) examine response sensitivity to location of the forcing function; and 3) compare the response of a floor constructed with new joists to that of a floor constructed with a combination of new and salvaged joists. Several floor systems were constructed from new and salvaged southern pine joists and tested using transverse vibration nondestructive evaluation techniques. The results indicate that joist response, and therefore joist stiffness, can be determined from a system approach with arbitrary location of the impact forcing function. The joist response is greatly dependent on the magnitude and location of the dead load it supports. The frequency of the floor system was reduced when salvaged joists were included in the system. But, it does not appear that individual degraded joists in the system can be detected from this type of test.

Restoration and repair of existing timber structures requires procedures to evaluate the condition, strength, and stiffness of *in situ* structural members and components. This is one of a series of reports related to the nondestructive structural evaluation of a timber floor system. The first report evaluated properties of new and salvaged individual floor joists (2). This report evaluates the free vibration responses of floor systems built in the laboratory using new and salvaged joists subjected to an impact forcing function. A future report will evaluate a floor system in an existing building and compare it to the individual floor joists and the laboratory-built system using both free and forced vibration. The objective of this research was to determine whether a system approach, as opposed to an individual member approach, is feasible to nondestructively evaluate a floor system. Specifically, this study 1) compared system responses to individual member responses; 2) examined the sensitivity of location of an impact forcing function and vibration measurement of the beam response; and 3) compared laboratory-built floor systems made with salvaged joists with some degree of degrade to a floor system made with new joists.

Most nondestructive evaluation (NDE) techniques are based on dynamic testing, either stress wave or vibration, of individual members. A summary of these techniques is given by Ross and Pellerin (7) and Arriaga et al. (1). *In situ* tests of floor systems are usually related to serviceability requirements based on human response to floor vibration. An overview of floor vibration design criteria is given by Dolan and Kalkert (3) and Dolan et al. (4). Experimental techniques for testing are given by Polensek (6) and Kermani et al. (5).

Transverse vibration NDE methods employed in this study are based on the relationship between stiffness and fre-

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quency of vibration. The fundamental natural frequency of a structural system is related to its stiffness by the following equation (7):

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

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

Equation [1] is derived from the characteristic equation of motion of a vibrating beam, which idealizes the continuous system as a mass, spring, dashpot system. The constant, 2.46, is based on boundary conditions for simply supported beams. Although Equation [**1**] represents an idealized system, its use for estimating the modulus of elasticity (MOE) of lumber is widely recognized. Consequently, we hypothesized that the relationship between frequency and stiffness may be useful in assessing the condition of in-service floor systems.

EXPERIMENTAL PROCEDURE

Three different floor systems were built at the Wood Research Laboratory at Purdue University, West Lafayette, Indiana. Each floor system was constructed with five randomly selected 50.8- by 406.4-mm southern pine joists spaced 304.8 mm on center, with a span of 8.23 m for the first two systems and 5.79 m for the third system **(Fig. 1).** The end supports were on blocked piers constructed of twenty 50.8- by 304.8-mm No. 1 or better southern pine plates stacked on top of each other. A 12.7-mm rod through the plates anchored the piers to the test floor **(Fig. 1). The** end supports for the floor systems simulated the floor in an existing building with a blocked pier arrangement. The joists were laterally braced by cross bridging 1.37 m on center. The floor decking was transverse 25.4- by 101.6-mm Douglas-fir boards fastened by 50.8-mm dry wall screws. The screws were necessary for the interchange of floor joists for the various floor systems tested.

Vibration of each floor system was initiated by an impact from a hammer. The free vibration response was measured at the bottom of each floor joist at the midspan using a linear variable differential transducer (LVDT). The time-deflection signal was recorded by oscilloscope and used to measure the fundamental frequency of each joist. A damped sine wave was observed for each system. Fundamental frequency was determined by measuring the time between successive peaks. A detailed description of the analysis procedure used is given in Ross and Pellerin (7).

The locations of the impact and the response measurement were varied. First, both impact and response were located at midspan of one joist. Then the impact was at midspan of that same joist, but the response location was at midspan of an adjacent joist. The response location was then moved to the midspan of the next joist. This sequence was repeated until readings were recorded with the response located at the midspan of all the joists. The impact location was then moved to the midspan of the next joist, and readings were taken with the response located at mid- span of all five joists until a complete matrix of impact and response locations was achieved.

