THE CURRENT STATUS OF ANALYSIS AND DESIGN FOR ANNOYING WOODEN FLOOR VIBRATIONS

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ABSTRACT

One result of improved material utilization in the design and construction of wooden buildings is a dramatic increase in undesirable, annoying floor vibrations. Whereas static criteria provide a sound method of ensuring a safe structure, these same criteria may not ensure that vibrational serviceability requirements are met. The major drawback of static criteria is that they do not address dynamic variables that become increasingly important as the span is lengthened, or the weight and/or the stiffness of the floor structure is reduced by either efficient design methods or the inclusion of engineered joist products. This paper discusses not only pertinent current research findings but suggests areas for future research to develop the dynamic criteria needed for the design of lightweight floor systems constructed with wood-based materials.

The development of such criteria may have a positive economic impact on the forest products industry. Although vibrational problems also occur in steel and concrete structures due to the reduction in weight of the floor components (steel joists and concrete slabs), researchers (Allen and Rainer 1976, 1985; Murray 1991) have made great strides in the understanding and control of vibrations in steel and concrete structures. If serviceability criteria for wooden structures are developed that will ensure acceptable vibrational performance, then the forest products industry will have the potential to be competitive in the profitable light-commercial construction market.

Keywords: Static, dynamic, vibration, wooden floors, frequency, amplitude, damping.

INTRODUCTION

Annoying floor vibrations are a phenomenon that virtually everyone has experienced at one time or another in a residential building. Having a record skip because someone has walked across the floor of a room where the stereo is playing is a classic example of an annoying vibration. A person sitting in a chair may be annoyed by another person's walking into or out of the room. The vibrations caused by the person's walking are felt by the person sitting, and attention is drawn away from whatever task is in hand. Other examples causing excessive vibration are children playing, animals walking or running, and items being accidentally dropped. In some cases, these vi-

brations are severe enough to cause items to fall from bookcases. Vibrations caused by these activities were not as severe when larger or full-size solid-sawn joists were used in residential floors due to the higher mass and shorter spans typically associated with solid-sawn lumber joists. Significant designer experience is also responsible for the lower dynamic severity associated with solid-sawn lumber joists. However, with changes in design and construction techniques, wooden floor systems are spanning greater lengths and are becoming lighter and more flexible. As a result, the number of complaints of annoying floor vibrations has risen.

Standard static criteria may not yield a satisfactory floor from a serviceability or vibrational standpoint. The most common static criterion used for design is limiting the live-load static deflection of a joist to the span/360 (Percival 1979). The problem with such a criterion is that it does not explicitly address vibrational variables. Although static deflection criteria such as span/360 will provide safety (as proven through history), they do not assure adequate serviceability when floors are subjected to dynamic loads that result in vibration.

Since the static criteria may not be adequate, recent research has been directed toward the development of an understanding of the dynamic variables or characteristics of perceptible floor vibration. One elusive goal of recent research has been to quantify the subjective perception of annoying vibrations and develop a design procedure or criterion that will reduce the number of unacceptable floors. This paper reviews the pertinent research and also suggests topics for future research so that the necessary understanding of floor vibration and improved wooden floor performance may be obtained.

UNDERSTANDING HUMAN RESPONSE TO VIBRATIONS

The study of human response to vibration essentially began with the Reiher and Meister experiment (1931). In this experiment, a scale of human tolerance defined by peak deflection and frequency was developed in relation to steady-state (continuous) vibrations applied for five minutes. The scale included the following divisions: 1) Not Perceptible, 2) Slightly Perceptible, 3) Distinctly Perceptible, 4) Strongly Perceptible, 5) Disturbing, 6) Very Disturbing, 7) Injurious. Reiher and Meister's study became very important in the years to follow since virtually all newly developed scales were in some way compared to this study.

Polensek (1970) developed a similar scale that demonstrated that people could identify different levels of vibration similar to those experienced in a residence. The vibrations were categorized as: 1) Perceptible, 2) Perceptible-Disturbing, 3) Disturbing, 4) Disturbing-Annoying, 5) Annoying. Polensek used vibrations that were short-term and transient (rapidly decaying), lasting less than 1 second. Human response was defined by peak deflections and frequency.

