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Predicting Floor Response Due to Human Activity

Prédiction du comportement d'un plancher soumis au mouvement des gens

Deckenverhalten auf menschliche Bewegungen

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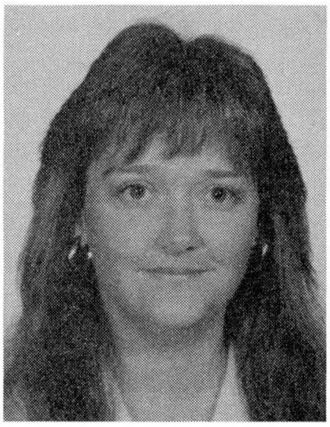

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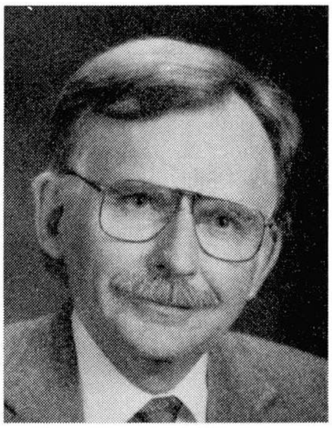

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SUMMARY

This paper presents the results of a study which compares actual floor vibration response data to data obtained from dynamic finite element models. Accelerations are reported for three actual floors subjected to various forces. The floors systems, which vary in size and complexity, are concrete and metal deck with steel supporting members consisting of open web joists and/or steel beams.

RESUME

Cet article présente les résultats d'une étude comparant la réponse à la vibration de planchers réels à celles obtenues par l'utilisation de modèles dynamiques d'éléments finis. L'article comprend un compte rendu des accélérations de trois planchers soumis à une diversité de forces. Les systèmes de planchers, dont les dimensions et le degré de complexité diffèrent, sont construits en béton armé et en acier, et ils sont supportés par des treillis métalliques légers ou des poutres en acier.

ZUSAMMENFASSUNG

Der Beitrag stellt gemessenen Deckenschwingungen Resultate von dynamischen Berechnungen mit finiten Elementen gegenüber. Beschleunigungen wurden für drei Deckensysteme mit verschiedenen Lasten ermittelt. Die Deckensysteme bestehen aus Beton auf Profilblechen, die mit Stahlleichtbauträgern und/oder Walzprofilen unterstützt sind.

1. INTRODUCTION

Providing a floor system which is free from annoying floor vibrations is most economically accomplished in the design phase of the building. This, however, requires design procedures which will predict a problem floor before it is built. Although not explicit in many of the available design procedures, three aspects must be considered to provide an acceptable floor system. The first involves determining the permissible levels of floor vibration for the intended occupancy. Second, an appropriate excitation function for the intended activities must be determined. The third aspect involves the prediction of floor response to specified excitation functions. These three aspects have, either separately or in combination, been the subject of a great deal of research.

1.1 Permissible levels of floor vibration

Permissible levels of floor vibration depend on occupancy requirements. Occupancy requirements range from limitations of sensitive equipment to the "comfort" of the occupants. Ungar, Sturz and Amick [1] present peak velocity requirements for several facility types which have either sensitive equipment or uses, such as optical research systems or microsurgery.

Comfort of the occupants is a function of human perception. This perception is affected by factors including the task or activity of the perceiver, the remoteness of the source and the movement of other objects in the surroundings. A person is distracted by acceleration levels as small as 0.5%g in an office or residential environment. People involved in an activity such as aerobics may be comfortable with acceleration levels up to 5%g [2]. Multiple use occupancies must therefore be carefully considered. Ellingwood and Tallin [3] provide guidelines for limits of steady-state vibration, damping and peak acceleration, according to occupancy.

Perception is also affected by the nature of the vibration response. Steady-state vibration will disturb at much lower levels than vibration which is transient. Many different scales are available which address the subjective evaluation of floor vibration. Factors included in these subjective evaluations include the natural frequency of the floor system, the maximum dynamic amplitude (acceleration, velocity or displacement) due to certain excitations, and the amount of damping present in the floor system.

