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MODELLING THE HUMAN INDUCED VIBRATIONS IN A CABLE-STAYED PEDESTRIAN TIMBER BRIDGE

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ABSTRACT

In this paper the data acquired on a pedestrian timber bridge under different "moving" loads configurations are reported and analysed by applying a time-frequency decomposition technique. This approach allows the authors to better identify the dynamic behavior of the bridge under the above loads. A first in situ experimental campaign was carried out on November 7, 2013, with the aim of recording the accelerations induced by people walking and running along the bridge (the so called human induced vibration – HIV). For this purpose, the footbridge was equipped by accelerometers. The pedestrian bridge under investigation is located not far from the town of Belluno, Italy, and connects the two sides of the outlet channel of the "Santa Croce" Lake. To better fit the structure to the surrounding naturalistic area, eco-friendly construction materials with low environmental impact were adopted during the design stage. In particular glued laminated timber (GLT) and steel elements are used, limiting the use of reinforced concrete only for the foundation system.

KEYWORDS: *human induced vibration, in situ testing, timber footbridge, time-frequencies analysis.*

INTRODUCTION

In recent years the use of timber as construction material has become quite common in all Europe, in particular for the design of pedestrian bridges, but not only. This is in general a preferred choice in all those applications where the structure has to fit well in the surrounding landscape. Thanks to the development of new construction materials, as for example the glued laminated timber (GLT), nowadays the designers are able to conceive footbridges with span longer than 100 m using timber elements [1]. As in the considered case study, the realization of large span footbridges usually requires the adoption of a hybrid solution coupling timber with steel. This coupling, together with the slenderness of the structural skeleton of the footbridge, makes quite complicated foreseeing during the design phase the vibrations induced by people crossing (walking and/or running) the bridge ([2] and [3]). It is well known that these problems are typically not dangerous in terms of structural/resistant safety, but are related to the comfort of the pedestrians. They are well documented in literature, and different procedures are proposed for the vibrations mitigation ([4]-[6], among the others), but an unified solution for "pedestrian-crowd loads" is not coded yet. A numerical procedure based on experimental tests was developed by the authors. The reader is referred to [7] and [8].

In this paper, the measured structural response of an existing GLT cable-stayed pedestrian bridge is reported, analysed and discussed. The authors are cooperating with the bridge designer and with the timber element producer to test different timber footbridges in order to better understand the dynamic behaviour of this type of structures, and develop a numerical model able to simulate the interaction among the structure and the human induced loads in a realistic manner.

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1 THE CASE STUDY: "TESA" FOOTBRIDGE

The footbridge studied in this paper is located in Farra d'Alpago, an Alpine village close to the town of Belluno (Figure 1-a).

a)  b) 

Figure 1 : Footbridge under study. a) location (red line indicates the bridge); b) lateral view

The bridge, built in 2005, connects the two sides of the outlet channel of the "Santa Croce" Lake. To better harmonize the structure with the surrounding naturalistic area, only eco-friendly materials (i.e. wood and steel) were adopted during the design stage, limiting the use of reinforced concrete to the foundations only. Particular care was paid to the protection of the wood specimens; in particular *ad hoc* protective treatments against the attack of environmental agents (i.e. rain, snow, fungus, molds, and so forth) were used. As one can see from Figure 1-b, the static scheme of the bridge is the classic cable-stayed solution. In total, sixteen steel cables are adopted; in particular, eight "internal-secondary" cables of diameter 32 mm, and other eight "external-main" cables of diameter 44 mm. From a geometric point of view, the span length is about 110 m subdivided into three segments (each of them made of curved GLT-BS14 and GLT-BS16 beams – as indicated in the DIN1052 code) of length 22.5m, 65m (in the middle) and 22.5 m, respectively; while the free crossing width of the deck is about 3.2 m. The two antennas are 16m high. The deck shows a classical "U-shape" cross section (Figure 2-a). It is realized by linking two main curved GLT beams with transversal U-shape steel tubular elements of high strength S355J0 (according to UNI EN10025 code). These elements are connected by steel braces of circular cross-section that provide the lateral stiffness. Each arcuate GLT beam are also posed over neoprene support on both ends (Figure 2-b). The structural scheme is completed mounting, on the "U-shape" elements, four longitudinal GLT rectangular beams (cross section 10x16.3 cm), used to carry the walking deck made of larch planking (thickness 4 cm).