Wiss and Parmelee (1974) studied experimentally the human response to both transient and damped-free vibrations. Whereas damped-free vibrations (damped motion in the absence of any imposed external forces) were defined by peak deflection and frequency, transient vibrations were defined by peak deflection, frequency, and damping. The vibrations lasted for 5 seconds and were synthesized from a mathematical model designed to simulate vibrations caused by a human dropping from tiptoes to heels (heel drop). The scale used to evaluate the transient vibrations included: 1) Imperceptible, 2) Barely Perceptible, 3) Distinctly Perceptible, 4) Strongly Perceptible, 5) Severe. An important result from this transient analysis was that as the damping increased, vibrations of a given frequency and peak deflection were less noticeable. When the damped-free vibration results were compared to those of the Reiher and Meister study, it was found that the limits were generally lower than that of Reiher and Meister. Two main reasons given by the authors for the discrepancies were the difference in duration time of the vibration and the difference in data evaluation. Wiss and Parmelee (1974) also ex-

plained that the results apply solely to the mathematical wave form used, and that their study findings do not directly apply to vibrations having non-identical characteristics, such as those due to walking.

Two years later, Atherton et al. (1976) experimentally evaluated 1,222 impact and 278 walking displacement-time traces from twenty-four full-size floors to determine which characteristics of a wood floor system were the best indicators of human response to vibration. Ratings were on a scale of 1–5 (larger annoyance to smaller annoyance). When the scale was compared to Reiher and Meister's, differences were evident. As with the Wiss and Parmelee study (1974), these differences were a result of differences in testing procedure and data evaluation. One notable result from this study was that the human subjects were more sensitive to walking vibrations than to single-impact vibrations.

The qualitative results from these tests combine to show that human response to floor vibration is dependent on frequency, amplitude, and damping. However, the quantitative results are difficult to compare and validate, primarily because the tests had different vibration sources, different durations, and different scales.

Selecting the type of vibration to use as a basis for analysis and design is an important issue that must be addressed before characteristics can be quantified and implemented in a design criterion. Floor vibrations can essentially be broken down into two categories: steady-state and transient. While steady-state vibrations are defined by frequency and displacement, transient vibrations are defined by frequency, displacement, and damping (Wiss and Parmelee 1974). Furthermore, International Standards Organization (ISO) 2631-2 (1989) defines a transient vibration as one in which there is a rapid build-up and subsequent damped decay for a time period of less than 2 seconds. On the other hand, a continuous vibration (sometimes referred to as steady-state) is defined as a vibration that remains unchanged over a specified time interval. ISO

2631-2 (1989) also defines intermittent vibrations as vibrations of short duration separated by intervals of significantly lower vibration magnitude that, if operated continuously, would produce continuous vibrations. Impulse sources, such as those produced by walking motions, while often falling into the category of intermittent vibrations, sometimes approach continuous vibrations (this will be discussed later). International Standards Organization (ISO 2631) (1989) apparently addresses this by specifying equal multiplication factors (used to ensure satisfactory vibrations with respect to human exposure) for the intermittent and continuous groups. In regard to continuous and transient vibrations, investigators have found significant differences in perception and application between the two categories of vibration.

Transient vibrations characterized by larger amplitudes and quick dissipation are more easily tolerated by humans than is a continuous steady-state vibration (Ellingwood and Tallin 1984). Therefore, at a given amplitude, human perception is much greater under steady-state than under damped transient vibrations, and steady-state vibrations are more likely to be viewed as annoying This difference becomes important when vibrations are applied and evaluated for design purposes. For example, it has been found that transient vibrations result from the impact of footfalls during normal walking (Wiss and Parmelee 1974). Because of the transient nature, the importance of human perception of short duration vibration becomes clear (Allen 1974). Hence, many researchers have opted to use heel impact tests since the transient characteristics of the response are thought to closely resemble those due to human activity (Chui 1988).

