Analysis of a metallic pedestrian bridge under dynamic human loads in pre and post reinforcement phases

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***Abstract*—**The purpose of this work is to study the dynamic behavior of a pedestrian bridge in Alicante, Spain. It is a very slender footbridge with vertical and horizontal vibration problems during the passage of pedestrians. Accelerations have been recorded by accelerometers installed at various locations of the bridge. Two scenarios, in free vibration (after the passage of a certain number of pedestrians on the bridge) and forced vibration produced by a fixed number of pedestrians walking on the bridge at a certain speed and frequency. In each test, the effect on the comfort of the pedestrians, the natural frequencies of vibration, the mode shapes and damping factors have been estimated. It has been found that the acceleration levels are much higher than the allowable by the Spanish standards and this should be considered in the restoration of the footbridge.

***Keywords*—**Dynamic identification, pedestrian bridge, induced vibration test, resonance, damping, free-vibration test.

I. INTRODUCTION

NOWADAYS Nowadays in the field of structural engineering there is a high interest towards the realization of even lighter and slender structures. This trend, which is highly spread in the field of pedestrian bridges, gave the designers the awareness of the central role played by the study of the dynamic structural behavior among the usual design parameters [1]. The studies in this area were initially focused on the structural behavior in response to vertical accelerations, especially with reference to the phenomena of resonance due to the coincidence of the passage of pedestrians and the natural frequencies of the structure [2]. In this way particularly problematic frequency ranges have been identified, such as, for example, 1.6-2.4 Hz for walking pedestrians or 2.0-3.5 Hz for running pedestrians [3]. Then, different behaviors of pedestrians have been mathematically modeled, considering them either individually or as a stream of people [4] [5] [6]. At the same time, research has been oriented to the study of problems of lateral vibrations generated by pedestrians [7], especially in structures with low lateral stiffness [8].

On the other hand, as high levels of excitation can be achieved with a small number of people [9], for the safety and comfort of the users throughout the life of the structure [10], it is strictly necessary to determine in a rigorous way the mass, stiffness and damping - all factors directly related to the mechanical characteristics of the materials and the design solutions selected - in order to avoid a high response of the structure to an excitation.

Studies aimed at identifying the mechanical and dynamical characteristics could also utilize Operational Modal Analysis methods [11][12][13][14]. An updated numerical model of the structure can be utilized to verify the correctness of the design solution to be implemented to improve the behavior of the structure[15].

With respect to the footbridge under study, for example, the dynamic tests showed that the reduced mass and the conditions of the route, with the presence of a cantilever beam, can generate a high response.

Among the various possible mitigation strategies an important role is played by vibration control by means of energy dissipators [16], hysteretic dampers [17][18], viscous damping systems [19], or tuned mass systems [20] and [21], rather than by changing the mass or stiffness utilizing new materials or restoring the structure.

The present paper analyzes the dynamic behavior of the steel footbridge of Postiguet Beach (Figs. 1-2) with the aim to mechanical characterize the structure in the pre- [22] and post-restoring state phases.

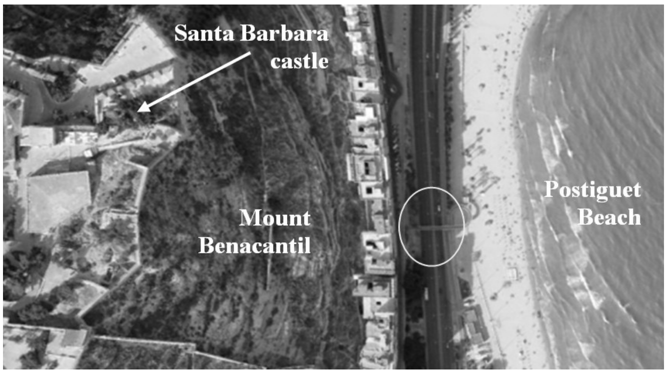

Fig. 1 Pedestrian bridge. Postiguet beach, Alicante, Spain.

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Fig. 2 Pedestrian bridge. Postiguet beach, Alicante, Spain.

For existing bridges, the seismic assessment after a retrofitting is a very important topic [23].

