

## HIL model and cable stayed footbridge monitoring/control

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### ABSTRACT

Elaborations from an experimental campaign on a footbridge are re-elaborated. After the parameters of a consistent numerical model have been calibrated, recorded signals and numerical analyses are exploited in view of improving the structural monitoring features adopted up to now. The transient character of human crossing is demanded to a further suitable numerical model. As an ultimate target of the investigation, the potential of simple structural control schemes on the cable tension is discussed.

**Keywords:** *Cable, Cable-stayed bridge, Human induced loading, Structural monitoring, Structural control*

### 1 INTRODUCTION

Footbridge denotes any pedestrian bridge, despite several classes of them can be defined as correctly done in some technical recommendations (see [1] among others). Indeed, the specific role of the link pedestrian connecting, by crossing a main motorway, the local subway station to an area gathering a sport forum and a theatre in the Southern area of Milan, Figure 1a), is quite different from the isolated footbridge in Figure 1b). It is a link, crossing a channel, along a walking/running path within a public resort. The latter bridge is the selected case study for this contribution. While the full occupation of the bridge deck area is a likely event in the first case, only groups of a few pedestrians are likely to cross the second one. The static design of the first bridge is conveniently carried out by associating a dense crowd with a dynamic investigation, as well emphasized in the existing literature [2-5]. By contrast, the static design of the second footbridge fully satisfies existing structural codes [6-8], leaving the dynamics effects feeling to the in service operations.

Thus the focus of this paper is on the possibility of anticipating at the design stage an understanding of the dynamic response of an isolated footbridge so that expensive a-posteriori countermeasures to possible drawbacks can be replaced by a-priori suitable design modifications.

For this purpose a finite element (FE) numerical model of the structural system is first pursued (within the software environment in [9]). For a cable-stayed bridge this necessarily means to adopt geometrically nonlinear schemes. In addition, a numerical model of the human induced loading (HIL) is required. The proposal of reference [10] is adopted. The main aspects are summarized in next section.

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The global numerical model, FE and HIL, is then used to simulate some structural responses. Likely damage scenarios are also simulated and the way by which the system can be reset is discussed.



a)



b)

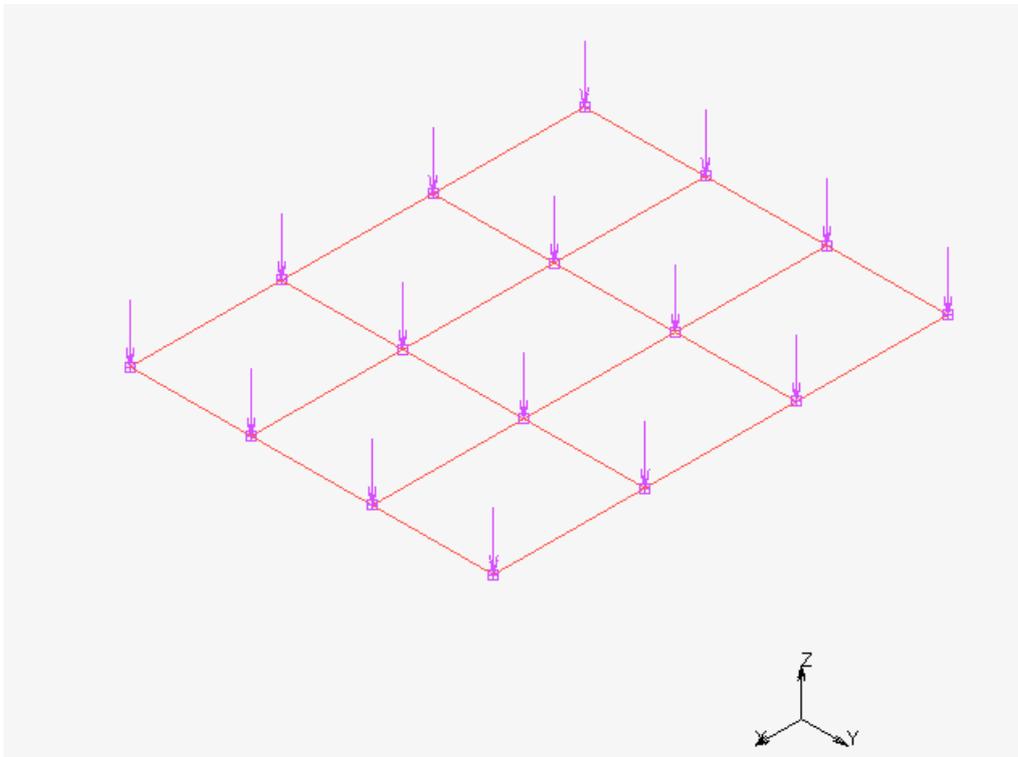
*Figure 1 – Two footbridges quite different for functionality, design requirements and performance: a) the link between the subway station and the sport forum of Assago in the Southern area of Milan, Italy; b) the timber pedestrian crossing located in the public resort area of Farra d’Alpago, in North-Eastern Italy.*

