Nondestructive structural evaluation of wood floor systems in historic buildings

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ABSTRACT

For a variety of reasons, comprehensive structural assessment of buildings is desired, but lacking. Currently, visual inspection and possibly some nondestructive testing (NDT) of individual structural members are the basis of assessment of a building's floor, for example. This research reports on a multiphase NDT project that focuses on evaluating component floor systems rather than individual members.

INTRODUCTION

Often continued use or adaptive reuse of historic buildings are perceived to be unsafe and financially risky. Sometimes even historic buildings are demolished because of the lack of economic, technically sound, comprehensive structural assessment methods. Cooperative research by Purdue University, U.S. Forest Service's Forest Products Laboratory and the National Park Service has as its goal to nondestructively assess the structural capacity of in-place wood floor systems in historic buildings. Our overall objective is to more efficiently inspect timber structures by evaluating component systems rather than individual members. This paper summarizes the results of the first three phases of laboratory-based research, which were preparatory to the evaluation of in-place floor systems in actual buildings. Included will be summaries of results of nondestructive evaluation (NDE) of individual wood joists and NDE of laboratory-built floor sections constructed from the previously evaluated joists.

BACKGROUND

The fundamental natural frequency of a structural system is related to the stiffness of the system. For distributed mass systems such as individual joists and floor systems, the relationship is (Ross et al. 1994):

$$EI = \frac{f^2 W L^3}{2.46g} \qquad (1)$$

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

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The fundamental natural frequency is dependent on the characteristics of the structure E, I, W, and L and does not depend on the agent causing the motion. However, damping in the system will result in a slightly different natural frequency compared to that of an undamped system (Richart et al., 1970). For free vibrations,

$$f_{damped}=f_{undamped}\sqrt{1-D^2}\,, \tag{2}$$

For forced vibration, the effect of damping is dependent on the type of forcing function. If the forcing function is a harmonic force, the resonant damped frequency occurs below the undamped natural frequency and is:

$$f_{damped}=f_{undamped}\sqrt{1-2D^2} \tag{3}$$

However, if the forcing function is a rotating mass type excitation, the resonant damped frequency occurs above the undamped natural frequency and is:

$$F_{damped}=f_{undamped}\frac{1}{\sqrt{1-2D^2}} \tag{4}$$

Where D=damping ratio which is defined as the ratio of damping in the system to that critical damping where no vibratory motion occurs. The damping ratio has been studied by a number of researchers; values as high as 0.15 for buildings might be expected depending on the nature of the material used and the friction in the connections (Rogers, 1959). Corder and Jordan (1975) tested a number of floor systems consisting of nominal 50.8 by 203.2 mm joists and a variety of sheathing materials either nailed and/or glued to the joists. They found the natural frequency of the floors to range between 14 and 20 Hertz. Damping ratios ranged from 0.027 to 0.083. Kermani et al (1996) found the damping ratio to be 0.05 for a groove-lock flooring system using medium density fiberboard sheathing.

The log decrement, δ, which is the rate of decay of vibration is related to the damping ratio (Richart et al. 1970):

$$\delta=\frac{2\pi D}{\sqrt{1-2D^2}} \tag{5}$$

Pellerin (1965) found log decrement values by both free and forced vibration for various sizes and grades of dimension lumber. Log decrements were determined from the time-amplitude response decay curve for free vibration and from the frequency-amplitude response curve for forced vibration. He found the error of measurement in the forced vibration case to be excessive and recommended the free vibration case for log decrement. Elliot (1997) found log decrement values by a dropped weight on a proprietary gymnasium floor system. Log decrement values for three successive drops were 0.184, 0.218, and 0.141.

There have been a number of studies to determine the natural frequencies of floor systems. These studies are usually related to serviceability requirements for human response to floor vibration. An overview of floor vibration design criteria is given by Dolan et al. (1994, 1999); experimental techniques are given by Polensek (1970) and Kemani et al. (1996).

