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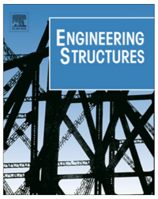

Vibration of lightweight steel floor systems with occupants: Modelling, formulation and dynamic properties

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ABSTRACT

Theoretical analyses are presented for investigating the vibration of lightweight steel floor systems with human occupants. A damped plate-oscillator model is proposed to obtain the dynamic properties of coupled floor-occupant systems. A generalized formulation of the damped plate-oscillator model is proposed. A complex eigenvalue analysis is performed with the use of state-space method and a validation study is conducted by comparing with other undamped plate-oscillator models. The dynamic properties obtained from the proposed model are verified by laboratory tests performed on full-scale lightweight cold-formed steel (CFS) floor systems. The influence of human occupants on the dynamic properties of lightweight steel floors are investigated in three scenarios: an unoccupied floor, a floor with one standing occupant and a floor with two standing occupants. Four human dynamical models in standing position, two with one degree of freedom (SDOF) and others with two degrees of freedom (2-DOF), are adopted in the proposed plate-oscillator model and the obtained results are compared to the test results. Comparisons are also made between the proposed plate-oscillator model with the integrated 2-DOF model for coupled floor-occupant systems. In addition, the need of recalibrating human models for lightweight floor systems is also discussed.

1. Introduction

Over the last several decades, vibration serviceability of floors induced by human occupant activities has become significant in structural design [1], especially for lightweight floor systems [2]. As an alternative to lightweight wood construction, lightweight steel floor systems supported by cold-formed steel (CFS) joists provide an efficient and economical structural system. During the past half century, CFS floor systems have been increasingly used in residential construction and other lightweight framing construction in North America. Initiated in 1999, multi-phase tests were carried out at the University of Waterloo to evaluate the vibration performance of CFS floor systems [3–10]. Although the comprehensive test results have contributed to better understanding of the performance of lightweight steel floor systems [11–15], there is still a lack of reliable models and adequate design guidelines pertinent to the vibration serviceability of lightweight steel floor systems. The objective of this study is, therefore, to propose a damped plate-oscillator model for evaluating the dynamic properties of lightweight steel floor systems with occupants and predict the response of such floor systems under human activities.

It is generally recognized that, besides generating loads, human occupants will interact with a structure, and such interaction, known as human-structure interaction, can be significant if the mass of the occupants is comparable to that of the structure [16]. For lightweight floors, vibration analysis ought to consider a coupled system of the floor and occupants because the dynamic properties of the latter may influence the overall response of the system considerably [17]. Significant progress has been made in researching human-structure interactions in the floor vibration induced by human activities [18,19]. One widely-known fact is that human occupants do not act merely as mass on the structure but behave as highly damped dynamical systems (20%–50% damping ratio) [20]. Thus, two important issues must be borne in mind. Firstly, human bodies may have a considerable influence on the modal mass and damping in lightweight floor systems and the dynamic characteristics therefore change with the location of human walking [21]. Secondly, the traditional modal analysis where damping is ignored or assumed to be proportional is not valid [22] because floor-occupant systems consist of a lightly damped structure system and human bodies with high damping.

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Although human-structure interaction has been investigated extensively and comprehensive understanding has been achieved, most previous studies are based on two-degree-of-freedom (2-DOF) human-structure models [23–26]. Such 2-DOF models were developed to describe coupled vibration of human occupants and the structure in which the human bodies and the structure were simulated as a single-degree-of-freedom (SDOF) model, respectively. Then, the dynamic properties such as natural frequencies and damping ratios could be examined parametrically for a certain range of ratios of frequency, mass and damping coefficients of SDOF models of human occupants and the structure. The 2-DOF human-structure models consider only one structural mode based on the rule of superposition of the linear vibration in which the total response can be obtained by summing up the contribution of each separate mode in modal analysis. However, human occupants may affect all the vibration modes of the structure not just one. Furthermore, the 2-DOF model is inadequate without taking into account the spatial variation of human occupants on the structure. For instance, the influence of human occupants on floor vibration can vary with their locations on the floor. Based on tests of a concrete slab occupied by humans in various situations, Sachse [27] concluded that the location of a human occupant affected the dynamic properties of the test structure and the influence of the occupant increased with the amplitude of the mode shape at the occupant's location. Therefore, it is desirable to develop integrated human-structure models to obtain realistic responses of structure.

Additionally, it is known that the dynamic properties of the human body are strongly related to the intensity of vibration. Thus, the human models used in biomechanics may need to modified before being adopted to model human occupants of building and bridge structures, because the vibration intensities usually encountered in such structures are considerably less than those employed by biomechanics to derive dynamic human models [20,18]. Existing human models proposed for application in civil engineering are primarily developed based on the dynamic behaviour of human occupants on a simply-supported beam, one-way slab or a test rig under laboratory conditions [16,28,29,18,30]. It is necessary to recalibrate the parameters of the human models by realistic full-scale test results, and thus to model human occupants on lightweight floor systems to investigate the vibration of such coupled floor-occupant systems based on the parameters obtained from tests of lightweight floors.