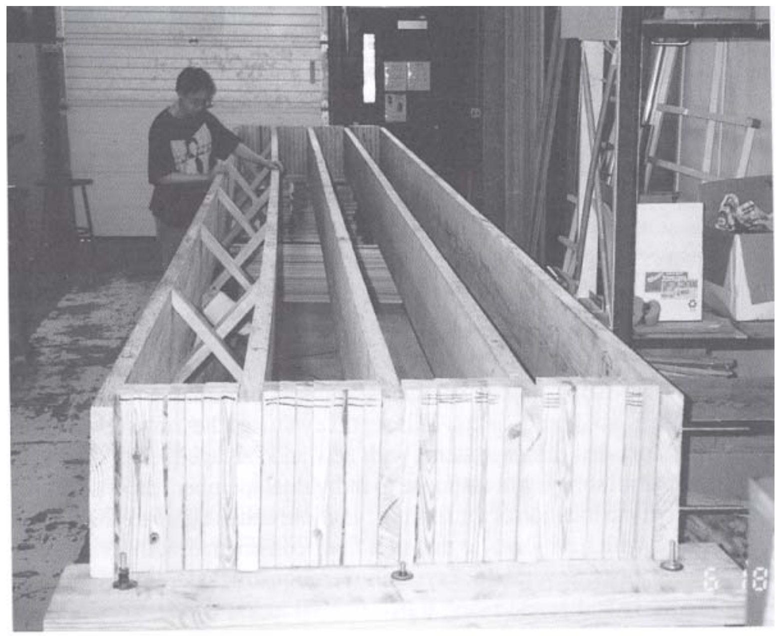

Figure 1. - Floor system under construction (top) and complete (bottom).

Fifteen new and nit& salvaged 50.8- by 406.4-mm joists were available. The salvaged joists were from a demolished warehouse built shortly after 1900. A visual inspection of the salvaged joists revealed seasoning checks and splits. Some of the salvaged joists had deteriorated material on their top edge where the subflooring had been nailed. Ultrasonic inspection through the cross section showed that decay did not extend beyond that which was visible.

TABLE 1. - Fundamental natural frequency of individual new joists used in the first two floor systems.

New joist no.	Frequency: Simply supported	Frequency: Blocked pier
	(Hz)	
Floorsystem 1		
4	14.5	12.8
5	12.8	14.1
7	14.6	13.0
2	13.7	13.7
1	13.2	11.4
Average	13.8	13.0
Floorsystem 2		
8	12.4	12.8
15	12.3	12.5
9	12.3	12.8
6	13.3	12.6
3	12.5	12.8
Average	12.6	12.7

The two floor systems with 8.23-m spans were constructed from the new joists. Five joists were randomly selected for each floor system, and the joists were then randomly positioned in the floor systems. The first floor system consisted of joist numbers 4, 5, 7, 2, and 1. The second system consisted of joist numbers 8, 15, 9, 6, and 3. The third floor system was constructed with a 5.79-m span because we were unable to locate salvaged joists with sufficient length to match the span of the first two floor systems. Different versions of the third floor system were constructed: one with all new joists (five joists), one with all salvaged joists (five joists), and three different combinations of new and salvaged joists. For the all-new version, the remaining five new joists were cut to the length of the salvaged joists and were randomly positioned. The salvaged joists in the new-and-salvaged-combined versions were those with the lowest stiffness, and they were randomly positioned in the floor system. The first combination of new and salvaged joists contained one salvaged joist and four new joists. Three configurations of this combination were built, with the salvaged joist in a different location each time (on the end, in the middle, or in one of the spaces in between the middle and the end). The second combination was two salvaged joists and three new joists. Six configurations were built of this combination, with the salvaged joists in different locations each time. The third combination was three salvaged joists and two new joists, which also resulted in six different configurations.

TABLE 2. -A comparison of the natural frequency of each joist as an individual and its natural frequency as part of a floor system.