EXPERIMENTAL PROCEDURE

The reported research was conducted in two phases. The first phase consisted of the static and nondestructive evaluation of individual joists (Cai et al. 2000a). In phase two, the joists from phase one were used to construct floor systems in the laboratory. The floor sections' free vibration performance in response to an impact was determined (Cai et al., 2000b). Also the floor sections' performance under forced vibration and their static stiffnesses were evaluated (Soltis et al., 2000). The joists and the lab-built floor sections were chosen to be similar to the composition of the floor system in a building on the Purdue University campus. The structural evaluation of this building's floor system is also a part of the research project and will be undertaken upon the completion of the preparatory laboratory phases.

Phase 1

Fifteen 50.8 by 406.4 mm by 9.15 m high quality joists were freshly cut from southern pine (Pinus taeda L.) logs and shipped to Purdue University. In the green condition, the joists were evaluated for the following forms of modulus of elasticity (E): static flatwise E (SFE), static edgewise E (SEE), vibration flatwise E, and stress wave E. The joists were then air-dried to equilibrium in the laboratory and retested for the same properties as in the green state, with the addition of vibration edgewise E.

Nine 50.8 by 406.4 mm southern pine joists with average length of 6.56 m (max-7.05 m and min=6.10 m) were salvaged from a razed warehouse built shortly after 1900. The specific southern pine species was unknown. The joists were air-dried to equilibrium in the laboratory and tested for the same properties as previously described for the air-dried, new joists.

Phase 2

Included in this phase, in addition to other configurations, were three floor sections, two built of new joists and the other constructed similarly of salvaged joists. These floor systems were tested for natural frequency, damping ratio and static stiffness.

Each system was constructed of five 50.8 by 406.4 mm southern pine joists spaced 304.8 mm on center, with a span of 5.94 m. The end supports simulated the end conditions of the Purdue University building that will be subsequently tested. The joists were laterally braced by 38.1 by 88.9 mm cross bridging 1.45 m on center. Floor decking was transverse 25.4 by 101.6 mm Douglas fir boards fastened by 50.8 mm dry wall screws. A floor system under construction in the Purdue University Wood Research Laboratory is shown in Fig. 1.

The floor systems were subjected to both free and forced vibration. Free vibration was initiated by impact from a hammer. The forced vibration was imposed by a motor with an eccentric rotating mass attached to the floor decking (Fig. 2). The motor speed could be continuously changed to a maximum of 1800 rpm. The rotating mass weighed 251 g with an eccentricity of 3 cm. The response to vibration was measured at the bottom of the joists using a linear variable differential transducer (LVDT). The time-deflection signal was recorded by oscilloscope. For free vibration, the damped natural frequency was determined as the inverse of the period measured from the time deflection signal; the damping ratio was determined from the same signal using the classical log-decrement technique. For forced vibration, the damped resonant frequency was determined by increasing the motor speed until maximum deflection resonance was observed and then measuring from the time-deflection signal.

The three floor systems will be referred to as new floor 1, new floor 2, and salvaged floor corresponding to whether the floor joists were new or salvaged material.

Previously, it had been determined that frequency results were not affected if the locations of excitation and measurement of response were within the center half span of the system (Cai et al. 2000b).

Floor stiffness (EI) was determined from load-deflection found by adding 182 kilograms static load in eight increments at midspan of the joists and distributed over the width of the floor.

New floor 1 was primarily tested to determine the effects of severe degrade in the ends of the joists. Since decay most often occurs at the supports where the joists are enclosed in masonry pockets where water may collect, we simulated a severe end degrade by sawing off about 0.3 m of one, then two and then three joists. Thus frequency, damping ratio and stiffness were determined for the intact floor, and after one, two, and three joist ends were cut. The center joist was the first to be cut, followed by an adjacent joist on each side of the center joist.

RESULTS

Cai et al. (2000a) reported the physical properties and elastic moduli of the individual joists as determined by static and vibration techniques. The results are summarized in Table 1.

The accuracy of frequency measurements was determined by doing ten replications on a floor system. We found the maximum and minimum values were +/- 0.1 Hz of the average frequency. This is less that one percent difference between average and extreme values. The accuracy of measurement of the damping ratio were more variable however. The classical log-decrement method fits a curve to successive peaks in the time-deflection response to hammer impact. Different hammer impacts can result in a different curve fit. Thus we averaged the results from five replications to determine damping ratio. This resulted in about a twelve percent difference between average and either extreme value.