The restoring process aims to improve the aesthetics of the bridge, which, just a few years after its construction (1993), showed widespread phenomena of degradation (corrosion-Fig. 3) due to a constant exposure to the marine environment. Hence a protection system has been designed made of composite materials with glass fibers and resin.

For the dynamic identification of the footbridge and the quantitative assessment of the high acceleration values observed from a qualitative point of view at the passage of pedestrians on it in the pre-reinforcement phase, and in order to have experimental results comparable with the behavior of the structure once restored, a test program has been established to examine the behavior of the bridge in forced vibration under the excitation produced by the flow of a fixed group of pedestrians that runs along the footbridge at different speeds previously set, and in free vibration after the group of people has passed. In this way, in each test the effects on the comfort of the pedestrians were assessed [24], together with the natural frequencies of vibration, the mode shapes and the damping factors. A numerical analysis has been performed using SAP2000 software [25] to compare and adjust the model to the frequencies and mode shapes experimentally recorded. With this numerical model, the dynamic structure-pedestrians interactions were analyzed.

Fig. 3 Actual condition of the transversal section of the footbridge.

II. GEOMETRICAL DESCRIPTION OF THE FOOTBRIDGE

Postiguet footbridge was designed in 1993 [26]. It was part of a project on the "regeneration of Postiguet beach and promenade", in front of the rocky side of Mount Benacantil. It had a metal box section with two slabs at its ends for a total width of the platform equal to 2.20 m. The wings of the section have longitudinal and transversal steel stiffeners of class A42b (f_u=420 N/mm^2) (Fig. 4) with a thickness equal to 10 mm and 8 mm, respectively; 20 mm thickness plates have been also placed in the support area.

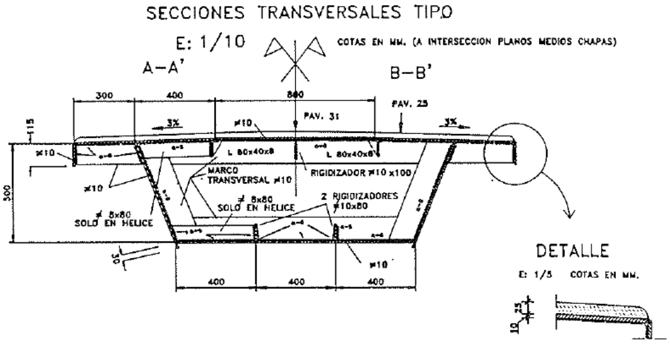

Fig. 4 Transversal box section [Original design in Spanish].

The structure is divided into 6 spans of 8.5 +24 +13 +19 +15 +12 m length (Fig. 5) and it is fixed at both ends, with the rotation around the vertical axis blocked. A static scheme of a continuous beam on supports has been assumed for the deck. The cross section of the walkway has a constant height of 0.5 m, thus resulting in a significant slenderness (height/span ratio) of the structure (equal to 1/48).

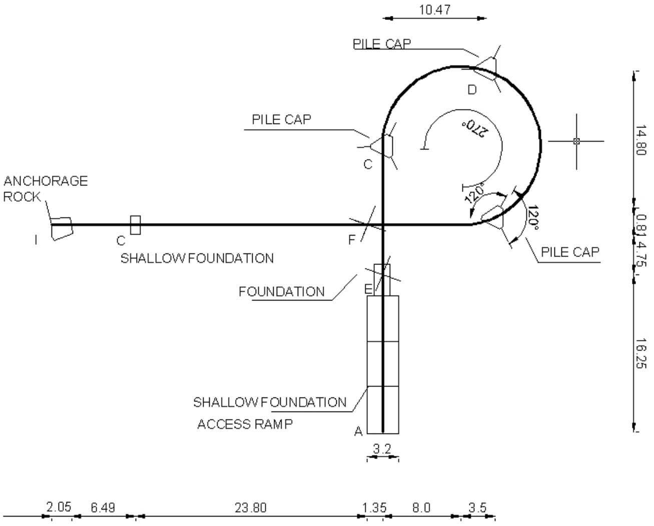

Fig. 5 Foundation.

The shape of the route consists of two straight perpendicular lines, connected by a 270 degrees helix, with a smooth and continuous variation of the slope. The straight sections and the helixes were connected by mean of two parabolic sections with a uniform slope of 5.45%. Finally, the ramp next to the beach shows a maximum 10% slope.

