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Jumping load models applied on a gymnasium floor

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ABSTRACT

Crowd induced dynamic loading in large structures, such as gymnasiums or stadiums, is usually modelled as a series of harmonic loads which are defined in terms of their Fourier coefficients. Different values of these Fourier coefficients that were obtained from full scale measurements can be found in codes. Recently, an alternative has been proposed, based on random generation of load time histories that take into account phase lags among individuals inside the crowd.

This paper presents the results of some studies carried out in order to compare the existing load models used to simulate periodic jumpings and develop a new load model.

Generally the testing is performed on platforms or structures that can be considered rigid because their natural frequencies are higher than the excitation frequencies associated with crowd loading. But in this paper, to validate these load models test have been performed on a structure designed to be a gymnasium, which has natural frequencies within that range.

Test results have been compared with predictions based on the load modelling alternatives with quite good agreement. A calibrated finite element model of the structure has been used for this purpose. The new model provides a clear improvement in the energy contained within higher frequencies.

1. Introduction

The interest for modelling of human activities on structures has been recurrent since the first accidents on suspension bridges in the nineteenth century like Broughton (1831) in the U.K. or Angers (1850) in France. The use of new materials allowing the design of slender structures, the simultaneous interest in the structural serviceability performance and accidents such as during the opening ceremony of the London Millenium Footbridge (10 June 2000) made it mandatory to carry out and in-depth analysis of the equivalent actions to be used in the numerical analysis of structures.

Human activities such as walking, dancing, jumping, running and aerobic exercises are regarded the most severe excitation source of slab floors. Therefore, there is a concern among researchers to evaluate the dynamic behaviour of structures under human activity effects, because these actions are considered as static loads in structural design [1,2].

One of the most influential research, conducted by Lenzen and Murray as early as 1969, suggested the use of the so-called "heel drop test" for assessing the vibration susceptibility of light floors under walking loads. Although the general applicability of their results has been questioned, its influence on National Codes (like the current Spanish "Código Técnico de la Edificación") has been extensive.

Current research authors are Ebrahimpour [3], Pernicaand Allen [4], with research on the vibration serviceability criteria and vibration criteria for assembly occupancies. More recently interesting contributions are due to Ellis and Ji [5]. Also important are European research projects [6,7] and the publication of SCI Guide P354 [8] incorporating new results such as the reduction factors for the Fourier coefficients representing the crowd activities has been of particular interest.

An alternative has been proposed by Sim [9] who has worked on the statistical characterization of phase lag among individuals of a crowd, based on test results. Thus, the load depends on random factors and is no longer the addition of pure harmonic loads.

UK Recommendations strongly suggest that dynamic testing or experimental modal analysis (EMA) of grandstands is undertaken when a structure may be subjected to coordinated crowd motions, when usage of the structure changes to involve "significantly greater dynamic crowd activity" or when complaints have been received. Generally the testing is performed on platforms or structures that can be considered rigid because their natural frequencies are higher than the excitation frequencies associated with crowd loading.

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This paper presents the results of some studies carried out in order to compare the existing load models used to simulate periodic jumping and develop a new load model.

To validate these load models, tests have been performed on a structure designed to be a gymnasium, which has natural frequencies within that range of the excitation frequencies. In this test the gym slab was instrumented with acceleration sensors and several volunteers jumped. In addition, a finite element model of the structure has been developed. The load models have been applied on this model to calculate predictions of the structural response. Test results have been compared with predictions based on the load modelling alternatives.

2. Modelling of the dynamic actions induced by jumping

Modelling of human-induced loads has proved to be very difficult and numerous approaches of varying complexity have been presented in the literature. In the current study, dynamic response of the studied structure has been determined under three dynamic human jumping loads to evaluate them. The third model is a new model proposed by the authors of this paper.

2.1. Model 1: SCI P354 model

The first model may be found in SCI P354 guide [8], where the acting load follows the procedure explained by Ellis [1] based on the typical Fourier series used to represent periodic human loading:

$$F(t) = W\left(1 + \sum_{j=1}^{3} \alpha_j \sin(\omega_j t + \phi_j)\right) \quad (1)$$

where W is the weight of the jumpers, ω_j is j times the jumping frequency, ϕ_j is the phase lag of the jth term and α_j is the Fourier coefficient (or dynamic load factor) of the jth term. α_j and ϕ_j values of the jth term are shown in Table 1 (p is the number of participants).