A comparison of frequencies found by both free and forced vibrations are given in Table 2. Values of measured and corrected values are presented. The measured value for the free vibration case is the damped free natural frequency, which is corrected to the undamped natural frequency using Equation (2). The damping ratio is found from the log decrement using Equation (5). The measured value for the forced vibration case is the damped forced frequency due to a rotating mass type excitation and is corrected to the undamped natural frequency using equation (4).

The results for a floor system with simulated joist end degrade is given in Table 3 and Figures 3 and 4. Measured frequencies, relative amplitude, damping ratios, and floor stiffnesses are given. Predicted vs. measured frequencies for various boundary conditions are given in Table 4.

DISCUSSION

In examining Table 1, the sizable and unexpected difference between flatwise and edgewise moduli is noted for the salvaged joists. Contrary to the case of the new joists, the edgewise modulus is about 30 percent less than the flatwise modulus for both the static and vibration test.

The undamped natural frequency is dependent on the stiffness, mass, span and boundary conditions of the floor system. In theory, it is independent of the method of vibration. A comparison of free vs. forced measured frequency (Table 2) indicates small discrepancies. Just comparing the two floors made of new joists indicated the forced vibration gave a somewhat more consistent result than the free vibration.

The undamped natural frequency in Table 2 is the measured damped frequency corrected for damping. Obviously, this correction is negligible to one decimal place and for the remainder of this discussion the natural and resonant frequencies are considered equal. It should be noted, however, that the damping corrections (Equations 2 and 4) are based on a lumped mass system whereas we are applying them to a distributed mass system.

The log decrement values for the floor systems (Table 2) vary from 0.140 to 0.182. Pellerin (1965) found values for individual dimension lumber varying from approximately 0.2 to 0.6. Corder and Jordan (1975) found values varying from about 0.17 to 0.5. Elliot (1997) found values for the same floor in successive impacts to vary from 0.14 to 0.22. It appears log decrement values are more difficult to measure and hence more variable.

Comparing the floors constructed of new and salvaged joists reinforced the findings of our previous study (Cai et al. 2000a). The lower frequency of the salvaged floor is due to its decreased stiffness (measured as 13.2×10^6 Nm^2) as compared to the stiffness of new floor 1 of 14.9×10^6 Nm^2 (Table 3).

We simulated joist end decay by sawing off the end of a joist. This creates a discontinuous member as part of the floor system still interconnected by bridging and floor decking. Our procedure was to saw through half the joist depth and measure floor response and stiffness then cut through the full depth and repeat the measurements. The values of partial cuts fall between those of no cut and full cut joist; these values are not reported but are shown on Fig. 3. We believe the effect of discontinuity is overcome by the system effect of the entire floor.

The effect of simulated joist end deterioration on new floor 1 (Table 3 and Fig. 3) indicates a decrease in floor stiffness and corresponding decrease in frequency, and an increase in the damping ratio as the joists are progressively cut. The effects of the loss of one or two joists are small compared to the loss of the third joist (Fig. 3); similar results were found for new floor 2. This indicates the systems effect of the floor will mask the effect on only one or two joists being decayed in a floor system. It also raises the question of whether a repair is needed or not if there is only one or two bad joists.

Either frequency or damping ratio could be used as an indicator of joist end decay. Both show small changes for one or two cut joists and a large change in value for three cut joists. Relative amplitude is not a good indicator of changes for cut joists. The amplitude is a relative value, dependent on the forcing function; thus applying a constant forcing function masked the effect of change in stiffness on amplitude.

