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Dynamic analysis for structural upgrade of footbridge located in Canna's River in Carbonia (Italy)

Gian Felice Giaccu¹, Stefano Punzo², Bruno Briseghella³, Luigi Fenu², Alireza Hosseini² and Francesco Mocci².

¹ University of Sassari, Sassari, Italy

² University of Cagliari, Cagliari 09124, Italy

³Fuzhou University, Fuzhou, China
lfenu@unica.it

Abstract. Understanding how pedestrians interact with the footbridge, in particular studying dynamic actions caused by pedestrian loads on footbridges, engineers can address any design deficiencies, such as excessive deflection, resonance, or discomfort experienced by pedestrians during bridge usage. For this, the paper consists in two main parts: In the first part, we extensively examine various factors essential for accurately modeling the dynamic actions induced by individual pedestrians or groups of pedestrians on footbridges. Our focus includes an analysis of relevant experimental studies conducted abroad, specifically regarding the closure of the Millennium Bridge. This section extensively discusses the identified issues and explores different mathematical models, particularly those capable of simulating dynamic forces resulting from walking, jogging, or jumping, whether by an individual or a group of walkers.

The second part of the study centers around utilizing Finite Element Method (FEM) models to analyze a specific footbridge located in Carbonia. This footbridge was inaugurated in November 2001 but had to be closed within a year.

Keywords: footbridge, pedestrian action, lateral vibrations, dynamic, resonance.

1 Introduction

Various physical phenomena contribute to vibrations in civil and industrial buildings, which can be categorized into two types: vibrations generated within the building's interior and vibrations originating from external sources. Notably, footbridges differ from other buildings due to their exceptionally low fundamental frequencies, comparable to those produced by pedestrian footsteps or running. Consequently, when footbridges experience high pedestrian loads (e.g., numerous pedestrians crossing simultaneously), the resulting oscillations can reach levels that not only inconvenience pedestrians but also lead to cyclic phenomena that may cause structural damage. Different examples highlighting this issue include the Millennium Bridge in London and the Solférino Bridge in Paris.

2 Mathematical models for dynamic actions

2.1 Action induced by pedestrians.

Various measurements have been conducted to quantify the vertical loads exerted by pedestrians on structures. These measurements consistently show that the vertical force produced by a single step closely resembles the shape depicted in Figure 1.

Numerous studies have focused on quantifying pedestrian walking forces, with a greater emphasis on the vertical component of the dynamic force rather than the horizontal one. Dallard's research in 2001 investigated the forces generated by pedestrian steps and identified three main directions: vertical, longitudinal, and lateral (or transversal) forces [1]. These force components are influenced by various factors, including pedestrian walking speed, step frequency, and step length.

In general approximately 40% of a pedestrian's weight contributes to the vertical force, while the lateral component accounts for only around 4%, and the longitudinal component comprises the remaining 56%. For instance, based on this estimation, a pedestrian weighing 75 kg (approximately 750 N) would exert a vertical force of 300 N, a longitudinal force of 420 N, and a lateral force of 30 N on the structure or scaffold.

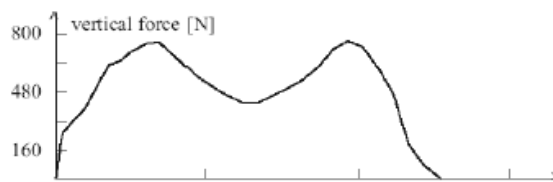


Fig.1. Time trend of vertical force produced by a step.

By observing a pedestrian's continuous walk, we generated the diagram depicted in Figure 2, illustrating the time trend of the vertical component. The diagram reveals a recurring pattern with an average period that corresponds to the inverse of the average frequency of a single step.

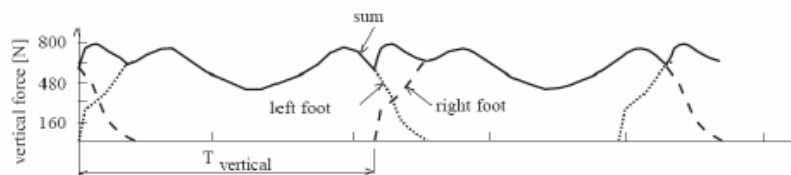


Fig. 2. Time trend of the vertical component for continuous walk

The lateral movement exerted by pedestrians walking on a supporting structure arises from the oscillation of their body's center of mass. This oscillation is a consequence of the stepping action, where each foot is alternately placed (Fig. 3). These oscillations

have a magnitude of approximately 1-2 cm.