New joist no.	Blockedpier individualjoist	Partialfloor bridging only	Partial floor bridging plus half deck	Floor system
		(Hz)		
Floor system 1				
4	12.80	12.40	11.70	10.70
5	14.10	12.00	11.10	10.40
7	13.00	11.80	11.10	10.30
2	13.70	11.70	11.10	10.40
1	11.40	12.10	11.10	10.50
Average	13.00	12.00	11.20	10.50
Floor system 2				
8	12.80	12.60	12.10	11.40
15	12.50	12.50	11.90	11.00
9	12.80	12.00	11.80	10.70
6	12.60	11.90	11.80	10.70
3	12.80	12.50	11.70	11.00
Average	12.70	12.30	11.90	11.00

RESULTS

Results from the first two floor systems apply to the following objectives:

- Comparing system response to individual joist response;
- Determining the sensitivity of sensor and forcing function location in response measurements.

Fundamental natural frequency results for the individual joists of the first two floor systems are given in **Table 1.** The MOE corresponding to the natural frequency for a simply supported beam end condition has been previously reported (2). Additionally, joists were tested with a blocked pier end condition to simulate the *in situ* floor. The blocked pier added a small but unknown amount of fixity to the support.

The results for the first two floor systems, which were comprised of joists, bridging, and decking, are given in **Tables 2, 3,** and **4. Table 2** compares the fundamental natural frequency of each joist as an individual (from **Table 1)** with its frequency as part of the floor system. The natural frequency is affected by change in stiffness (Eq. [**1**]) and load sharing. Thus, **Table 2** indicates frequencies at various stages of construction. Frequencies are given for the five joists connected by bridging only, for the five joists connected by bridging plus every other deck board, and for the entire floor system consisting of joists, bridging, and all deck boards. The values in **Table** 2 are based on locating both the impact forcing function and the LVDT sensor at midspan of the joists being evaluated. **Tables 3** and **4** indicate the sensitivity to locations of the impact forcing function and the LVDT sensor. All impacts and sensor measurements were made at midspan. For example, the natural frequency of joist number 7 was 10.5 Hz, which was found by measuring the midspan response of joist number 7 while impacting the midspan of joist number 4.

Results from the third floor system apply to the objective of comparing a floor made of new joists with one that may be degraded and consists of a combination of new joists and one, two, or three salvaged joists at various locations. The floor systems included bridging and decking. **Table 5** gives results for the joists vibrated individually on a simple support and then as part of the floor system. Both impact and response measurements were at midspan of the individual joists and at midspan of the center joist for the floor system. The natural frequencies in **Table 5** are for a 5.79-m span, whereas the frequencies in **Tables 1** through **4** are for an 8.23-m span. The floor decking was shimmed in areas of deterioration of the salvaged joists. We believe lower frequencies would have occurred if we had not shimmed. The average frequencies for the third floor system are given in **Table 6.**

Discussion

In this study, laboratory-built floor systems that simulated possible conditions of in-place floor systems were investigated to better understand the vibration characteristics of the in-place system. The ultimate objective was to determine stiffness of the in-place floor joists from the vibration characteristics. Equation **[1]** assumes joists are simply supported. An in-place floor system sits in a pocket in a masonry wall. In the laboratory-built systems, a blocked pier arrangement simulated this in-place end support. The effect of these boundary conditions are variable, with changes up to about 15 percent. This change is less than would be expected if the beams were fixed-ended as opposed to pin-ended Hence, the block pier arrangement adds little to the end fixity of the beams.

The average natural frequencies of the joists in floor systems 1 and 2 were 81 and 87 percent, respectively, of the frequency when the joists were tested individually **(Table 2).** This difference is attributed to the weight of the individual joists, which is about 75 percent of the weight of the joist, bridging, and decking. The discrepancy between the 75 and the 81 and 87 percent may be variability, some partial tee beam action affecting the moment of inertia, or some damping from load sharing with adjacent joists. The limited sample size of the two floor systems did not allow any study of the variability. The tee beam effect was studied by testing a system consisting of joists and bridging only and a system consisting of joists, bridging, and every other deck board removed **(Table 2).** Full tee beam effect would increase the

TABLE3. - Natural frequencies measured on each joist in floor system 1 with impact forcing function and LVDT at different locations.

Sensor location (joist no.)	Frequency: Impact location (joist no.) 4	5	7	2	1
	(Hz)				
4	10.7	10.6	10.4	10.4	10.4
5	10.4	10.4	10.4	10.4	10.4
7	10.5	10.4	10.3	10.4	10.5
2	10.3	10.4	10.4	10.4	10.5
1	10.4	10.3	10.3	10.4	10.5
Average	10.5	10.4	10.4	10.4	10.5

TABLE 4. - Natural frequencies measured one each joist in floor system 2 with impact forcing function and LVDT at different locations.