Equation (1) relates frequency to stiffness for a continuous system that is simply supported on pin reactions at each end. Using the floor stiffness values of Table 3 and Equation (1) results in the predicted frequencies for the pinned/pinned end case to be larger than the measured frequencies (Table 4). There are two possible explanations for this. The first is Equation (1) is for an idealized spring-dashpot system with viscous damping. This may not be a good predictor of the actual floor system with friction damping. A discrepancy between predicted and measured frequencies was also found by Bainbridge et al. (1996). A second explanation may be related to boundary conditions. Cutting off the joist ends results in the cut joist being a cantilever beam interacting with the floor system. For a fixed end cantilever beam, the constant of equation (1) becomes 0.314. Using this constant value predicts frequencies of the fixed/cantilever case smaller than the measured values (Table 4). The boundary conditions for our floor system with joist ends cut off are undetermined but fall within the two cases used for prediction. A better prediction of the floor system frequency is made by taking a weighted average of the constants, 2.46 and 0.314. For example, with one of the five joists cut, the weighted average constant is (4 x 2.46 + 1 x 0.314)/5=2.03. Using this constant results in a predicted frequency of 18.4 Hz (Table 4).

Conclusions

The surprisingly large reduction in edgewise modulus of elasticity of the salvaged joists is a cause for concern.

Both free and forced vibration was compared and both gave satisfactory results. Free vibration has the advantage that it is simple to apply and frequency and damping can be obtained. Forced vibration gives more consistent results. Its disadvantage is that no damping data can be obtained.

We simulated decay at the joist ends by completely cutting through joists near an end support. The results indicate natural frequency decreases and damping ratio increases as additional joints are cut. Either frequency or damping ratio are good indicators; however, frequency can be measured more accurately than damping ratio. Small changes in frequency and damping ratio are observed when one or two joist ends are lost whereas a larger change is observed when the third joist end is lost. This indicates the systems effect of a floor with bridging and decking may make it difftcult to determine the decay in only one or two joists in the system. A floor with many decayed joists should be easily uncovered. This conclusion raises the question of whether deterioration limited to one or two joists in a floor system has a significant effect on the structural integrity and needs to be repaired.

The effects of the deterioration in the salvaged joist floor was detectable by a decrease in frequency and/or increase in damping ratio when compared to a new joist floor.

In summary this procedure holds promise as an inspection technique. Future research is necessary to see if similar results are obrained for a range of floor spans and joist sizes.

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Table 1. Properties of 50.8 by 406 mm joists

	MC	Width	Thickness	Density[a]	SFE[b]	SEE[b]	VFE[b]	VEE[b]	SWE[b]
	%	mm		kg/m^3	$(10^6)kN/m^2$				
New									
Green									
Avg.	56.3	406.4	79.7	777.4	12.20	10.62	12.68	N/A	14.06
Cov[c]	34.4	0.2	3.7	11.9	18.00	13.00	18.40		14.00
Dried									
Avg.	10.2	388.6	47.4	599.5	14.06	15.79	15.86	14.27	17.03
Cov[c]	2.3	0.7	4.5	5.3	16.20	11.50	16.80	20.70	16.70
Salvaged									
Avg.	9.7	393.7	48.8	626.8	12.06	8.34	11.72	8.62	13.92
Cov	3.2	1.9	8.7	13.8	33.10	23.40	32.40	17.80	22.30

[a] Weight and volume at indicated moisture content
[b] SFE = static flatwise E; SEE = static edgewise E; VFE = vibration flatwise E; SWE = stress wave E
[c] Coefftcient of variation = standard deviation/average

Table 2. Comparison of results found from free and forced vibation

	Measured Frequencey (Hz)		Log Decrement	Avg. Damping Ratio	Undamped Natural Frequency (Hz)	
Floor System	Free	Forced			Free	Forced
New Floor 1	16.3	16.2	0.164	.0261	16.3	16.2
New Floor 2	15.9	16.3	0.140	.0223	15.9	16.3
Salvaged Floor	14.8	14.9	0.182	.0290	14.8	14.9

Table 3. Effect of simulated joist and deterioration on floor response

Number of Joists With Ends Cut	Measured Frequency (Hz)		Relative Amplitude	Log Decrement	Avg. Damping Ratio	Floor Stiffness $x10^6$nm2
	Free	Forced				
0	16.3	16.2	2.7	0.164	.0261	14.90
1	16.1	16.0	2.6	0.188	.0299	13.85
2	15.1	15.0	2.8	0.188	.0299	11.20
3	12.0	12.4	2.6	0.239	.0380	8.65