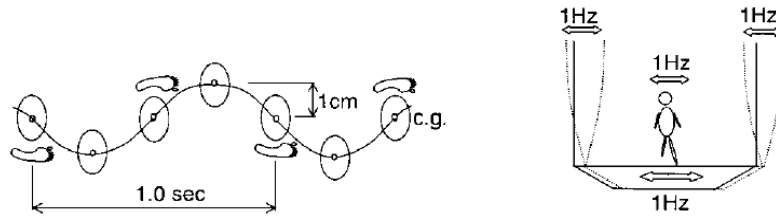


Fig. 3. Oscillation of the center of body mass during the movement

The frequency of the lateral component corresponds to half the frequency of a pedestrian's steps, ranging from 0.7 to 1.4 Hz. By examining a continuous walk, we generated the diagram presented in Figure 4, showcasing the temporal variation of the lateral component. Similarly, we observe a time trend in this case with an average period equal to twice the inverse of the average frequency per step.

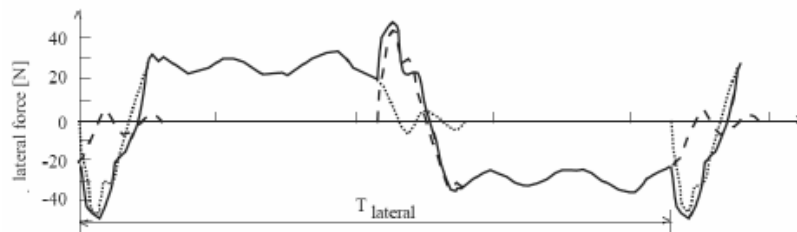


Fig. 4. Time trend of the lateral component for continuous walk

One of the most common load model for the study of very flexible structures is the one that considers the force induced by a single pedestrian as a periodical force.

$$F_p(t) = G_0 + G_1 \cdot \sin(2\pi \cdot f \cdot t) + \sum_{i=2}^n G_i \cdot \sin(2 \cdot \pi \cdot i \cdot f \cdot t + \varphi_i) \quad \text{Eq.1}$$

where:

$F_p(t)$ is the periodical force induced by a pedestrian to model;

G_0 is the static force represented by the vertical component;

G_1 is the size of the first harmonic (fundamental harmonic);

G_i are the sizes of the i -th harmonic component;

f is the step's frequency;

φ_i are the initial phases of the i -th harmonic components;

n is the number of the harmonic which have been considered;

The various sizes of the harmonic i -th G_i are given by the product of the vertical static force G_0 for a coefficient α_i called load factor.

Determining the dynamic behavior of a footbridge becomes more complicated when multiple individuals simultaneously exert their actions upon it, unlike the case of a single pedestrian. This complexity arises due to the unique characteristics of each pedestrian, such as weight, step frequency, and speed. Furthermore, as the number of people on the bridge increases, the generated loads lose synchronization with both each other and the footbridge. It is important to note that in the previous equation for a single pedestrian, the initial phase differs for each individual due to their varied entry times onto the footbridge and their movement speeds while on it.

Consequently, in scenarios involving crowd-induced loads, methods based on probability calculus and statistical processes have been developed to address this issue[2].

The current model we are studying is not only about the random movements of pedestrians with different frequencies and initial phases on a footbridge experiencing various vibrations but also aims to estimate the equivalent number of pedestrians (N_{eq}) uniformly distributed on the footbridge. These pedestrians are assumed to move in phase and at the same frequency as the natural frequency of the footbridge, producing a similar effect on the random pedestrians.

As a result, relations have been modelled, as follows:

$$N_{eq} = 10,8 \cdot \sqrt{N} \xi \quad \text{Eq.2}$$

where N is the number of the pedestrian who are on the footbridge (density by superficial area) and ξ is the critical damping. In case of very dense crowd:

$$N_{eq} = 1,85 \cdot \sqrt{N} \quad \text{Eq.3}$$

3 Case Study: A Pedestrian footbridge located in Carbonia

In 2001, construction efforts were initiated in Carbonia to enhance the conditions of a council housing district adjacent to the Cannas River. The primary objective of these efforts was to restructure public and private areas, including the construction of garages for the houses in Cannas street and in Iglesias boulevard as well as the realization of a new footbridge on Cannas replacing the old ones (Figure 6). Among the problems that

caused the quick closing, there was the presence of a 10 cm oak footsteps surface that needed to be maintained due to its quick worsening caused by elements.



Fig. 6. The footbridge on Cannas River

4 The F.E.M. model

Various three-dimensional models of the footbridge were analyzed through Finite Element Method (F.E.M.) modeling. These models differed significantly when comparing their static and dynamic analyses. A precise and detailed model was created for the static study, considering structural elements such as twisting stiffening, where a significant portion of the structure was represented using plate elements (Figure 7). In contrast, for the dynamic analysis, a simplified and coarse model was employed [3,4] (Figure 8).