Table 1
Fourier coefficients and phase lag. Model 1.

j	α_j	ϕ_j
1	$1.61p^{-0.082}$	$\pi/6$
2	$0.94p^{-0.24}$	$-\pi/6$
3	$0.44p^{-0.31}$	$-\pi/2$

Fig. 1 is consistent with a main jumping frequency of 2.5 Hz, and Fourier coefficients associated with three jumpers.

2.2. Model 2: statistical model

The second methodology is based on the PhD Thesis titled Human-Structure Interaction in Cantilever Grandstand, by Sim presented at the University of Oxford [9]. This work considers randomness in the phase lag among individuals in the crowd. The load contribution associated with the ith jump of each individual has the following form:

$$F(t) = Wk_{p,i}\cos^2\left(\frac{\pi(t - t_{eff,i})}{t_{p,i}}\right); \quad \text{for} \quad \frac{-t_{p,i}}{2} \leqslant (t - t_{eff,i}) \leqslant \frac{t_{p,i}}{2} \quad (2)$$

where W is the weight of the jumper, $k_{p,i}$ is the impact factor, $t_{p,i}$ is the contact period and $t_{eff,i}$ is the effective time. Those three parameters $[k_{p,i}; t_{p,i}; t_{eff,i}]$ are set for each individual and each jump with a statistical model proposed by Sim [9], which is dependent on the main jumping frequency.

Fig. 2 has been built under the same assumptions of Fig. 1, but with the second methodology. The time lags and contact duration differences result in a much different pattern.

2.3. Model 3: Proposed model. Modified statistical model

The main motivation to develop a new model is due that in various engineering projects with real and complex structures, it has been shown that the models 1 and 2 described previously do not reproduce adequately the response of the structure at frequencies above the human activity range. Fig. 3 shows the result of the load model applications that will be described in the result section, corresponding to the response of the test structure to an excitation caused by jumping people at 2 Hz. It can be seen that both models underestimate the energy contained in higher frequencies (above 8 Hz), respect to the experimental values. The model 2 with the squared cosine function is richer in frequencies than the first model, but it does not yet reach the experimental values.

The amount of energy in higher frequency range can be comparable with the energy contained in the human activity frequency range and its first harmonics. Especially at points away from the area of human action, where you can find passive people, sitting, dining, chatting, etc. This information is very important for the design of possible isolation systems and design of the structures.

So, as will be proved at the results section in Section 6 models 1 and 2 do not adequately predict the energy contained at high frequencies within the jump force profile. The third dynamic load

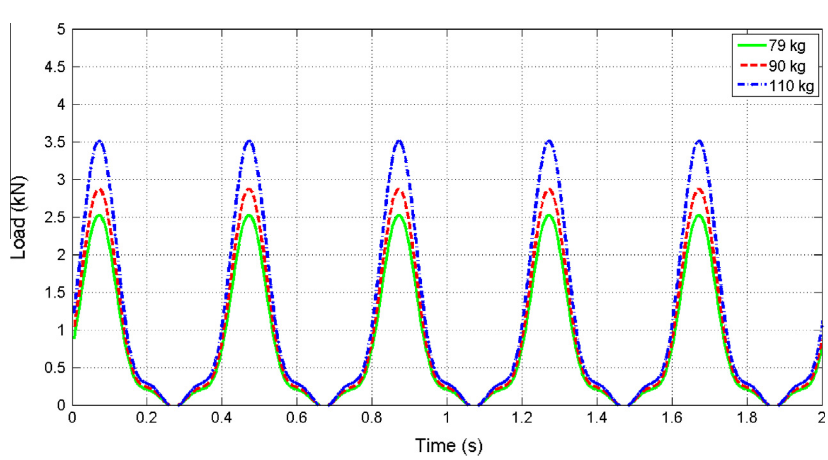

Fig. 1. Dynamic loads of three people at 2.5 Hz. SCI P354 model.