1.2 Excitation functions for various activities

At the present time, most of the design criteria utilize either a single impact function to assess vibrations which are transient in nature or a sinusoidal function to assess steady-state vibrations from rhythmic activities. The floor excitation in office and residential environments is generally due to the intermittent movement of occupants. The vibration response is, therefore, considered transient and floor response is commonly evaluated on the basis of a single impact function. The heel-drop impact is the basis for several design criteria. For rhythmic activities such as dancing, aerobics, hand clapping, etc. the forcing function is commonly approximated as sinusoidal with a magnitude pertaining to the activity and the number of participants [4].

The use of these simplified excitation functions is driven by the computational abilities of design engineers and can be implemented using hand calculations for simplified systems. More complicated excitation functions, which require advanced or automated analysis procedures, are available. In particular, Ellingwood and Tallin [3] quantify a force function due to a single person walking. The force varies in time, magnitude and location. It may also be useful to note that there are entire scientific journals dedicated to the study of human locomotion, providing information which could be developed into statistically based excitation functions.

1.3 Prediction of floor response

As noted previously, many of the currently available design criteria were developed for implementation in hand calculations. These calculations vary widely in their complexity. One recommendation for commercial environments [3] uses a limiting static deflection to assure an acceptable dynamic response. Other recommendations require that the first natural frequency be kept greater than the second or third multiple of the excitation function to avoid resonance[2]. This is commonly referred to as frequency tuning.

More complex criteria include methods for computing a dynamic amplitude to be included in the subjective rating. Two such examples are the methods presented by Murray [5] and Allen[2]. These methods are derived from closed form solutions for excitation functions applied to a simple beam, a cantilever beam or an equivalent single degree of freedom system. Effects of the individual components (beams, girders and columns) are then superimposed to compute a system response.

2. IMPLEMENTING NEW ANALYSIS CAPABILITIES

The currently available methods, which utilize hand calculations, for determining dynamic response are often much too limiting. Irregular bay shapes and continuous members are nearly impossible to assess with such methods. For these situations, gross simplifications or other analysis measures must be implemented. As personal computer hardware and software capabilities increase, while prices decline, the application of dynamic computer analysis solutions is becoming quite practical for the design engineer. PC based structural analysis software is becoming increasingly user friendly and computationally very powerful. Graphical and menu driven input processors make the modeling of entire floor systems simple and efficient. Dynamic capabilities allow the designer to subject a floor system to time dependent forces at any location. Modal damping can also be included in the model. Output results include response spectra and time histories for displacement, velocity and acceleration, at any node in the model.

Assuming that accurate results are obtained, this type of analysis capability could have a great impact on the determination of floor vibration serviceability requirements. The accuracy of analysis results can begin to be assessed using case studies of the dynamic responses for actual floors. This paper summarizes case studies of three floors of varying complexity. All of the floor systems are concrete and metal deck with steel framing members.

2.1 Description of the analytical models

The dynamic finite element analyses presented in this paper were carried out on a commercially available structural analysis software package. The finite element models utilize beam elements for modeling the steel framing members, and plate elements for modeling the concrete slab and deck, in a single plane. These models are best described as grid models. The level of complexity was chosen with the design engineer in mind.

Plans of the three floors are shown in Appendix A. Floors A and B are bare test floors and floor C is a finished floor in an occupied clothing and shoe retail store. Floor A consists of two deep joist members supported by masonry walls. The heavy lines indicate the locations of continuous support. The model consists of a mesh of approximately 0.61 m (2 ft) square and modal damping was estimated, from experimental data, at 2.5%. Floor B is a 9.14 m (30 ft) square bay supported continuously along two edges by a masonry wall, as shown in the plan. The finite element mesh is 0.305 m (1 ft) square and the modal damping was estimated, from experimental data, at 1%. Floor C is a multi-bay floor system. The bay analyzed is trapezoidal in shape. The model is broken up into a mesh of approximately 0.76 m (2.5 ft) square and modal damping was estimated, from experimental data, at 5%.