The intermediate supports are five simple supports, aligned to the deck, with a metallic circular hollow section of A52 steel (f_u=520 N/mm^2), connected to the beam through supports in confined neoprene. The foundation of the deck closest to Mount Benacantil (see Fig. 1) has a fixed joint made with 8 ϕ32 DYWIDAG 85/105 steel bars with a length of 12.5 m. Similarly, on the side next to the beach, at the first support, the fixed joint is obtained with GEWI ϕ32 AEH500N steel bars (Fig. 4) (f_u=500 N/mm^2).

The other supports have isolated foundations (plinths) on three oblique micropiles each, with a 1H/3V slope, distributed to 120º in plan and stuck in the sand up to the rock, except for the foundation closer to the side of Mount Benacantil, which has a shallow foundation in direct contact with the rock

III. Experimental Evaluation Of The Dynamic Behavior

In order to identify the dynamic behavior of the footbridge, tests have been carried out to determine the natural frequencies of vibration, the damping factors for the main vibration modes, and the horizontal and vertical accelerations, with a total of 11 different measure points of the structure (Fig. 6a, b), obtaining values much higher than those recommended by the Spanish code. In this way, the dynamic properties have been determined.

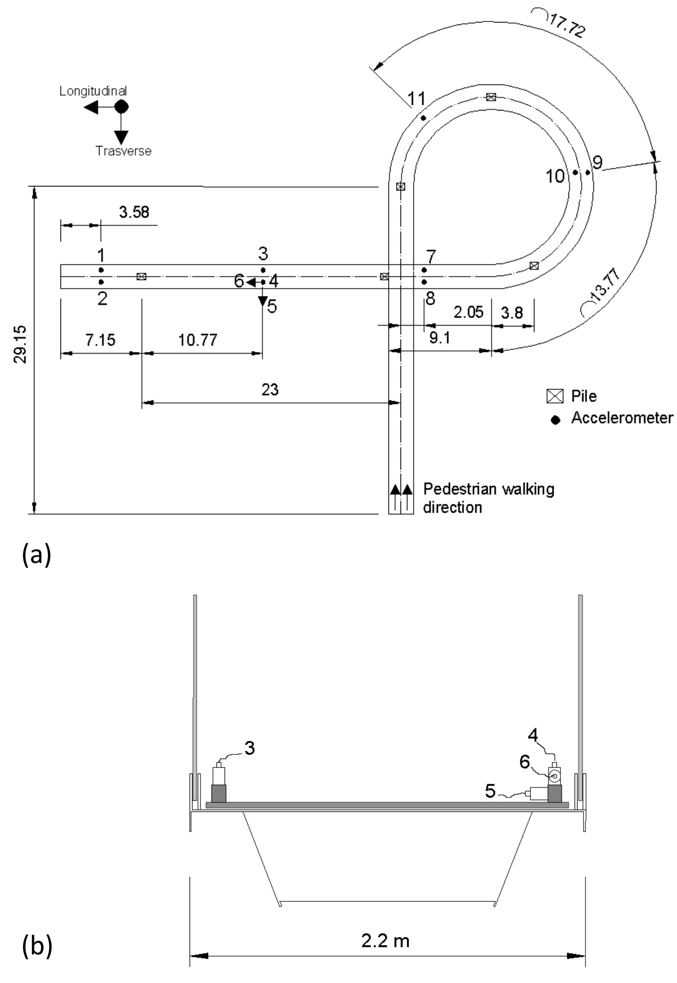

Fig. 6 Positioning of the accelerometers: (a) plan section, (b) transversal section of the footbridge.

A. Identification of the natural frequencies

To determine the natural vibration frequencies of the structure, free vibrations of the walkway have been recorded in November 2010. The footbridge was closed to the traffic and the tests were carried out during night time, thus limiting a possible existing traffic below the bridge during the tests and to avoid unexpected excitations that could change the dynamic response of the structure. Eleven seismic accelerometers have been utilized for the test (Table I). In the table “V”, “T” and “L” indicate the direction of acquisition of each accelerometer, that is, respectively, vertical, transversal, longitudinal to the footbridge deck. PBC Piezotronics Model 393A03 (Table II) have been utilized. They have been installed on the footbridge as shown in Fig. 5. For the test PCB signal conditioners and data acquisition equipment Kyowa Model PCD-320 were also used.