However, if one assumes that the major cause of annoying floor vibrations is walking, then the heel-impact test may not totally represent the vibrational response. Ellingwood and Tallin (1984) found in a numerical study that when single footfall force/time traces were combined at discrete time and distance intervals to pro-

duce walking motions, a near steady-state floor response was reached at the center span of an 8-m (26-ft) floor. It was concluded that since there is the potential for human activity to approach a steady-state condition, (under which vibration tolerance levels are known to be much less for a given amplitude), then a heel impact test is probably not an accurate representation of vibration due to walking since it produces an isolated transient pulse. In addition, as previously stated, Wiss and Parmelee (1974) found that vibrations similar to one heel-drop were not necessarily applicable to walking vibrations. Therefore, design criteria based on an isolated heel-drop test might not provide the best representation of human activities.

QUANTIFYING MAJOR PARAMETERS

In order for improved design criteria to be established, the important vibrational parameters of frequency, amplitude, and damping must be quantified. Accurate quantification of these parameters should yield accurate design criteria since human response to vibration is dependent on these variables. Therefore, it is important that the quantitative values be as accurately determined as possible.

Frequency

Two important aspects of frequency analysis that should be considered are natural frequencies (the frequencies at which a structure oscillates for a given mode of vibration) and separation of adjacent frequencies (i.e., higher modes). Natural frequencies of floors have been calculated primarily from free vibration analysis and theoretical estimations. Frequencies obtained from free vibration in the laboratory are the most accurate (provided that the connections in the floor system do not yield). In this analysis, an acceleration trace is obtained from a floor impact, and the frequency can be determined from the response curve. The limitation to this procedure is that frequencies are only representative of the floor configuration tested; therefore, predicting the frequencies for

other floors is difficult. Also, the number of specimens required to obtain sufficient data for statistical analyses makes the associated cost of experimentation prohibitive. Because of these limitations, many investigators have chosen to use theoretical estimations that can be applied to floors of varying properties and sizes. A major concern with these estimations is that the calculations are so complex that many researchers have opted to use simplified equations that result in lower accuracy (Allen 1974). These simplied equations are often derived from orthotropic stiffened plate theory or grillage models that do not sufficiently represent the partial composite action associated with wooden floors (Filliatrault et al. 1990). Some investigators such as Smith and Chui (1988) have investigated zero composite action between the sheathing and joists.

An example of the difference arising from addressing composite action (both parallel and perpendicular to joist length) can be observed by comparing the Filliatrault et al. study of 1990 and the Smith and Chui study of 1988. Filliatrault et al.'s study used a numerical computer model that simulated free vibration analysis to determine the natural frequencies of wooden floor systems assuming composite action. These numerical results were then compared to experimental results obtained by Smith and Chui for floors where all four edges were supported and where only the ends of the joists were supported. Good agreement was found between the numerical and experimental results for both cases. In the ensuing sensitivity analysis, Filliatrault et al. compared the numerical results to Smith and Chui's numerical predictions of the natural frequencies, with the result that Smith and Chui's frequency predictions, assuming no composite action, were generally lower than those predicted by Filliatrault et al. The neglect of occupancy loading in the Smith and Chui study also had a major effect on the results. Filliatrault et al. concluded that composite action should be included when a more accurate representation of floor frequency response is desired.

In addition to investigating zero composite

action, Smith and Chui (1988) also investigated composite action parallel to joist length. In a later article, Smith and Chui (1992) stated that by utilizing composite action parallel to joist length, a more accurate frequency prediction could be obtained than by assuming zero composite action.

The other main aspect of frequency that should be addressed is the separation of adjacent frequencies. As joists are spaced closer together, or when the width of a floor is greater than its span, a potential exists for a reduction in the spacing between adjacent frequencies (Chui 1986). This reduction in spacing between adjacent frequencies can become a problem since closely spaced modes of vibration can interact to produce high amplitudes (Ohlsson 1982; Filliatrault et al. 1990). Therefore, separating the adjacent frequencies to reduce the amplitude of vibration becomes desirable.