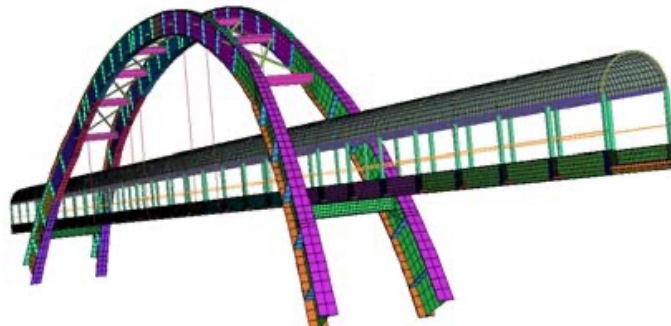


Fig. 7. The global F.E.M. model for the static analysis

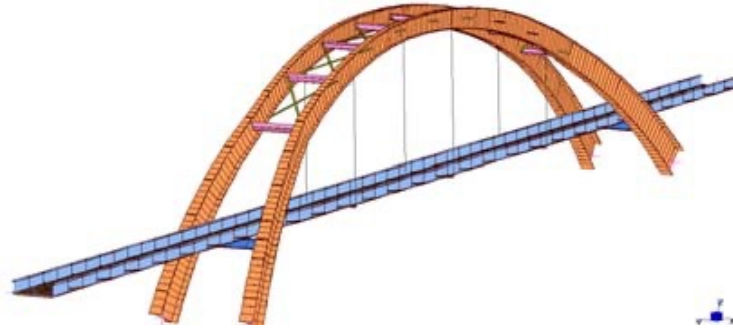


Fig. 8. The global F.E.M. model for the dynamic analysis

5 The Sétra technical guide

Due to the inadequacy of our existing regulations in addressing the impacts of pedestrians on footbridges, we have referred to the guidelines provided by the Technic Department of the Engineers of Transportation, Roads, and Bridges (Service d'Etudes Techniques des Routes et Autoroutes - Sétra) from the French Ministry of Infrastructure and Transportation. This methodology aims to mitigate the vibrational risks induced by pedestrian footsteps on the structure. However, resonance is not the sole concern to be considered. It is crucial to note that even very lightweight footbridges may experience vibrational phenomena.

6 The structural recovery

An initial improvement to enhance the footbridge's dynamic response to pedestrian forces is to replace the deteriorated original wooden scaffold with a new slab made of corrugated plate reinforced with concrete, increasing the stiffness.

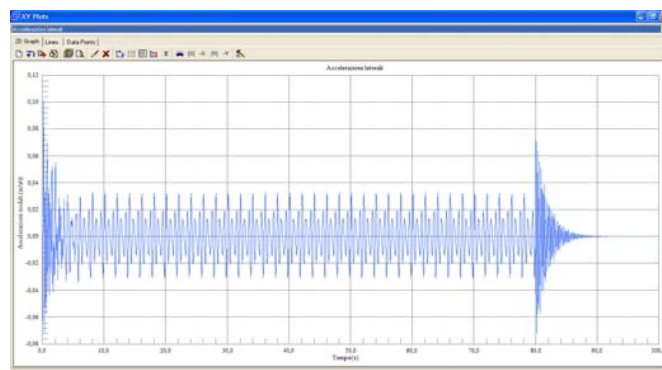


Fig. 9. Transversal accelerations of the most pressurized node.

After the improvements the maximum values reached by the transversal accelerations are quite different from the ones found before. The values reach in the initial transitory $0,1 \text{ m/s}^2$, then, in the stationary phase they remain about $0,03/\text{s}^2$. In terms of displacement the maximum value reaches half millimetre. As a result, this is an efficient solution for transversal oscillation problem.

7 References

- [1] Fjalar Hauksson, 2005. Master's Dissertation by Fjalar Hauksson, Division of Structural Mechanics, Lund University. Dynamic behaviour of footbridges subjected to pedestrian-induced vibrations. Lund, Sweden.
- [2] Sétra (service d'Études techniques des routes et autoroutes). October 2006.FOOTBRIDGES. Assessment of vibrational behaviour of footbridges under pedestrian loading. Technical guide.
- [3] P. Żółtowski, J. Pechna, K. Żółtowski, H. Zobel. Bulletin of the polish academy of science. 2006. Analysis of dynamic loads on lightweight footbridge caused by lorry passing underneath. Vol. 54, No. 1.
- [4] C. Melchor Blanco, Ph. Bouillard, E. Bodarwé, L. Ney. 9th Samtech. Users Conference 2005Structural dynamic design of a footbridge under pedestrian loading.