a)  b) 

Figure 2: Structural scheme of the deck. a) view from the bottom ; b) detail of the *neoprene* support

1.1 First experimental campaign

On November 7, 2013 the first experimental campaign was performed. The aim of this first set of measurements was the acquisition of the dynamic response (in detail, the acceleration components of relevant points along the footbridge deck were measured) under different loading conditions.

The data acquisition is tailored to standard tri- and uni-axial Kinematics accelerometer, while the data transmission is obtained by wireless transceivers developed by the authors [7]. These devices are able to cover the entire span length of the bridge [10]-[11], without the need for the

intermediate storage stations. During the in situ tests, a total of six accelerometers is deployed; namely, two uni-axial accelerometers are anchored to the "internal-main" cables and labelled as WSa5_ch1 and WSa5_ch2, and other four tri-axial devices, with the *i*-th accelerometers denoted as WSa*i*, *i*=1,..,4, , are located in *ad hoc* positions along the deck. Further details about the sensor configuration are provided in Figure 3.

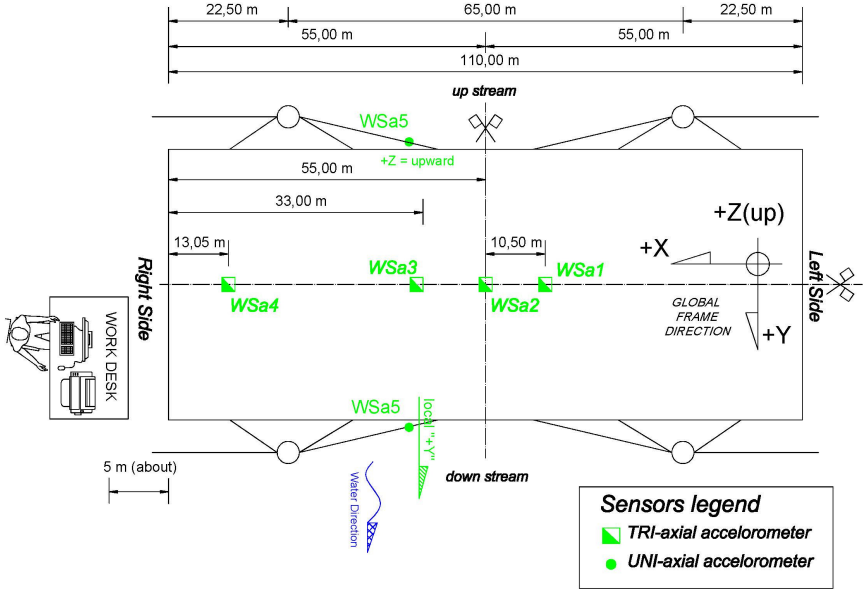


Figure 3. Sensors equipment configuration employed during the first tests in situ

Different types of loads are considered during the experimental campaign. A first set of acquisitions is focused on the records of the acceleration due to wind loads (environmental loads). These acquisitions are used for the calibration and verification of the data acquisition-transmission system. The following tests are focused on the records of the dynamic response of the footbridge under the so called "human induced loads" (HIL), such as running and walking. Different configurations are considered and are described in the following.

2 DATA ACQUISITION AND DATA ANALYSIS

2.1 Time-Frequency analysis of the signals

The classical approach to the data analysis is based on the use of the "standard" Fast Fourier Transform (FFT), that allows one to decompose the original signal into a series of trigonometric functions. This approach limits the possibility to capture the time-varying behaviour, or in other words as the frequencies evolve over the time. Thus, the classic approach is not enough sophisticated to characterize the signal recorded on field, especially if the dependence over the time is crucial, as in the case of HIL, where the movement of the pedestrians over the deck, and so the corresponding dynamic response of the footbridge, are sensitive to the time variation [12]. Thus, in order to highlight the interaction between the pedestrians and the structure and to identify when a particular "dynamic mode" is activated by the humans, a time-frequency analysis of the records on field is developed.