The framing members are steel joists (lightweight truss members designed to carry distributed loads). The floor slabs are constructed of lightweight (Floors A and B) or normal weight (Floor C) concrete on 14.3 mm (9/16 in.) metal deck and have a total thickness of 63.5 mm (2.5 in.). Floor C has rolled steel W sections for girders which are continuous over the supports. This is a common lightweight framing configuration for small to medium size commercial buildings in North America.

At relatively small dynamic loads, such as those created by people walking, the steel members behave compositely with the concrete slab; therefore, transformed section properties must be utilized to obtain an accurate response from the analytical model. Due to the nature of the connections in joist supported floor systems, joist members are modeled with pinned member ends, resulting in no moment transfer in the framing members over the center girder and no rotational restraint at the columns. However, it must be noted that this is not the case for rolled shapes with shear connectors; the rotational restraint of the shear connector is often sufficient to transfer moment at small loads.

The models presented use a 2.67 kN (600 lb.) ramp function over a time period of 50 milliseconds as the excitation force. The location of this force, and the time data, is noted as point A on each of the plans in the appendix. The actual floor is excited by the heel-drop of a 0.845 kN (190 lb.) man, which is closely approximated by the ramp function noted above.

2.2 Summary of results

Comparisons of finite element and actual readings for floors A, B, C are shown in Figures 1, 2, and 3, respectively. Graphs are included which show acceleration time histories over a period of five seconds. A fourier transform was performed on each of the signals and the frequency responses are also represented in graphs in Figure 1,2 and 3.

All three models very accurately predicted the dominant frequencies in the dynamic responses. In floors A and B the peak accelerations in the experimental data exceeded those predicted by the finite element model. This may be attributed to an inaccurate prediction of the magnitude of the actual heel drop impact. The actual heel-drop impact was not measured. The experimental and model peak accelerations noted for floor C are amazingly similar. Particularly when the complexity of the actual floor system and relative simplicity of the model used are considered. In this model, the actual heel drop impact may have been more closely predicted by the model.