Smith and Chui (1988), and Filliatrault et al. (1990) have found that improvements in floor performance can be achieved by raising the fundamental frequency and increasing the spacing between adjacent frequencies. An increase in the fundamental frequency can be obtained by increasing the stiffness of the floor system, and an increase in spacing between adjacent frequencies can be obtained by either introducing bridging or increasing the material property homogeneity of the floor system. To ensure acceptable floor performance, Ohlsson (1982) concluded that the fundamental frequency for all floors should be well above 6 Hz, and that it should be above 8 Hz for wooden floors, due to their reduced weight. This threshold of 8 Hz also agrees with ISO standard 2631 (1989). Raising the natural frequency above 8 Hz is beneficial for two reasons: 1) humans are very sensitive to frequencies in the 4–8 Hz range, and the highest annoyance to vibration occurs at approximately 5 Hz (Grether 1971); and 2) at frequencies below 8 Hz there is a possibility of resonance due to human activities (Ellingwood and Tallin 1984). As for the separation of adjacent frequencies, a minimum separation has not been determined, but the further apart the frequencies are the better the floor performance will be (generally).

Although Murray's (1975) study deals with the prediction of first natural frequencies, its formulation for steel and concrete structures prohibits its direct application for predicting first natural frequencies for wooden structures.

Amplitude

Researchers express vibrational amplitude in three ways: 1) deflection, 2) velocity, and 3) acceleration. The choice is dependent on research objectives and on how well the variable describes the behavior observed in the study.

Atherton et al. (1976) found that deflection is the best single indicator of both single impact and walking floor vibrations, but that a composite variable containing deflection, frequency, and damping better describes vibrational characteristics. A drawback in using deflection as an indicator of amplitude is that, for small deflections, data are not reliable due to the inherent limitations in accuracy of the measuring device.

Although velocity is believed to be the parameter that best describes human disturbance above 8 Hz (Ohlsson 1988; ISO 1987), it is seldom measured directly in the literature. However, it should be noted that Ohlsson (1982, 1984, 1988, 1991) utilized velocity to quantify amplitude.

Acceleration is the parameter most often used by researchers since it simplifies data analysis, is easily measured, and has been found to correlate well with human tolerance to vibration. A design criterion based on amplitude alone is difficult to establish accurately because human response to vibration is subjective regardless of the variable used (Allen and Rainer 1985). While each measurement has its drawbacks, vibrational amplitude in any of these forms is a very important characteristic of floor behavior and should be included in reporting the results of all experimental and numerical investigations.

Because vibrational amplitude is such an important parameter, it is generally felt that floor performance can be improved by reduc-

ing the amplitudes of floor response. Many studies predict amplitude and other dynamic characteristics, assuming that the floor can be analyzed as a one-degree-of-freedom spring-dashpot system. Using this model assumes that frequencies are well separated and that the response at the center of the floor is dominated by the fundamental mode of vibration. However, Ohlsson (1988) stated that this approach oversimplifies the problem; for example, Ohlsson (1982) found that initial peak velocity was highly dependent on higher modes. However, the magnitude of error made by assuming a one-degree-of-freedom system has not been quantified.

Smith and Chui (1988) have suggested a root mean square (RMS) acceleration design criterion based on a spring-dashpot system and a heel impact vibration impulse. Root mean square acceleration was chosen since it had been found to have good correlation with human perception by the British Standards Institute 5268 (1984). In addition, the calculated RMS acceleration is frequency-weighted by an appropriate factor because humans can tolerate higher vibrational magnitudes at high frequencies than at low frequencies. This factor, as given in ISO 2631 (1978) for frequencies between 8 and 80 Hz, is equal to $8/f_n$, where f_n is the fundamental frequency of the floor system. The design criterion suggested by Smith and Chui (1988) is that for a floor to have acceptable vibrational performance, its frequency-weighted RMS acceleration should be less than 0.45 m/s^2 when calculated for the first 1 second of vibration. After testing six floors, Chui (1988) concluded that the proposed limit is a suitable threshold level.

