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Assessment of dynamic properties of a crowd model for human–structure interaction modeling

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ABSTRACT

Occupants of a structure are thought to behave as a dynamic spring-mass-damper system interacting with the structure through a phenomenon known as human–structure interaction. Understanding this interaction is critical for vibration serviceability as neglecting to account for its effects may result in an overestimation of the dynamic response of a structure, and as a result, a more costly structural design. An experimental study has been performed and the results are compared with analytical models constructed with the parameters proposed by the Joint Working Group (JWG) in the United Kingdom for modeling occupants as a spring-mass-damper system. The results indicate that the parameters of the "active and mostly standing" crowd model satisfactorily represent the dynamic response of the structure with passive occupants standing with bent knees. However, the parameters of the "predominantly seated" crowd model did not adequately simulate the dynamic response of the structure when passive occupants were seated on the structure. A new set of parameters for passive standing occupants, not specifically addressed by the Joint Working Group, was also assessed yielding acceptable results. This study asserts that at least three different models, with varying parameters, are necessary to thoroughly understand the effects of human–structure interaction. The experimental results confirm the applicability of the JWG parameters for active occupants and verify the appropriateness of previously proposed parameters for modeling the passive standing occupant.

1. Introduction

The structural design of assembly-type structures, where crowd-induced excitation is expected, is subject to the design criterion of vibration serviceability. The lightweight and flexible nature of these structures makes them potentially susceptible to vibration from synchronized crowd motion. If the level of vibration is significant, the occupants may become concerned or panic, possibly leading to a safety issue. Despite the recognition of this criterion, guidance for designing and assessing a structure is limited.

The most comprehensive design guidance, and the only including human–structure interaction, is provided by the Joint Working Group in the United Kingdom (UK) in its publication "Dynamic performance requirements for permanent grandstands subject to crowd action: recommendations for management, design and assessment" [5]. This publication recommends one of two approaches for design and assessment of vibration serviceability. The preferred approach, Route 2, requires the structural engineer to estimate the dynamic response of the occupied structure for comparison with acceptable accelerations ranges. The dynamic response of a structure is likely to be predicted at a higher level of acceleration if the effects of the occupants, (additional mass and damping) and their interaction with the structure are not considered. This overestimation of the dynamic response may result in a stiffer and more costly structural design if vibration serviceability is controlling the design. Understanding human–structure interaction (HSI), especially the damping component, is critical for improved estimation of the dynamic response of structures and efficiency in vibration serviceability design.

The effects of human–structure interaction were first observed by Lenzen [6]. Dynamic results indicated that occupants did not simply behave as an additional mass. Subsequent studies, including Ellis and Ji [3], Littler [7], Brownjohn and Zheng [1], Reynolds et al. [11] and Salyards and Noss [13], have confirmed that the occupant acts as a dynamic spring-mass-damper system attached to the empty structure thereby affecting the dynamic properties of the combined system. In terms of damping, the addition of occupants consistently demonstrated an increase in damping of the occupied system over the empty structure. This is an important effect of

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human–structure interaction because predication of the dynamic response of a structure utilizing the empty structure properties is likely to yield an overestimation of the response. It is important that the increase in damping can be accurately quantified such that response prediction is improved. However, to understand the influence of HSI on damping, the effects on frequency also need to be considered. Depending on the relative ratio of frequency of the occupant to the structure and the relative ratio of the mass of the occupants to the structure, the frequency appears to either increase or decrease from that of the empty structure [3]. The apparent increase is surprising as additional mass causes a decrease in frequency. However, this apparent increase may be the result of the inability to identify the actual lowest frequency because of the heavy damping of the occupant [15].

To simulate the effects of human–structure interaction, the occupant has been modeled as a dynamic system attached to the empty structure model. A number of biomechanical models of the human body have been developed [12,16,8]. It has been shown that the simplest of these, a SDOF model, is effective for modeling human–structure interaction [2]. The models utilized by Dougill et al. [2] were adopted by the Joint Working Group as the models recommended for use when modeling human–structure interaction [5]. The model was utilized by Pavic and Reynolds [9] in the estimation of the dynamic response of an occupied stadium structure and was deemed acceptable based on the predicted response. However, the verification of these models has been based solely on the level of the dynamic response, and the dynamic properties have not been assessed. This study examines the dynamic properties of an occupied structure and compares them to the properties of an analytical model representing the occupied system using the JWG occupant parameters.