## **2 THE HIL SCHEME**

As illustrated in [10] and exploited in [11-12], the human induced loading (HIL) idealization applies to a group of persons which crosses the bridge, being aligned on the deck section width. They can proceed as a sequence of couples, triplets and so on.

For sake of exemplification, assume that the group is made by 4 persons, proceedings as two couples. They covers four transversal strips, which can be easily discretized as a grid of 16 nodes as

in Figure 2. It is assumed that the persons are aligned 2 by 2 along the transversal direction,  $y$ . The action of each person on the deck is represented by 4 of the sixteen vectors in the figure. The intensity of each vector is different one from the other, accounting for the specific features of each person as well as from the actual location on the deck of the person.



*Figure 2 – Schematic representation of a group of 4 persons. It is assumed that the person are aligned 2 by 2 along the transversal direction,  $y$ .*

The scheme in Figure 2 can be regarded as a sort of initial condition at time 0. However, in a Lagrangian representation, the same figure with different vector intensities, can also be regarded as the position at time  $t_i$ , provided that the coordinates are translated of a quantity  $v t_i$  in the direction of the motion,  $v$  being the pedestrian group velocity.

Going in further details, each person acts by a vertical force, an added mass and a transversal force that change sign at each step. Each of these quantities are then split to the 4 surrounding nodes. The model of reference [10] assumes that the two force components are obtained as realizations from a stochastic random field model, provided that a deterministic shape function rearranges some non-stationarity intrinsic in the action to be idealized. As said, the realizations correspond to different time steps and due to the uniform translation, their values can then assembled, for each node of the finite element discretization of the deck, into its associated load time history.