Table 4. Predicted vs. Measured Frequency for New Floor 1

Number of Joists With Ends Cut	Measured Frequency (Hz)		Predicted Frequency (Hz) w/support conditions		
	Free	Forced	Pinned/Pinned	Fixed Cantilever	Weighted Average
0	16.3	16.2	21.1	7.5	
1	16.1	16.0	20.3	7.3	18.4
2	15.1	15.0	18.2	6.5	14.7
3	12.0	12.4	16.0	5.7	11.0

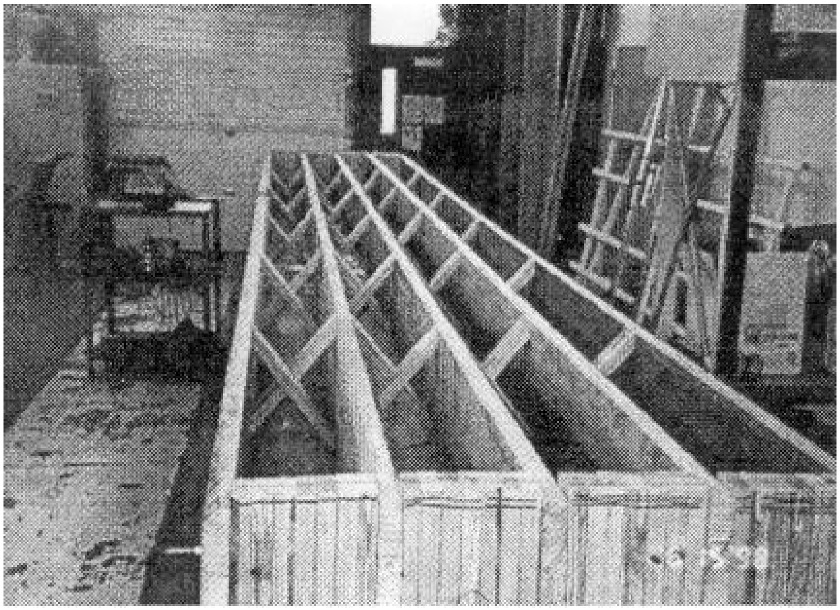

Figure 1. Test floor system under construction in Purdue University Wood Research Laboratory