Damping

In addition to frequency and amplitude, damping is a major characteristic of floor vibration. Damping is important because it dissipates vibrational energy. For example, an almost continuous motion will result due to the interaction of vibrations if the floor has little damping in one of its lower modes (Allen and Rainer 1976). This continuous motion, or near

steady-state vibration, has previously been shown to be more annoying than damped (transient) vibrations (Ellingwood and Tallin 1984). Therefore, higher damping in floors should ensure that vibrations will be predominantly transient and more easily tolerated.

The two sources of structural damping in wood systems are slip damping (interlayer or hysteretic) and material damping (internal) (Yeh et al. 1971; Polensek 1988). Damping in wood systems is predominantly a result of friction; therefore, interlayer damping at surfaces in contact at joints and yielding of connectors comprise the vast majority of the damping whereas internal damping is of minor importance (Ungar 1973). Because the majority of damping occurs in the joints, the type of connectors used to attach the sheathing becomes the dominant factor in determining the magnitude of damping present in the system.

In addition to structural damping, human bodies also provide a source of damping that can affect human perception to vibration (Polensek 1988). For example, in a numerical study by Foschi and Gupta (1987), a receiver simulating person A was used to determine the vibrational tolerance when an impactor, or person B, applied a footfall force to another point on the floor. The responses at the receiver, or person A, were quantified using the results of the previously mentioned study by Wiss and Parmelee (1974). It was found that the damping associated with the receiver had a greater effect on displacement levels, and therefore floor performance, than did the damping associated with the floor construction. Therefore, when considering damping of the entire floor, the effects associated with people should not be ignored since they have a substantial effect on total system damping, and on the perception of the floor performance.

As with the other important dynamic variables, some assumptions are made when damping is evaluated. The first assumption, made by many investigators who determine damping numerically, is that the sheathing-to-joist connectors behave in a linear manner. Those who use the linear theory justify it by

the fact that the vibration of wooden floors is a serviceability problem and not a structural problem (Filliatrault et al. 1990). However, floors subjected to very high loads (overloads) may exhibit sufficient sheathing-to-joist slip to warrant a nonlinear analysis.

Assuming linearity appears to be a valid assumption for evaluating damping under low amplitude vibrations where minimal slip occurs, but for amplitudes where slip does occur, the connections should be considered nonlinear. In other words, material damping can be determined using a linear system, whereas friction damping may require a nonlinear analysis.

Another assumption, that has previously been mentioned, is that the floor acts as a single-degree-of-freedom system (as previously defined). If this is the case, the simplest way to evaluate damping is from time-amplitude traces under free-vibration considering only the fundamental mode. Evaluating only the fundamental mode is a result of the assumption of viscous damping, where damping force is proportional to the velocity and opposite to the direction of motion. Viscous damping is also based on the observation that the peak deflection and maximum damping take place during the first cycle. Since many investigators are interested in determining only the peak response of floor systems, they question the need for improving the accuracy of models to simulate post-peak response. However, since changes in deflection across the entire floor are caused by the second and higher modes of vibration, the viscous damping assumption becomes inaccurate when applied to the entire system (Polensek 1988). Therefore, evaluating only the fundamental mode imparts error into the analysis, and solid rationale does exist to investigate the damping associated with higher modes of vibration.

Assuming a single-degree-of-freedom system, Polensek (1975) experimentally determined the average damping ratios for thirty-four nailed wood-joist floors. In addition, the damping impact of three men, two sitting in chairs at midspan and one lying near midspan,

was evaluated. Results showed that the average damping ratios of the floor specimens (expressed as a percent of critical damping) ranged between 0.04 and 0.06, corresponding to the maximum peak-to-valley deflection amplitudes of 0.0027 and 0.0055 inches. The presence of the three men increased the average damping ratio from 0.05 to 0.12, indicating that people have a significant effect on damping.

DESIGN CRITERIA

Numerical

Frequency, acceleration, and velocity calculations will not be included because of their complexity and large space requirements. The reader is advised to obtain the corresponding documents for these specific equations. However, pertinent equation variables will be included in this discussion.