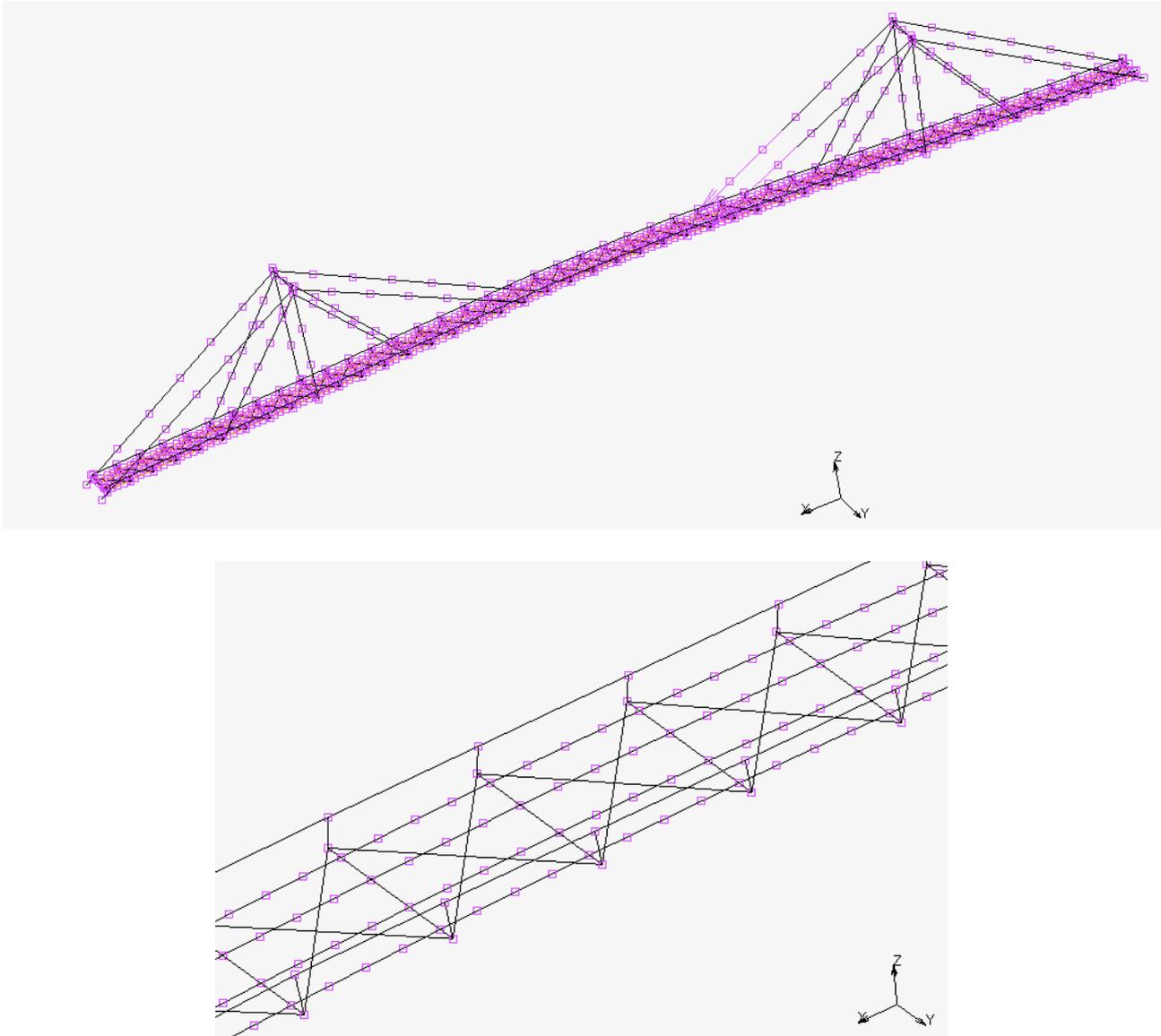
### 3 THE FE NUMERICAL MODEL

The footbridge of Figure 1b) has been the object of a refined discretization within the software [9]. A special feature of this software is the ability to treat cables as 3D beam elements (with very low bending and shear stiffness) in large deformation. In particular, a sufficient number of nodes along each cable was provided to match the cable frequencies as caught by an accurate testing campaign [13] of the whole structural system.

The zoom on the central deck, as at the bottom of Figure 3, illustrates the deck features: 2 lateral timber beams, linked by equi-spaced transversal U-shape beams in steel (with their diagonal

braces in the horizontal plane). These steel beams support 4 equi-spaced longitudinal timber beams whose nodes are interested by the load time histories induced by the person walking from one end of the footbridge to the other.

The adopted FE model is given in Figure 3, while transient dynamic analyses were carried out under the loading time histories simulated, as reported in the previous section, for a group of 6 persons walking as a sequence of three couples.



*Figure 3 – Finite element model of the footbridge case study. It is 100m long and consists of 3 spans, the central one being 66 m long. The detail on the bottom explains the beams assemblage.*

The 4 long cables show a diameter of 44 mm, while the short ones have a diameter of 32 m. The calibration on the experimental results led the authors to a tension in the internal long cables of 103 kN.

In view of a monitoring of the structural systems from accelerometers on the deck, reference [13] introduced the following reasoning. The acceleration (say its vertical component) recorded in middle section of the deck cannot be regarded as stationary due to the advancing of the HIL. It should be therefore studied at least by introducing suitable time windows [11]. Moreover, the central part of the signal (starting when the group enters the bridge and ending at its full leaving) corresponds to the situation of monitoring exactly under the HIL. In other words, in this time

window, large peaks prevail masking all the other modes of the deck. To avoid this situation, one focus on the first part of the record (data collected at the middle span and pedestrians just entering the footbridge). For a 100 s crossing, one just select the first 20 s to compute the associated periodogram. Then, it is shown in [13] that decreases of the tension in a couple of internal long cable is easily detected by comparing the periodograms in the two situations, as shown in Figure 4.