Table I. Direction of the accelerations recorded at different acquisition points.

1	2	3	4	5	6	7	8	9	10	11
V	V	V	V	T	L	V	V	V	V	V

Table II. Technical characteristics of the accelerometers.

Sensibility	Resolution in bandwidth	Measure range	Frequency range [Hz]
1000 mV/g (+-5%)	0.00001 g rms	± 5 g pk	0.5-2000

In total 11 points (1-11) have been analyzed, with a 30 minutes recording time, only excited by ambient vibrations. Thus the natural frequencies of vibration of the first eight modes in the range 0-11 Hz have been obtained (Table III), together with the characteristics of the vibration modes.

Table III. Technical characteristics of the accelerometers.

Mode	Recorded frequency (Hz)	Mode shape
1	1.18	Longitudinal
2	1.77	Longitudinal
3	2.89	Transversal
4	3.64	Vertical
5	4.2	Vertical
6	4.64	Vertical
7	7.69	Vertical
8	10.94	Vertical

Analyzing these results, the presence of various modes of vibration in the frequency range typically excited by the passage of pedestrians can be identified, both in the vertical (Fig. 7a), and in the horizontal (Fig. 7b) components, i.e. vertical frequency values in the range [1.6 - 2.4 Hz] correspond to the dynamic effects due to excitation of pedestrians walking or running slightly on the deck, as well as vertical frequencies in the range [3.5 - 4.5 Hz] correspond to the effect of the second harmonic generated by the excitation due to the passage of pedestrians.

On the other hand, modes of vibration associated to the horizontal excitation ([0.8 to 1.2 Hz] and [2.6 to 3.4 Hz]), easily excitable by pedestrians, were also identified. The structure can therefore show vibration problems due to too close frequencies of pedestrians and structure, as demonstrated in the latter phases of the test.

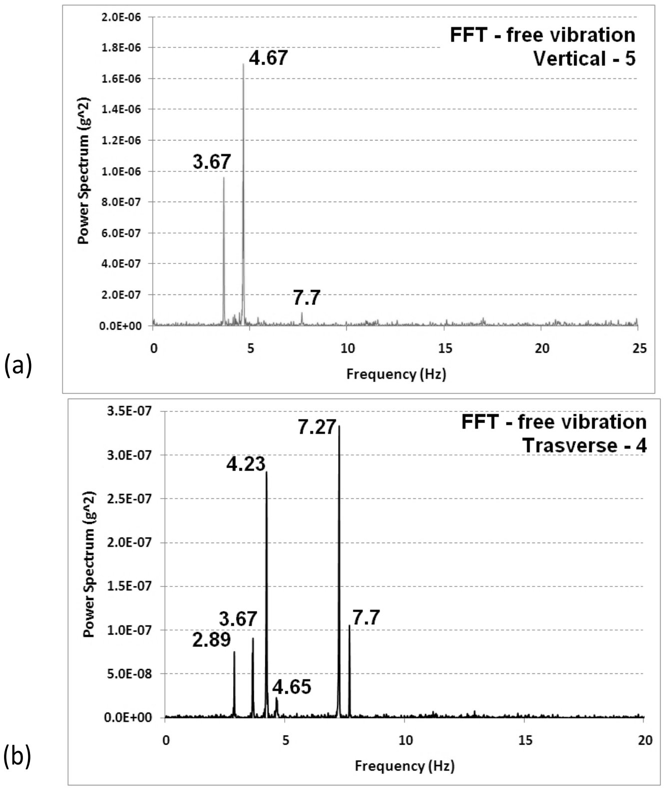

Fig. 7 Natural frequencies from the FFT analysis in free vibration. a) Accel. n° 5. b) Accel. n° 4.

B. Identification of the natural frequencies

In order to assess the levels of vibration within the structure different scenarios have been considered based upon the results obtained from ambient vibration tests, and avoiding the presence of vibrations very close to those easily excitable by pedestrians, thus creating a complete record of accelerations in the eleven points along the structure.