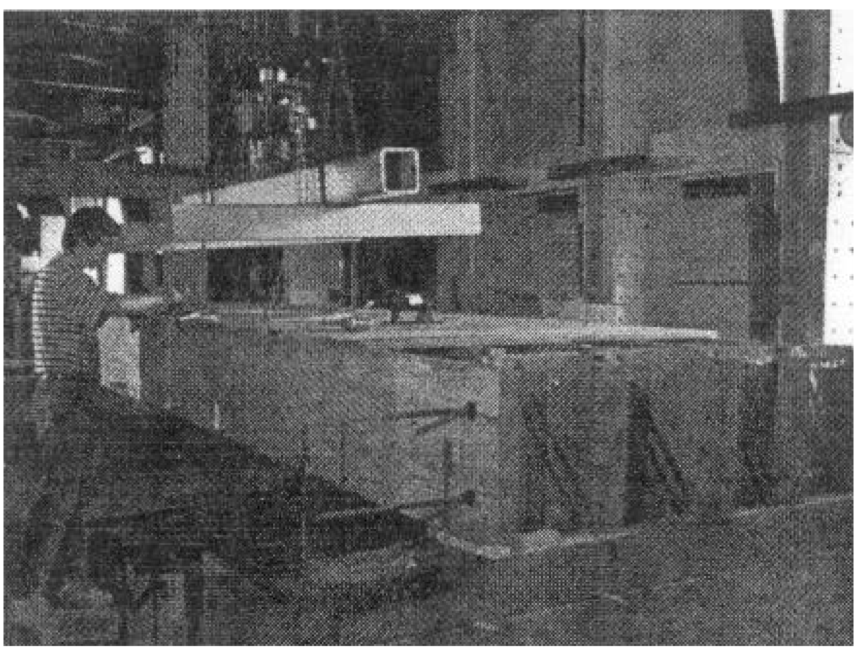

Figure 2. Forcing function attached to decking of floor system

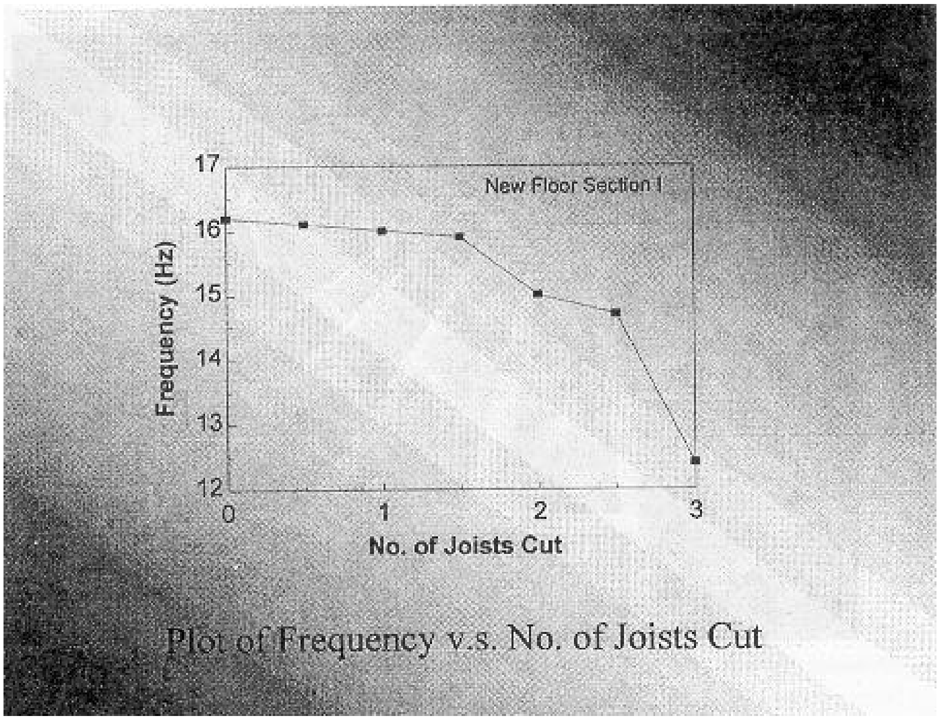

Figure 3. Plot of frequency vs. number of joist cut

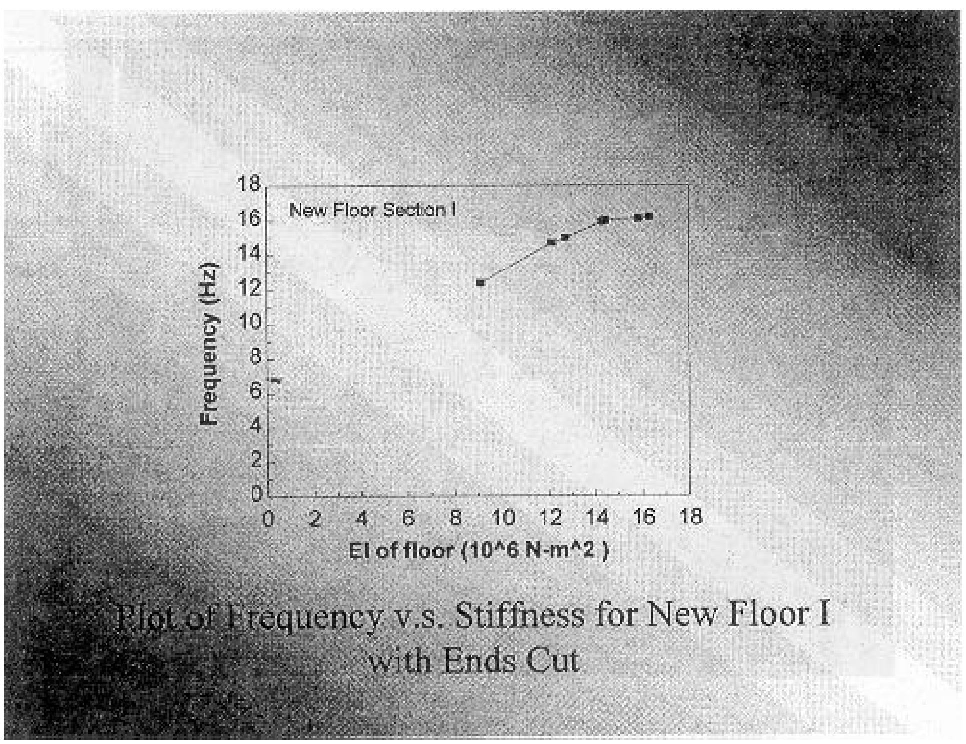