1.1. Overview of experimental program

The laboratory floor structure, design and constructed as a flexible structure specifically for vibration serviceability research, is located at The Pennsylvania State University. The concrete floor slab is 8.23 m (27 ft) by 3.35 m (11 ft), including a 0.15 m (6 in) overhang along the exterior edges. The floor is supported by five equally spaced 14K4 open-web steel joists which span between W8x13 beams at each end as shown in Fig. 1. The wide-flange beams are supported by four steel pipes approximately 0.9 m (3 ft) above the slab-on-grade. When the structure was originally constructed in 1999, it was determined, through experimental modal analysis, to have a first natural frequency of 7.04 Hz [10,4]. However, when data was collected for this study, the natural frequency was experimentally determined to be 6.6 Hz and this decrease was attributed to the cracking observed in the concrete deck at the mid-span location of the joists across the entire width of the structure.

Experimental measurements were collected using data acquisition hardware by IOTech, a Wavebook 516/E with two eight-channel dynamic signal conditioning modules. Real-time vibration analysis software package, eZ-Analyst, was used for data collection and signal processing. Traditional experimental modal analysis methods were applied to the occupied structure using an electrodynamic shaker, APS Dynamics model 400, to excite the structure with a swept-sine signal. The response of the structure was measured by seismic accelerometers from PCB Piezotronics, model 393A03. The location of the excitation (shaker) and response measurements (accelerometers) are shown in Fig. 2. The modal parameters of the occupied structure were determined using Vibrant Technology's ME'scopeVES 5.0 software utilizing a global curve fitting process.

The structure was occupied by groups of occupants varying in size, resulting in a range of mass ratios, as shown in Table 1. The mass ratio is defined as the mass of the occupants divided by the mass of the structure. Typical mass ratios for stadium structures have been calculated to be between 0.25 and 0.75. Due to the strength capacity of the floor structure, higher mass ratios were unattainable. The occupants were distributed in a grid-like position with the same aspect ratio of the floor and centered on the floor as shown in Fig. 3. Occupants were arranged on the structure to locate the center of mass of the crowd as close to the center of the structure as possible to minimize the effects of an imbalanced crowd on asymmetrical modes. The number of tests and the variety of scenarios tested was limited based on access to the structure and availability of a sufficient number of volunteers.

Measurements were made when the crowd was positioned in a dense array, i.e. occupants spaced at 51 cm (20 in) on center, and when the crowd was positioned in a sparse array, i.e. occupants spaced at 71 cm (28 in) on center. Each volunteer was asked to position themselves in one of three postures: standing with straight knees, standing with bent knees, or seated on a bench as depicted in Fig. 4. Modal analysis was performed three times for each combination of mass ratio, dense or sparse population, and posture. Modal analysis was also performed on the empty structure in between subsequent occupied tests to verify the reliability of the measurements. Modal parameters of natural frequency and damping ratio were determined for each scenario for subsequent comparison with the analytical modeling results.

1.2. Analytical modeling

A finite element model of the empty structure was developed in SAP2000. A simple in-plane modeling approach, effectively modeling the inherent composite behavior between the steel joists and the concrete slab at the low-level of vibration of interest for vibration serviceability, was selected for this study. The joists are modeled as beam elements in the same plane as the concrete slab with

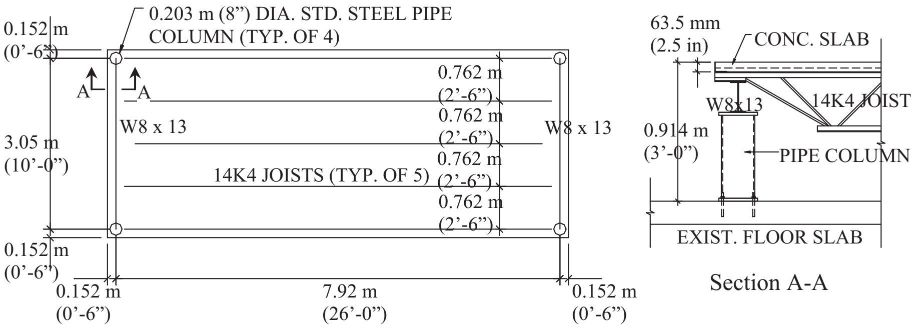

Fig. 1. Experimental floor structure, plan and elevation views (from [10].