Following the time-frequency procedure proposed by Choi-Williams (CW) [13] and Cohen [13] , let *t* denote the time and ω the pulsation; by introducing the Fourier Transform *W(t-u)* for the kernel function $\Phi(\theta,\tau)$ of CW, which is given by

$$\Phi(\theta,\tau) = e^{\frac{-\theta^2\tau^2}{s}}, \; s \in \Re, \tag{1}$$

the time-frequency distribution $P(t,\omega)$ can be written as:

$$P(t,\omega)=\frac{1}{4\pi^2}\int\int_{-\infty}^{+\infty}W\left(t-u\right)e^{-i\tau\varpi}R_{t,1}\left(t,\tau\right)dud\tau, \quad (2)$$

where $R_{t,1}$ is the autocorrelation function, u and τ replace t and θ replace ω when integrating $R_{t,1}$.

2.2 HIL tests carried out and data result

The tests carried out on field during the experimental campaign can be summarized in two groups :

- *test I - walking loads*: in this configuration different cases, regarding a round trip along the bridge, are considered. In particular in this paper the following tests are analysed: a person (*test Ia*) and six persons (*test Ib*);
- *test II- running loads*: this configuration consists of a round trip along the bridge of a running person.

In order to give a better interpretation of the data, each record is classified into two different sets: crossing from the right to the left side of the footbridge (labelled as *RtoL*), and from the left to the ride side (labelled as *RtoL*). All the accelerations are acquired with a sampling frequency of 100 Hz.

- test Ia

As defined above this test consists of collecting records of the accelerations of the footbridge due to a round trip along the deck. The mass of the person is 85 Kg. Further details about this test are summarized in Table 1.

Table 1: Walking (round trip) of one person.

Type	ID
Day/Time	November 7,2013 / 2.48 pm
Test type	walking (round trip)
Air temperature	15°C
Pedestrian(s) num.	1 person
Total Pedestrian(s) mass	85 Kg
Total time duration	≈2:30 min
RtoL time duration	≈1:15 min
LtoR time duration	≈1:15 min
Average velocity of the pedestrian(s)	1.45 m/s

Following the procedure proposed in the previous paragraph the time-frequency analysis is performed for the data acquired by WSa2. Along Y axis three main frequencies (average values) appear: 1.35 Hz: constant over the time; 5.00 Hz: it activates only during the time period from 30 to 70 sec for the *RtoL*, and from 80 to 120 sec for the *LtoR*. This means that this particular frequency is detected when the pedestrian is located about 15-20 m before the position of the sensor WSa2; 5.80 Hz: it activates only during the time period from 10 to 32 sec for the *RtoL*. Several vertical lines (mostly located between 35 and 60 sec), that represent the shifts in terms of frequencies, appear during the *RtoL* crossing, while they disappear during the *LtoR* crossing. These shifts can be related to noise into the signal due to the overlapping of the waves associated to the movement of the pedestrian from the sides towards the mid-span. Along Z axis two main frequencies (average values) appear: 2.00 Hz: it activates during the time periods from 35 to 70 sec for the *RtoL*, and from 105 to 150 sec for the *LtoR*. This means that this particular frequency is detected while the pedestrian is located about 10 m before the position the sensor WSa2 and about 40 m after it; 6.00 Hz: it activates only during the time period from 30 to 70 sec for the *RtoL*. Once again, this means that this particular frequency is detected while the pedestrian is located about 10 m before the position the sensor WSa2, and about 40 m after it. During the *LtoR* crossing, this frequency almost disappear. One can observe that, also for the results along the Z axis, the time-frequency plot for the *LtoR* crossing is more “clear/clean” with respect to the *RtoL* crossing. Moreover, the time-frequency

plots along the Z axis show, in general, a clear trend compared with the ones along the transversal Y axis.