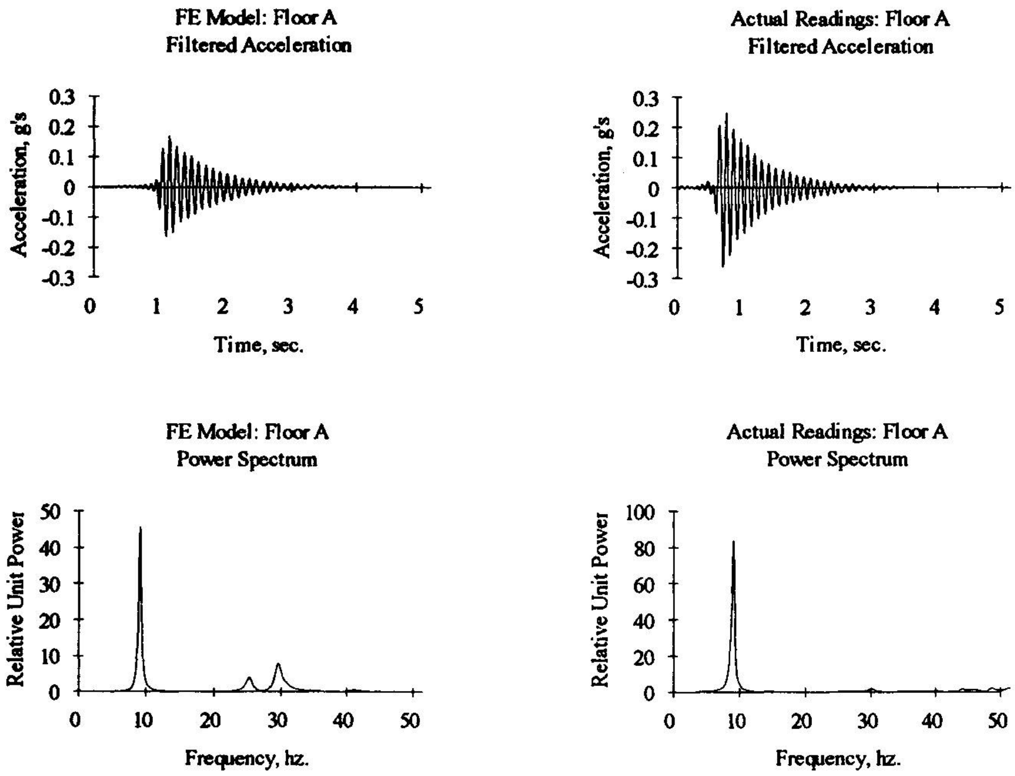

Figure 1 Comparison of Finite Element Results to Actual Results for Floor A

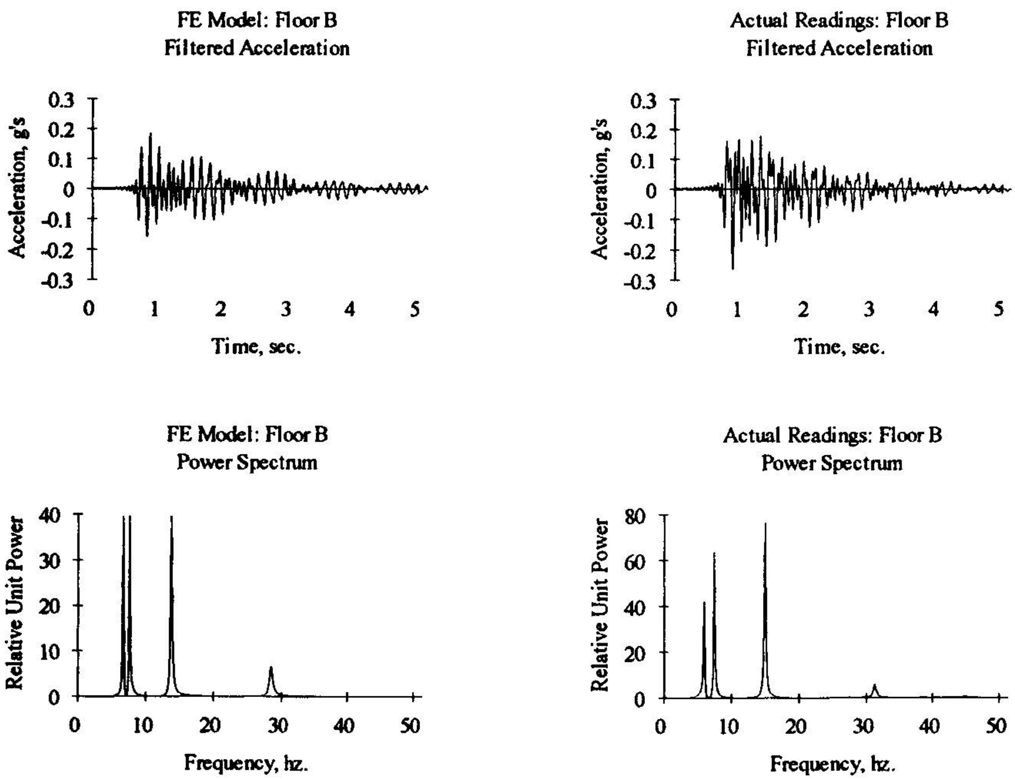

Figure 2 Comparison of Finite Element Results to Actual Results for Floor B

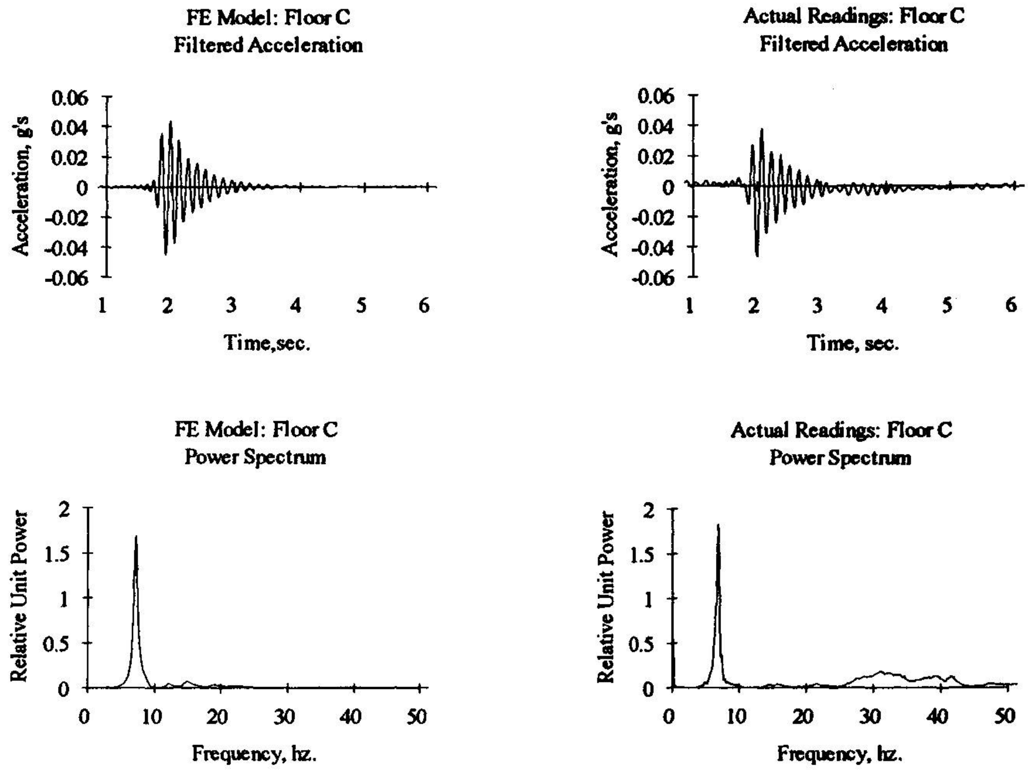

Figure 3 Comparison of Finite Element Results to Actual Results for Floor C

3. CONCLUSIONS

Most of the currently available design criteria were developed with practical computational methods in mind. With the ever increasing use of computer analyses, the definition of "practical computational methods" is becoming much more advanced. In order to fully utilize the expanding analysis capabilities, criteria must be developed which include more exact excitation functions, explicit limitations for frequency ranges and dynamic amplitudes for different occupancies, along with accurate model constraints (i.e. the level of complexity required for a model to accurately predict vibration response).

