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A stochastic load model for pedestrian-induced lateral forces on footbridges

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A B S T R A C T

In the past decade, several researchers have studied the phenomenon of excessive pedestrian-induced lateral vibrations and full-scale measurements of various bridges under crowd loading have been carried out. These tests have verified the existence of a form of instability for which a transition between limited and excessive lateral vibrations occurs for a small increase in the number of people occupying the bridge. This disproportionate increase in the lateral vibration amplitude is caused by a dynamic interaction between the pedestrian and the laterally moving structure, although the governing mechanism which generates the load is still somewhat disputed.

Theoretical work has also been undertaken, but unlike current codes of practice and design guidelines, which are primarily based on the empirical full-scale observations, many of the theoretical hypotheses lack the proper experimental evidence to support their applicability. Recently, an extensive experimental campaign was carried out, in which the lateral forces generated by pedestrians during walking on a laterally moving treadmill were determined for various combinations of lateral frequencies (0.33–1.07 Hz) and amplitudes (4.5–48 mm). It was shown that large amplitude vibrations are the result of correlated pedestrian forces in the form of "negative damping", with magnitudes that depend on the relationship between the pacing frequency and the frequency of the lateral movement.

Herewith, a novel stochastic load model for the frequency and amplitude dependent pedestrian-induced lateral forces is presented. The lateral forces are modelled as a sum of an "equivalent static force" and "motion-induced" (or self-excited) forces which are quantified through equivalent pedestrian damping and mass coefficients. The parameters in the model are based directly on measured lateral forces from a large group of pedestrians. Thereby, the model is currently the most statistically reliable analytical tool for modelling of pedestrian-induced lateral vibrations. Through simplified numerical simulations, it is shown that the modal response of a footbridge subject to a pedestrian crowd is sensitive to the selection of the pacing rate distribution within the group, the magnitude of ambient wind loads and the total duration of the load event. In a particular simulation, the selection of these parameters ultimately affects the critical number of pedestrians needed to trigger excessive vibrations. Finally, as an example, it is shown that the prediction of the critical number of pedestrians matches well with observations made during the opening of the London Millennium Bridge.

1. Introduction

In long-span footbridges, the possibility of excessive pedestrian-induced lateral vibrations is a serious threat to the design and therefore provisions for the installation of mechanical damping devices and full scale dynamic testing has become an integrated part of their design process [1–3]. As the bridge spans increase, the avoidance of crowd-induced lateral vibrations becomes more difficult and the necessary amount of additional damping easily exceeds the limit of what is practically possible or economically acceptable [4]. In some cases, this means that modifications in the initial structural layout may be necessary, e.g. to provide additional horizontal stiffness. Alternatively, an informed decision can be made to accept that excessive lateral vibrations may occasionally occur. In this case dampers may be avoided or introduced to provide the minimum amount of damping needed to avoid the problem on a daily basis. This strategy was adopted for the newly built Tri-Country arch footbridge in Weil-am-Rhein in Germany, which features a record breaking clear span of 230 m [5]. Shortly after its opening, full scale pedestrian tests were carried out, in which the possibility of excessive lateral vibrations was verified. However, the conditions under which excessive vibrations occurred were associated with a large crowd density with a low probability of occurrence and hence no dampers were installed [5].

For design purposes, a successful implementation of this strategy, relies on an accurate representation of the pedestrian-induced load and the criterion for the number of pedestrians needed to trigger excessive lateral vibrations. However, current state-of-the-art guidelines [6–10] offer only a limited insight into this field, as they are primarily based on empirical observations

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