Since it is well known that natural frequencies are dependent on floor stiffness and mass, Foschi and Gupta (1987) numerically developed a quantitative reliability-based design criterion based on individual joist stiffness and maximum deflection. The criterion proposes that for a concentrated load of 1 kN acting at midspan of a joist with the average modulus of elasticity of the system, a limiting absolute static deflection of 1 mm should be adhered to, independent of span length. The criterion is also based on numerical information that was related to the effects of humans on floor system damping (previously described), and on the assumption that the sheathing-to-joist connectors exhibit linear load-slip characteristics.

A second criterion has been proposed by Ohlsson (1991). As with the previous criterion, it is based upon a concentrated static load of 1 kN. However, in this case, the load is applied at the center of the floor, thus taking into account the joists and sheathing (entire floor), as opposed to just a single joist. It is suggested that the maximum deflection should be limited to 1.5 mm. In addition, the floor's undamped fundamental frequency should be

higher than 8 Hz and the variables needed for this calculation include: mode number, mass per unit area of floor (kg/m²), floor span and width (m), and equivalent plate bending rigidity parallel and perpendicular to joist length (Nm²/m). The third aspect of this criterion is that the maximum velocity should be limited to a value based on the fundamental frequency and damping ratio. The only additional variable needed for this calculation with regard to the frequency calculation is the frequency itself.

The third numerical criterion has been suggested by Smith and Chui (1988). As with Ohlsson's (1991) criteria, one stipulation is that the floor's fundamental frequency should be above 8 Hz. The proposed design method includes a calculation for the undamped fundamental natural frequency and is found to be dependent on: number of joists, floor span and width (m), joist MOE (N/mm²) and moment of inertia (mm⁴), sheathing thickness (mm) and density (kg/m³), and joist depth (mm), thickness (mm), and density (kg/m³). The second stipulation of the proposed design method is that the calculated frequency-weighted RMS acceleration should be less than 0.45 m/s² for the first 1 second of vibration. The variables needed to calculate RMS acceleration included: floor mass in the vertical direction (kg), viscous damping ratio, duration of excitation (sec), undamped fundamental natural frequency (Hz), and the angular fundamental natural frequency (rad/sec).

EXPERIMENTAL

In 1985, Onysko proposed serviceability criteria based on a field study of consumer response. In this study, formal and informal interviews, administered in a random door-to-door fashion, were used to screen potential occupants in order that the sample would represent both acceptable and nonacceptable floors. A total of 107 occupants were then chosen from five areas of Canada to represent the entire country: Ottawa and Hull, Regina, Saskatoon, Toronto, and Montreal. Interestingly, the finding that building practices were similar throughout the country led to the realization

that geographical representation was less important than originally thought. After the occupants were chosen, in-house testing took place at their residences and strategic questions were used that led to a human evaluation of floor performance.

Onysko's (1985) assessments were acceptability-based and not perception-based. Acceptability-based refers to assessments made in a real-life situation, i.e. the house in which the subjects live, as opposed to perception-based, which refers to a controlled environment where only specific effects are evaluated. For floor vibrations, feeling, seeing, and hearing are all important perception modes and are included in an acceptability-based assessment. However, in a perception-based assessment, only one of the three can be examined at a time; thus it is difficult to relate the results to a real-life situation (Onysko 1985).

Analysis of the results led Onysko to propose two design criteria, both of which are based on limiting the maximum floor deflection. The first criterion is recommended for living areas (1a-b), the second criteria for bedroom areas (2a-b):

$$Y \le \frac{6.7}{SPAN^{1.22}} \qquad 3.0 \le SPAN < 6.0 \qquad (1a)$$

$$Y \le 1.75 \qquad SPAN < 3.0 \qquad (1b)$$

$$Y \le \frac{8.9}{SPAN^{1.22}} \qquad 3.8 \le SPAN < 6.0 \qquad (2a)$$

$$Y \le 1.75 \qquad SPAN < 3.8 \qquad (2b)$$

where SPAN is in meters and Y is in millimeters. In both cases, SPAN corresponds to the clear span, and Y is the deflection as a result of a concentrated load of 1 kN acting at the midspan of the floor. There are three primary reasons for the difference in criteria between living areas and bedrooms: 1) the majority of bedroom floors were found acceptable; 2) since bedroom spans were generally shorter than the spans for living areas, partition walls were thought to have a highly significant moderating effect on deflections; and 3) bed placement restricted the area over which disturbances might have been created. The significant in-

fluence of partition walls in bedrooms led Onysko (1985) to conclude that there is a higher degree of uncertainty in the bedroom criterion than in the living-area criterion. As with Ohlsson's numerical criterion (1991), both of Onysko's (1985) criteria take into account the entire floor (sheathing and joists).