- ***test Ib***

In this test, the records of a round trip along the deck of six persons is considered. The average mass is 80 Kg. The pedestrians proceed in pairs by keeping a distance of 1 m between each other in the longitudinal direction of the footbridge, and a distance of about 0.5-0.7 from the closest lateral edge of the footbridge. Further details about this test are summarized in Table 2.

Table 2 : Walking (round trip) of six persons.

Type	ID
Day/Time	November 7,2013 / 3.00 pm
Test type	walking (round trip)
Air temperature	15°C
Pedestrian(s) num.	6 persons
Total Pedestrian(s) mass	480 Kg
Total time duration	≈2:42 min
RtoL time duration	≈1:21 min
LtoR time duration	≈1:21 min
Average velocity of the pedestrian(s)	1.35 m/s

As an example in Figure 4, the time-frequency plots from the data acquired by sensor WSa2 along the transversal Y axis and gravity Z axis are reported. During this test, along Y axis, only one frequency clearly appears at 1.35 Hz, and it is constant over the entire duration of the data acquisition. Another frequency appears at 5.00 Hz in the time period between 50 and 70 sec for the *RtoL* crossing, and in the time period from 100 to 160 sec for the *LtoR* crossing. Once again, the *LtoR* plot shows many vertical lines; in particular, one can observe that in the time period between 125 and 140 sec, there is a consistent frequency shift, due to the overlapping of the waves associated to the movement of the pedestrians from the sides toward the mid-span. Instead along the vertical (gravity) Z axis only one frequency clearly appears at 2.00 Hz, and it is activated in the time period between 50 and 80 sec for the *RtoL* crossing, and between 100 and 160 sec for the *LtoR* crossing. Moreover one more frequency of 6.00 Hz seems to be "slightly" activated between 50 and 70 sec for the *RtoL* crossing, and between 130 and 150 sec for the *LtoR* crossing.

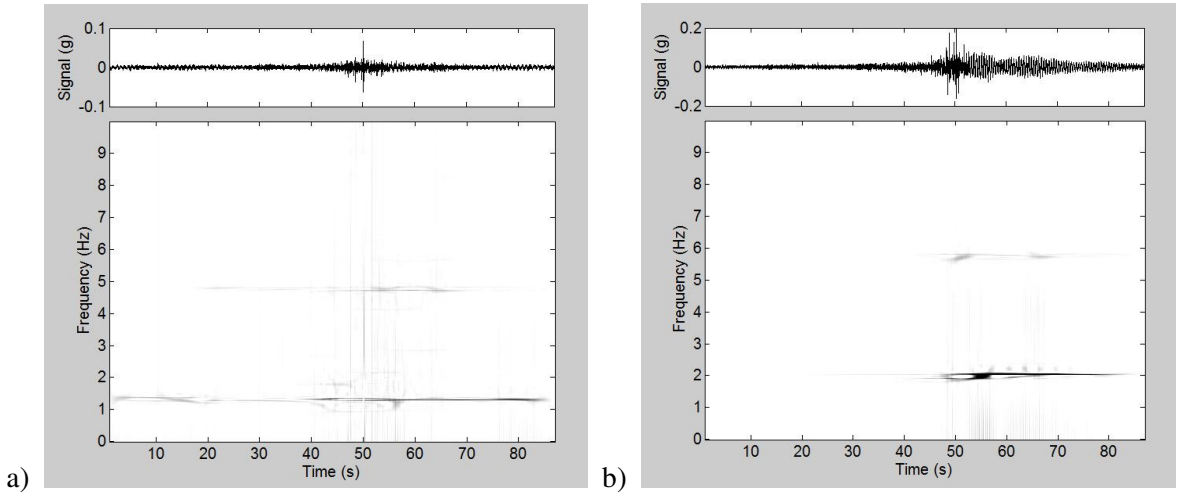


Figure 4. Time-frequency plots from the data recorded by sensor WSa2 during *test Ib*. a) *RtoL* data along Y transversal axis; b) *RtoL* data along Z gravity axis