Figure 4. Plot of frequency vs. stiffness for new floor 1 with ends cut

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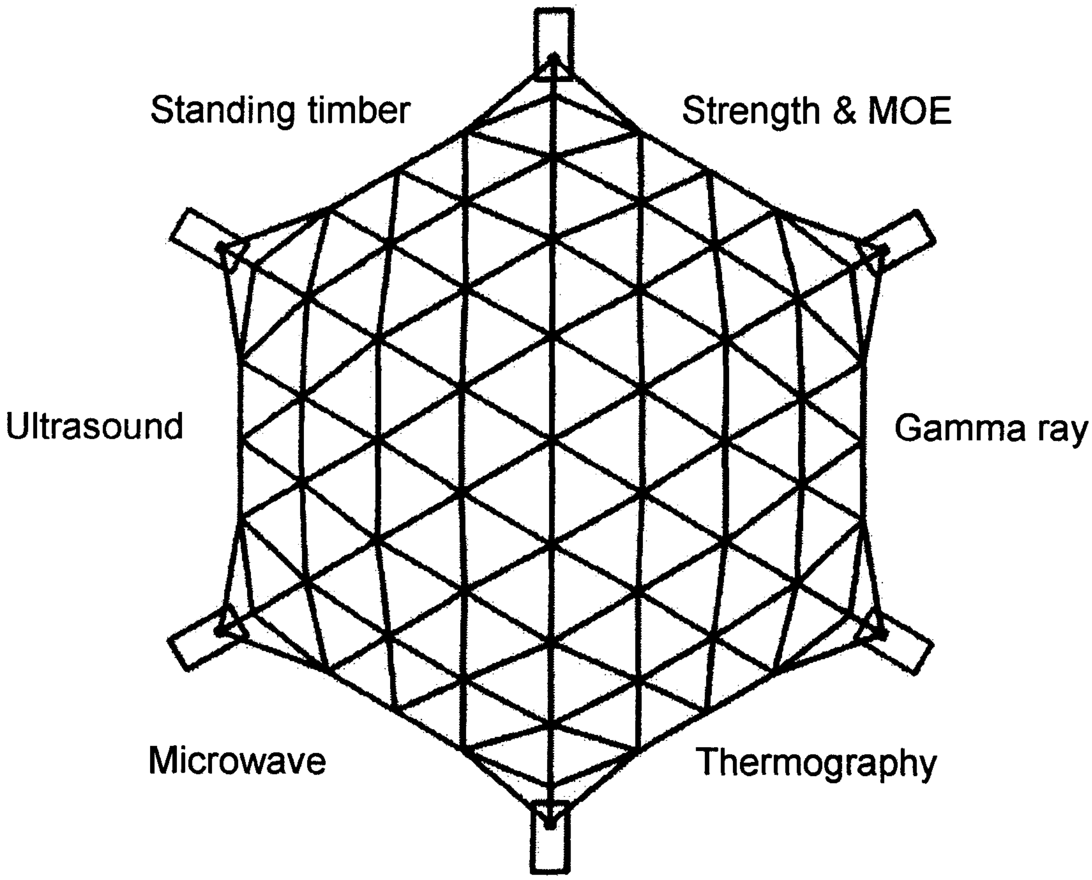

University of Western Hungary, Sopron
13 -15 September 2000