As a point of interest, Onysko (1975) evaluated acceptability versus nonacceptability of floor vibrations by an exhaustive statistical analysis of questionnaires given to the employees of the Eastern Forest Products Laboratory of Canada (now Forintek Canada Corporation). These questionnaires were concerned with the presence of vibrations at the participants' places of residence. Of the 140 questionnaires distributed, 104 were returned; numerous conclusions were drawn from the analysis. However, the most important conclusion was that the noise produced by the vibration of furniture and cabinets was more responsible for dissatisfaction with floors than was the perception of bodily vibration.

In summary, four design criteria have been presented: three numerical and one experimental. Three of the four criteria are based on limiting the static deflection of a 1 kN concentrated load acting at either the midspan of a joist or the center of a floor. In the fourth, a limiting RMS acceleration is used. As to which criterion is better or more accurate, this issue has not been resolved.

CONCLUSIONS

Although a good deal of research has been conducted in the area of floor vibrations for wooden buildings, it is apparent that a conclusive dynamic serviceability criterion has not been established. A standard evaluation procedure and a numeric design procedure that accurately models a typical floor installation are needed to develop a dynamic floor design criterion. Ideally, a numeric design procedure should model the sheathing-to-joist connectors in a nonlinear fashion, and evaluation of the second and higher modes of vibration should be included in the analysis. Using vibrations for floor excitation that more closely resemble walking vibrations would result in

more conservative design criteria. The use of steady-state vibrations would cover the "worst case scenario." Also, the effec:s of the presence of people and/or mass might be included. However, since the cost of most residential structures does not justify a detailed engineering analysis, any proposed design criterion should be simple, for easy implementation into current building codes. A criterion expressed in terms of a maximum deflection due to a concentrated static load, such as the criteria proposed by Foschi and Gupta (1987), Ohlsson (1991), and Onysko (1985), would be a candidate for easy implementation.

The development of an accurate design criterion will be beneficial for two reasons. The first and most important reason is that it will provide improved comfort to those who live in well-designed wooden structures. Second, it has the potential to expand the use of products in light-commercial building construction by showing that wooden structures perform acceptably.

NEEDS FOR FUTURE RESEARCH

An issue that must be resolved is the formulation of a design criterion to be used at the design stage. It should be possible for a designer to estimate dynamic serviceability by knowing the size, span, materials, and construction details of the floor. The criterion could be similar in principle to estimating the fundamental period of a high rise building by the number of stories. Another important topic to be addressed is vibrational transmission between adjacent rooms or floors. Such transmission is manifested in multi-span floors between adjacent rooms when partition walls are present. Other topics include the evaluation of engineered wood products, the effect of adhesive application on total floor system serviceability, and the quantificetion of effects associated with higher modes of vibration.

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REFERENCES

ALLEN, D. E. 1974. Vibrational behavior of long-span floor slabs. Canadian J. Civil Eng. 1:108–115.

———, AND J. H. RAINER. 1976. Vibration criteria for long-span floors. Canadian J. Civil Eng. 3(2):165–173.

———, AND ———. 1985. Vibration criteria for assembly occupancies. Canadian J. Civil Eng. 12:617–623.

ATHERTON, G. H., A. POLENSEK, AND S. E. CORDER. 1976. Human response to walking and impact vibration of wood floors. Forest Prod. J. 26(10):40–47.

BRITISH STANDARDS INSTITUTE. 1984. Code of practice for the structural use of timber. Part 2. Standard 5268. London, UK.