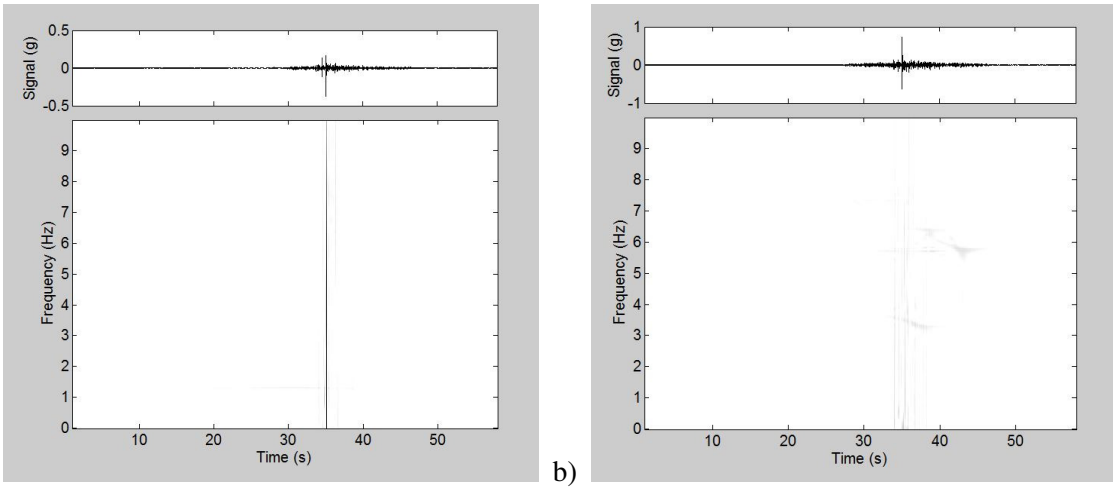
- ***test II***

During this test, the footbridge response under a running person along the deck (round trip) is recorded. The average mass is 85 Kg. Further details about this test are summarized in Table 3.

Table 3 : Running (round trip) of one person.

Type	ID
Day/Time	November 7,2013 / 3.15 pm
Test type	running (round trip)
Air temperature	15°C
Pedestrian(s) num.	1 person
Total Pedestrian(s) mass	85 Kg
Total time duration	≈0:46 min
RtoL time duration	≈0:23 min
LtoR time duration	≈0:23 min
Average velocity of the pedestrian(s)	4.78 m/s

In Figure 5, as an example, the time-frequency plots from the data acquired by sensor WSa2 along the transversal Y axis and gravity Z axis are reported. In this test, only one frequency clearly appears, along Y axis, at 1.35 Hz during the *LtoR* crossing. During the *RtoL* crossing, only one vertical line appears at about 35 sec, and it can be associated to one "jump" of the pedestrian in the proximity of sensor WSa2. Moreover, one can observe that during the *LtoR* crossing some frequency shifts appear between around 70 and 85 sec. Once again, these shifts are associated to the overlapping of the waves associated with the motion of the pedestrian. Also along the Z axis only one frequency clearly appears at 2.00 Hz during the *LtoR* crossing. During the *RtoL* crossing a frequency shift appears at about 35 sec, and can be associated to one "jump" of the pedestrian in the proximity of sensor WSa2, as observed also for the previous plot along the Y axis.



a) b)

Figure 5. Time-frequency plots from the data recorded by sensor WSa2 during *test II*. a) *RtoL* data along Y transversal axis; b) *RtoL* data along Z gravity axis

3 NUMERICAL MODEL OF PEDESTRIAN(S) LOAD(S)

A numerical model of the pedestrian(s) load(s) is developed and implemented within a finite element model of the footbridge built within MARC Mentat2010 environment [16]. Given the distribution of the nodes of the mesh and the configuration of the pedestrian(s) , the force-time trend can be easily defined following simple kinematics considerations. In particular, in this paper the numerical implementation of the previously described *test Ib* is considered as an example. The following hypotheses are introduced when developing this model:

- Each person is considered as a point load on the node of the mesh. The mass is assumed to be 80 Kg/person (that is 785 N/person). The transversal (along Y axis) component of the load is assumed to be 10% of the component along the gravity (Z) axis;
- The distance between each pair of the mesh nodes is assumed to be 62.5 cm, which is comparable with a human average footstep during a "normal" walk;
- "Mass" and "load" are moving along the deck as described by assigning the above defined force-time trend to each node of the mesh;
- The velocity of the pedestrian crossing the footbridge is held constant along the simulation of a *uniform linear motion*, and is assumed, for the example herein reported, to be 1.35 m/s;
- The spatial configuration of the pedestrians is assumed the same along the simulation. In other words, the distance between two consecutive pedestrian in both the longitudinal and transversal directions of the deck is fixed. This implies that, during the walk, each following pedestrian takes the place of his/her predecessor.

Further details of the pedestrians loads model are summarized in Figure 6-a. Once the model has been implemented in the finite elements software, a dynamic transient analysis is performed. The above described time-frequency analysis approach is applied to the acceleration time histories obtained from the numerical simulation. In Figure 6-b, the results for the node of the mesh corresponding to the location of sensor WSa2 are reported.

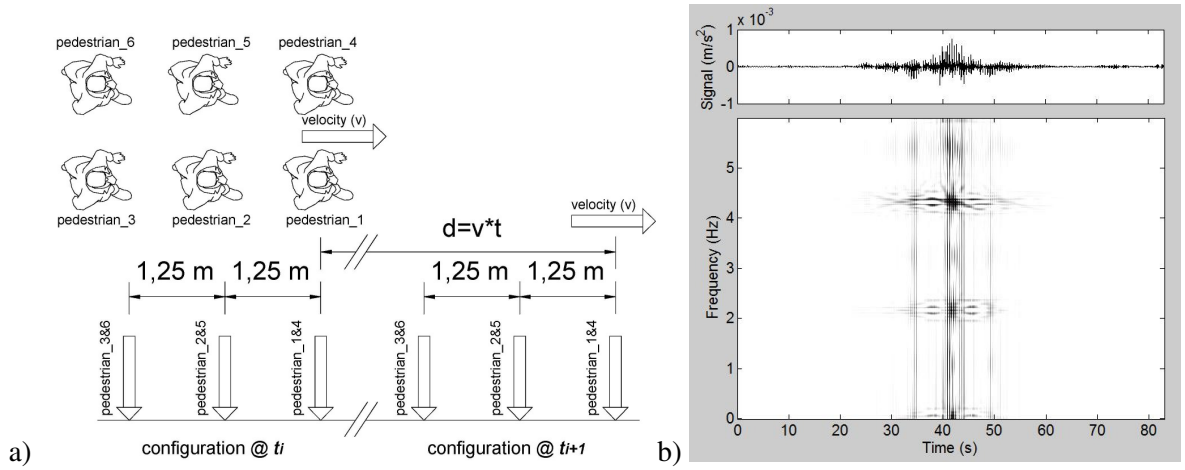


Figure 6. Pedestrians model implemented for *test Ib*. a) Scheme of the loads induced by pedestrians; b) Time-frequency plots of the acceleration response simulated at node ID647 (WSa2) for the *RtoL* crossing along Z gravity axis

As one can see from the above plots, the results achieved by the proposed model fit well the on field measurements (the reader is referred to Figure 4-b for a comparison). Some discrepancies can be related basically to two aspects: first, the average value of the velocity is assumed constant for the proposed model and could be not exactly the same as during the test on field (in other words, during the test probably the pedestrian walked with a *non*-uniform linear motion); second, the assumption of an equal distribution of the mass/load among the persons could be too restrictive.

CONCLUSIONS

In this paper the dynamic response data under HIL were carried out on field during experimental tests. The results are analysed and compared in order to identify the behaviour of the structure. Numerical model of the pedestrian(s) load(s) is implemented. It is worth noting that this is a preliminary approach in order to introduce a numerical procedure that reproduces the pedestrian(s) load(s), and it represents a "deterministic" strategy to identify the HIL. A more sophisticate model (based on a stochastic simulations approach) is in process of elaboration and definition by the authors.

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