With this aim, two scenarios have been defined. The first corresponds to the transit of a group of nine persons arranged in 3rows, with a total weight of 6.18 kN, moving along the whole structure at different speeds (90 steps/min, 135 steps/min and 198 steps/min [3],[7]) (Fig. 8). The induced accelerations were recorded in points 1-8, at a sampling frequency of 200 Hz. The second scenario was to evaluate the effect of the cantilever balcony beam in the curve area of the walkway, under the influence of a person jumping in a central position of the cross section at a frequency of 135 steps/min. The values of acceleration were recorded. For a proper synchronization of the pedestrians walk, a metronome was used, and set at each frequency selected to excite the footbridge.

Fig. 8 Test on the footbridge. Disposition of the pedestrian stream.

Table IV summarizes, for each case, the values of the maximum accelerations recorded in sections 4, 5, 6 and 9, associated with the vertical, lateral and horizontal centerline displacement of the straight spans, as well as the vertical displacement of the curved part of the footbridge.

Table IV. Maximum recorded accelerations [g]

Frequency (steps/min)	nº pedestrians	Accelerometer			
		4	5	6	9
90	9	0.079	0.011	0.013	-
135	9	0.215	0.065	0.067	-
198	9	0.144	0.054	0.051	
135	1	-	-	-	0.48

Table V. Records of maximum accelerations. Estimation of the vibration perception of the risk [14]

Accelerometer	Maximum value (g)	Maximum admissible value (g)	Risk
3	0.36	0.125	Very disturbing
4	0.215	0.125	Very disturbing
5	0.065	0.075	Disturbing
6	0.067	0.075	Very annoying
7	0.199	0.125	Very annoying
8	0.231	0.125	Very annoying
9	0.482	0.125	Very annoying
10	0.455	0.125	Very annoying
11	0.52	0.125	Very annoying

Table VI. Limit values of acceleration suggested by the Ministry of Public Works and Transport

Risk rating	Limit accelerations
Imperceptible to easily perceptible	$a \leq 0.025$ g
Clearly perceptible to disturbing	$0.025g \leq a \leq 0.075g$
Disturbing to very disturbing	$0.075g \leq a \leq 0.125g$

In addition, Table V summarizes the maximum values of accelerations obtained from all the different load cases considered (n° pedestrians, cadence). These values are compared with those recommended by the Spanish Ministry of Public Works and Transport [14] (Table VI). It is possible to notice that the values of the accelerations recorded significantly exceed the recommended limits.