CHUI, Y. H. 1986. Vibrational performance of timber floors and the related human discomfort criteria. J. Inst. Wood Sci. 10(5):183–188.

———. 1988. Evaluation of vibrational performance of light-weight wooden floors. International Conference on Timber Engineering. Forest Products Research Society, Madison, WI. I:707–715.

ELLINGWOOD, B., AND A. TALLIN. 1984. Structural serviceability: Floor vibrations. ASCE J. Struct. Eng. 110(2): 401–418.

FILLIATRAULT, A., B. FOLZ, AND R. O. FOSCHI. 1990. Finite-strip free-vibration analysis of wood floors. ASCE J. Struct. Eng. 166(8):2127–2142.

FOSCHI, R. O., AND A. GUPTA. 1987. Reliability of floors under impact vibration. Canadian J. Civil Eng. 14:683–689.

GRETHER, W. F. 1971. Vibrations and human performance. Human Factors 13(3):203–216.

INTERNATIONAL STANDARDS ORGANIZATION (ISO). 1978. Guide for the evaluation of human exposure to vibration. Standard 2631. Geneva, Switzerland.

———. 1987. Guide for the evaluation of human exposure to vibration. Standard 2631. Geneva, Switzerland.

———. 1989. Guide for the evaluation of human exposure to vibration. Standard 2631. Geneva, Switzerland.

MURRAY, T. M. 1975. Design to prevent floor vibrations. AISC Engineering Journal Third Quarter, pp. 82–87.

———. 1991. Building floor vibrations. AISC Engineering Journal Third Quarter, pp. 102–109.

OHLSSON, S. 1982. Floor vibration and human discomfort. Doctoral thesis, Chalmers University of Technology, Division of Steel and Timber Structures. Gothenburg, Sweden (ISBN 91-7032-077-2).

———. 1984. Springiness and human-induced floor vibrations: A design guide. Swedish Council for Building Research, Stockholm, Sweden.

———. 1988. A design approach for footstep-induced floor vibration. International Conference on Timber Engineering, Forest Products Research Society, Madison, WI. I:722–729.

———. 1991. Serviceability criteria—especially floor vibration criteria. International Timber Engineering Conference, TRADA Technology Ltd., High Wycombe, UK. I:1.58-1.65.

ONYSKO, D. M. 1975. Performance of wood-joist floors: A questionnaire survey. Report No. OPX12OE. Forest Products Laboratory, Ottawa, Canada.

———. 1985. Serviceability criteria for residential floors based on a field study of consumer response. Project No. 03-50-10-008. Forintek Canada Corporation, Ottawa, Canada.

PERCIVAL, D. H. 1979. History of L/360. Forest Prod. J. 29(8):26–27.

POLENSEK, A. 1970. Human response to vibration of wood-joist floor systems. Wood Sci: 3(2) 111–119.

———. 1975. Damping capacity of nailed wood-joist floors. Wood Sci. 8(2):141–151.

———. 1988. Structural damping and its effect on human response to floor vibrations. International Conference on Timber Engineering, Forest Products Research Society, Madison, WI. I:746–755.

REIHER, H., AND F. J. MEISTER. 1931. The effect of vibration on people. Forschung auf dem Gebiete des Ingenieurwesens 2(11):381–386. Translation: Rep. F-TS-616-RE. Air Material Command, Wright Field, OH (1946).

SMITH, I., AND Y. H. CHUI. 1988. Design of lightweight wooden floors to avoid human discomfort. Canadian J. Civil Eng. 15:254–262.

———. 1992. Discussion of finite strip free-vibration analysis of wood floors. ASCE J. Struct. Eng. 118(5): 1428–1431.

UNGAR, E. E. 1973. The status of engineering knowledge concerning the damping of built-up structures. J. Sound Vibration 26(1):141–154.

WISS, J. F., AND R. A. PARMELEE. 1974. Human perception of transient vibrations. ASCE J. Struct. Eng. 100(4): 773–787.

YEH, C.-T., B. J. HARTZ, AND C. B. BROWN. 1971. Damping sources in wood structures. J. Sound Vibration. 19(4): 411–419.