Sensor location (joist no.)	Frequency: Impact location (joist no.) 8	15	9	6	3
	(Hz)				
8	11.4	11.4	10.7	10.7	11.3
15	11.4	11	10.7	10.7	11
9	11.1	10.8	10.7	10.8	10.8
6	11.3	11	10.7	10.7	10.8
3	11.2	11.1	10.7	10.8	11
Average	11.3	11.1	10.7	10.7	11.0

frequencies considerably, which contradicts the results seen in Table 2. Thus, we concluded that using the moment of inertia of the individuals joists was appropriate. The load-sharing effect on system damping is outside the scope of this study.

To verify that difference in weight had the largest influence on joist frequency, we added an 11.3-kg weight and a 22.6-kg weight at midspan of joist 3. The frequency of the individual joist without the weight was 12.8 Hz (**Table 2**). Addition of the two weights resulted in the frequency decreasing to 11.9 and 10.8 Hz, respectively. These decreases are the same relative magnitude as seen when adding the decking and bridging. We also added two 11.2-kg weights at the quarter points from the ends of the span and measured a frequency of 11.4 Hz. This indicates that not only the weight itself but also the location might cause the free vibration deflection to be different.

It is not necessary to apply the impact forcing function to the joist of which response is being measured. Impacting the far edge joist resulted in approximately the same frequency for the near edge joist when the near edge joist was impacted **(Tables 3** and **4**). This has implications for testing in-place floors with limited accessibility.

The fundamental frequencies of individual and salvaged joists differed by about 15 percent **(Table 5**) due to differences in beam stiffness as previously reported (2). However, when the joists were incorporated into the floor system, the difference was about 7 percent. It appears that a systems effect is occurring, but we have no rational explanation for it.

Table 6 shows the effect of one, two, or three low-MOE salvaged joists combined with high-MOE new joists. This was intended to simulate if degraded joists could be determined from a system inspection. The floor frequency decreased as more salvaged joists were added. However, more floor systems need to be tested before concluding the usefulness of this procedure as an inspection tool.

Conclusion

This study examined the feasibility of using transverse vibration NDE in a

TABLE 5. - Natural frequencies of individual new and salvaged joists in floor system 3.

Position	New joist frequency		Salvaged joist frequency	
	Simple support	Floor system	Simple support	Floor system
	(Hz)			
1	21.2	16.9	18.9	17.1
2	19.8	17.2	19.8	17.1
3	21.9	17.1	17.9	15.6
4	22.1	17.2	16.2	15.2
5	21.2	17.1	20.2	15.2
Average	21.2	17.1	18.6	16.0

TABLE 6. -Average natural frequencies of the floor systems that included one, two, or three salvaged joists (floor system 3).

Floorsystem	Average frequency[a]	
	Salvaged joists on one side	Salvaged joists centered
	(Hz)	
One salvaged joist	16.7	16.9
Two salvaged joists	16.2	16.3
Three salvaged joists	16.1	15.3

[a] Average frequency of floor system with all new joists was 17.1 Hz, and that for a system with all salvaged joists was 16.0 Hz.

floor system. The location of the impact forcing function had no effect on the frequency of any individual joist in the system. However, it does not appear that individual degraded joists in the system can be detected from system impact vibration.

The magnitude and location of dead load is a predominate factor in determining fundamental frequency and, hence, joist stiffness. The difference in weight between a single joist and a joist with bridging and decking accounted for most of the difference in joist frequency when measured as an individual member and as part of a floor system. The location of the dead load is significant and warrants further study. When the location of the dead load was at midspan, the joist vibrated in its fundamental mode. However, when the load was located at the quarter-span locations from each end, joist vibration was apparently forced into a higher mode.

Other parameters affecting joist frequency to a lesser extent are the boundary conditions used in this study and system load sharing. The boundary conditions of a blocked pier to simulate a joist bearing on a pocket in a masonry wall provided a small amount of end fixity, which had minimal effect on frequency. A systems effect, which occurs from load sharing, was primarily observed for the floor systems constructed of new and salvaged joists. Although floor frequency decreased as the number of salvaged joists increased, the systems effect prevented detection of the low MOE joists when vibrating the system.

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