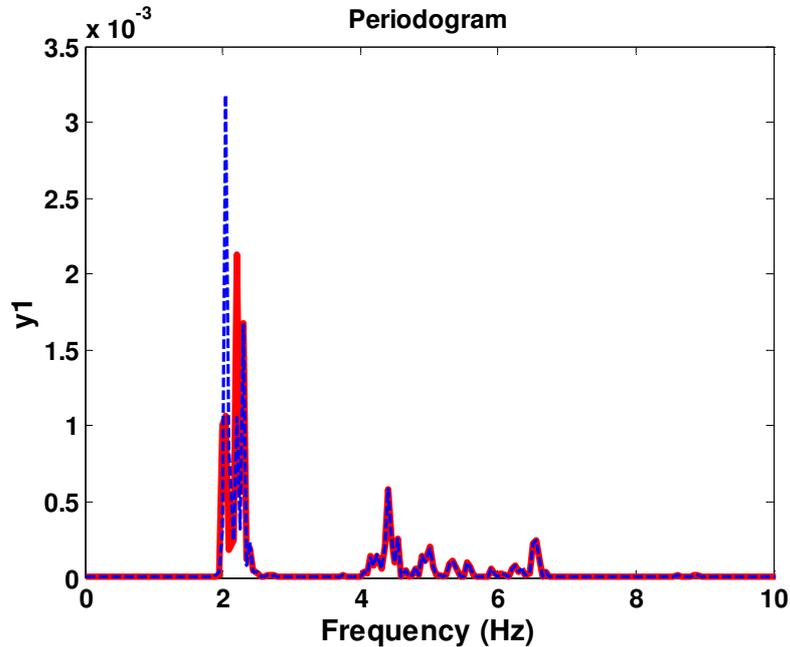


Figure 4 – Comparison of the periodogram associated with the middle span vertical acceleration record in the original (dashed line) and damaged (solid line) conditions.

#### 4 A CONTROL ATTEMPT

For a system of the type investigated in this paper, a real time control arrangement [14] would result too expensive. Moreover, the isolation features of the site would not allow one to rely on the availability of the installed devices, mainly due to the frequently recorded vandalism acts.

This is why one is supposed to plan the countermeasure to a detected decrease of tension in a cable as a sort of periodical management. In this specific case, one could act by giving an elongation to one or more of the external long cables which still preserve the anchorage used to provide them the design initial tension. Figure 5 shows the tension time history for the situation named “damaged” in Figure 4 and the improvement achieved, in term of cable tension, after a horizontal extra-elongation of 1 cm.

#### 5 CONCLUSION

This contribution investigates the feasibility of a dynamic study of a footbridge at the design stage. Being the crossing by a crowd quite unlikely for this specific case study, mainly due to its peculiar location, the action induced by a limited number of persons must be introduced as HIL in view of estimating the footbridge vibrating response.

The structural system is studied by its finite element idealization, while the human induced load is simulated as the realization of a suitable stochastic random field.

The monitoring issue is mainly addressed to the tension in the significant cables. It is approached by the classical migration of the spectral peak on subsets of the acceleration measures collected at the deck middle section.

An attempt of controlling (resetting) the system by acting on the external long cable is eventually discussed.

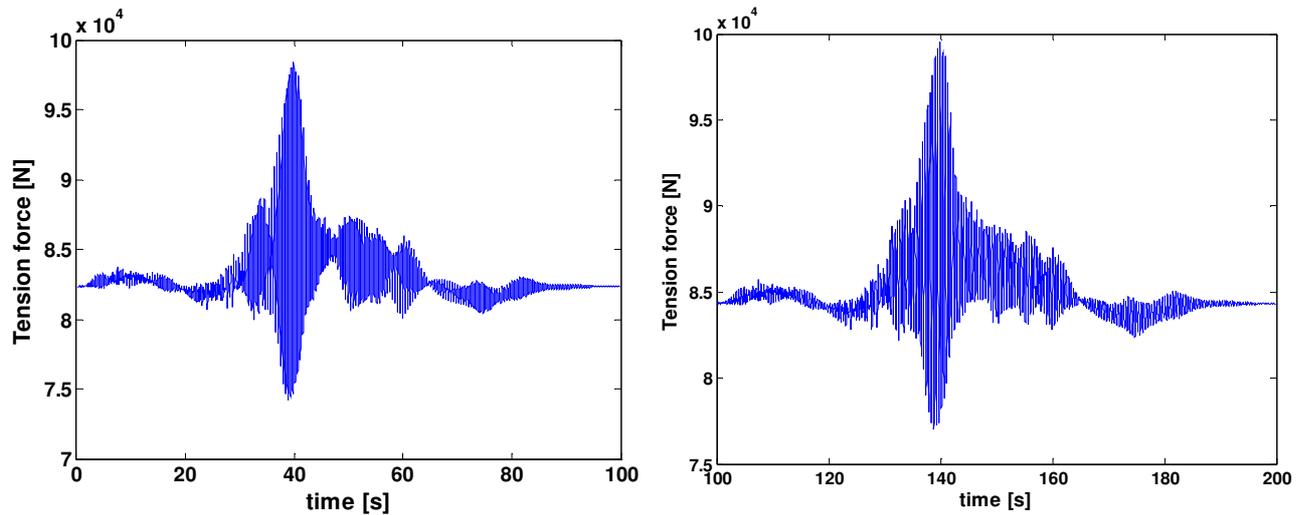


Figure 5 – Time history of the tension in one of the weak internal cable (right side) and tension in the same cable after the extra-elongation countermeasure (left side).

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