Nicholson and Bergman [31] adopted the Green's function of the vibrating plate to obtain the natural frequencies and mode shapes of the undamped plate–oscillator system. The forced response of the combined system is also determined by modal analysis for both proportional damping and general damping. The same technique was also applied for the vibration analysis of a class of constrained and/or combined linear dynamical systems [32]. However, the dynamic properties of the undamped plate-oscillator system may not be applicable for the floor-occupant system. Foschi et al. [33,34] made an early effort to investigate the combined transient dynamic response of floor systems with occupants based on a finite-strip formulation. The floor systems with various complexities commonly applied in construction were modeled by using finite strips combined into T-beam elements, and the occupants were idealized as damped oscillators. Two human models were compared: a simple 2-DOF model and a more-detailed undamped 11-DOF model. Further applications were extended to develop the design criteria for residential wooden floor systems and a SDOF human model was proposed [17]. Nevertheless, the finite-strip formulation might only be applicable for one-way stiffened floor systems without accounting for effects of the transverse elements such as blocking, bridging and strongbacks. Furthermore, Foschi et al. [33,34,17] applied the impulse due to heel drop impact for the dynamic response of floors but did not investigate the response induced by walking, although they recognised that the use of heel drop impacts to develop design guidelines for lightweight floors was questioned by Allen and Rainer [35]. Zhou and Ji [36–38] developed a beam/plate and spring-mass system to represent a structure occupied by a crowd of people and investigated crowd-structure interaction without considering the damping associated with crowd and structure. In addition, considerable research was also conducted to develop the combined vibrational systems for investigation of human-structure interaction in other structures such as stadia and footbridges [39].

In the present study, a damped plate-oscillator model is proposed to represent lightweight steel floor systems with occupants. Firstly, the model is validated by other models in [31,34]. Then, the dynamic properties obtained from the proposed model are compared with test results. The influence of human occupants is investigated in three scenarios: an unoccupied floor, a floor with one stationary occupant and a floor with two stationary occupants. Two types of human models are adopted: SDOF and 2-DOF. Several existing models of a standing human are also examined.

2. Damped plate-oscillator model

To simplify the presentation, occupants are modeled by SDOF oscillators and the floor is represented by an orthotropic plate. Then, the coupled floor-occupant system can be simulated by a damped plate-oscillator model as illustrated in Fig. 1, which is a rectangular orthotropic plate of constant thickness h connected to N_o linear, damped oscillators at locations of $(\xi_i, \eta_i), i = 1, 2, \ldots, N_o$. The dimensions of the plate are $0 \leqslant x \leqslant a$ and $0 \leqslant y \leqslant b$. The occupant-induced force, $f(x, y, t)$, is located at the position of one occupant, and $g(t)$ is an external force applied to the oscillator.

2.1. Formulation

Using the dot denoting differentiation with respect to time t, the governing equation for the orthotropic plate is

$$\nabla_o^4 w(x,y,t) + c\dot{w}(x,y,t) + \rho h\ddot{w}(x,y,t) = f(x,y,t) + \sum_{i=1}^{N_p} \{k_{hi}[z_i(t) - w(\xi_i,\eta_i,t)] + c_{hi}[\dot{z}_i(t) - \dot{w}(\xi_i,\eta_i,t)]\}\delta(x-\xi_i)\delta(y-\eta_i) \tag{1}$$

where $w(x, y, t)$ is the vertical deflection of the plate; c is the viscous damping constant for the plate; ρ is the mass density; k_{hi}, c_{hi} and $z_i(t)$ are the stiffness, damping constant and displacement of ith oscillator; δ is the Dirac delta function; and ∇_o^4 is the biharmonic operator for orthotropic plates, which can be expressed as

$$\nabla_o^4 = D_x \frac{\partial^4}{\partial x^4} + 2H \frac{\partial^4}{\partial x^2 \partial y^2} + D_y \frac{\partial^4}{\partial y^4} \tag{2}$$

in which D_x and D_y are the flexural rigidity of the plate in the x-direction and y-direction, respectively; $D_{xy} = G_{xy}h^3/12$ is torsional

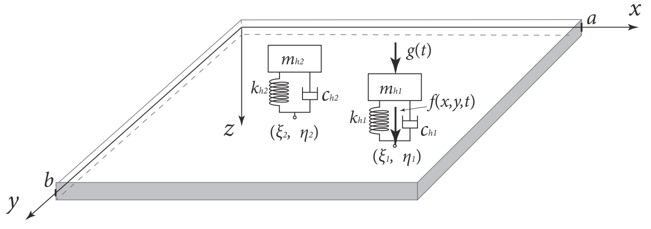

Fig. 1. A damped plate-oscillator model.