ACKNOWLEDGEMENTS

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APPENDIX A

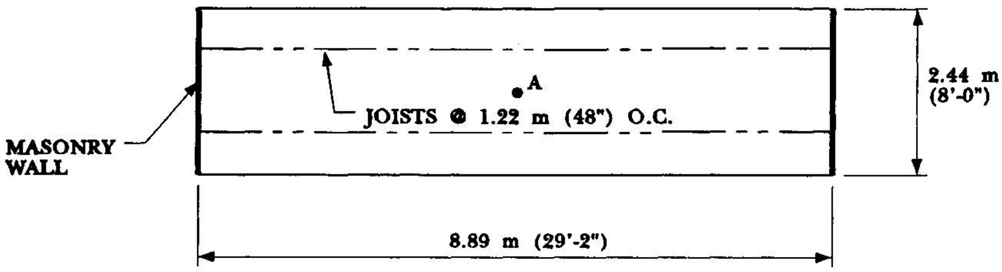

Figure A.1 Plan of Floor A

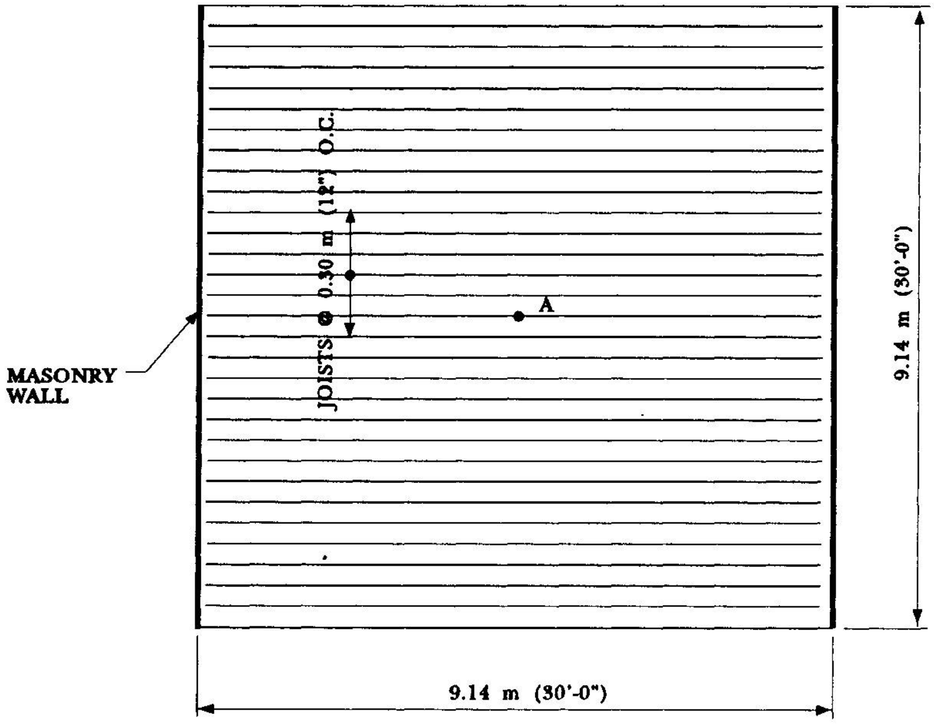

Figure A.2 Plan of Floor B

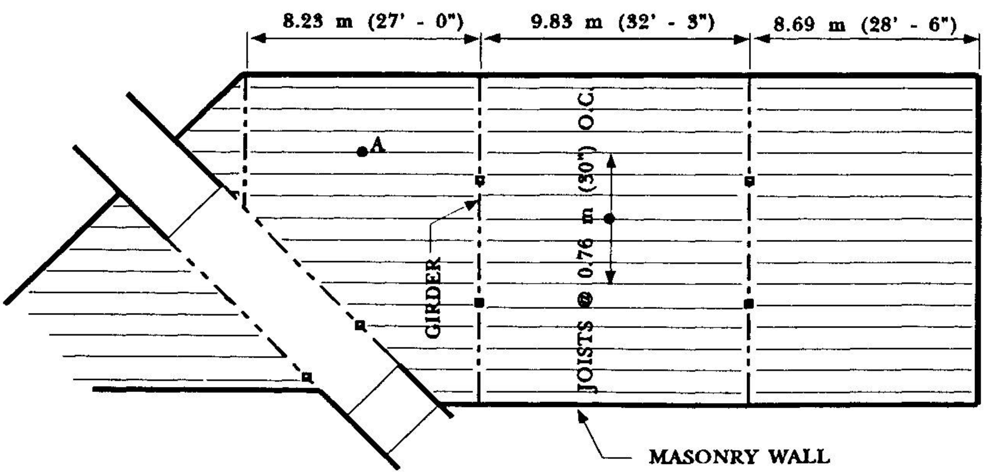

Figure A.3 Plan of Floor C