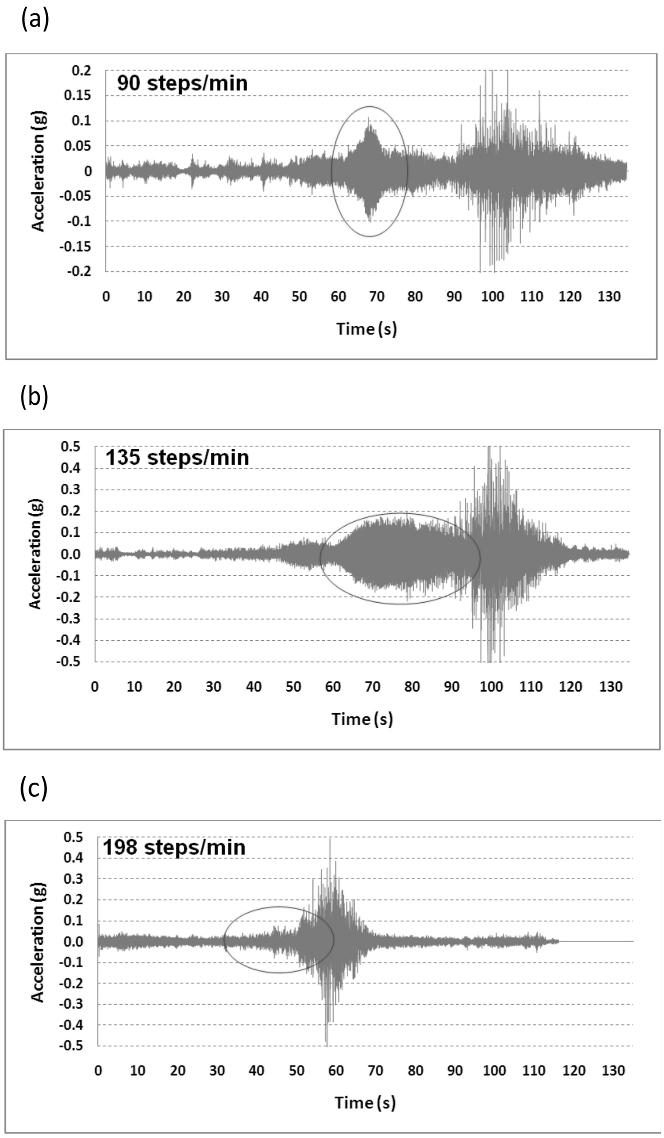

Fig. 9 Effect of the resonance at the pedestrian step in the central part. Accelerometer 3. a) 90 steps/min; b) 135 steps/min; c) 198 steps/min.

Finally, it was performed an analysis of the influence of the geometry on the dynamic behavior through the study of the vibrations induced by the passage of pedestrians on the footbridge, both in group and individually. For the cantilever balcony beam, it is noted that for both the excitation frequencies of 90 and 135 steps/min, an amplification of the vertical accelerations in position 3 was produced due to the effect of resonance, which shows the close values between the main frequencies of walking pedestrians and those of the structure (Fig. 9). It is worth noting that this phenomenon was imperceptible at higher frequencies, e.g. in the case of the excitation at 198 steps/min.

It can be concluded that the pedestrian bridge before restoration was very susceptible to the passage of pedestrians walking or running lightly, frequent situations during the life of the structure. On the other hand, in addition to the absence of the effect of resonance, it is also difficult to synchronize a group of people at high speeds, despite the use of the metronome, reason why the values recorded for 198 steps/min were low.

C. Evaluation of the damping factor

To obtain the damping factor associated to the main bending mode, free vibration tests after the excitation of a pulse load were performed. The pulse load consisted in a concentrated load applied at the points of the footbridge associated with the excited mode where the damping factor had to be determined. A load equal to 1.8 kN was applied in points 3 and 9 (Fig. 6).

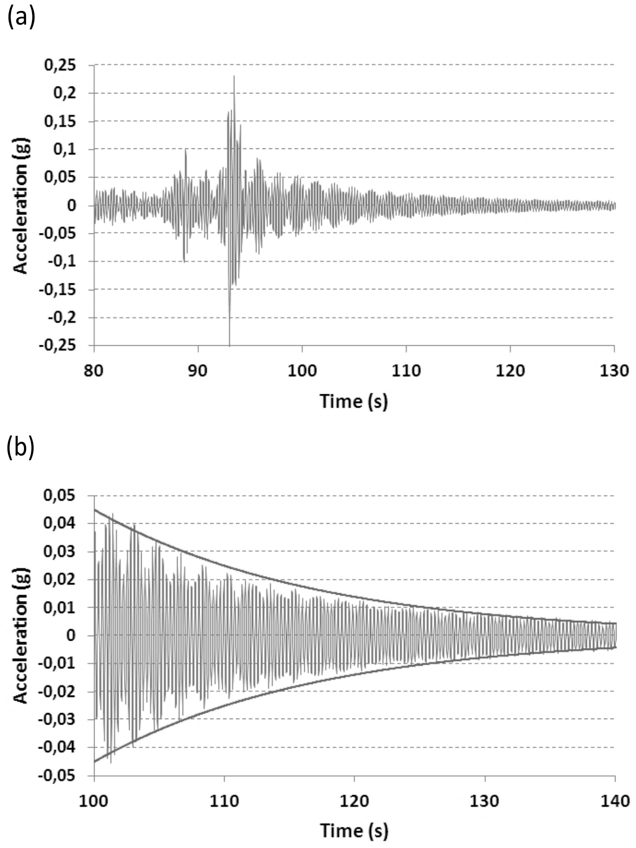

Fig. 10 (a) Time history response after an impact load on the deck. (b) Decay curve to evaluate the damping ratio.

Response of accelerometer number 4 was filtered between 3 and 4 Hz; the damping factor for the first two vertical vibration modes (3.64 Hz, 4.64 Hz) is then obtained by the technique of the logarithmic decrement from the damped curve after the excitation phase, obtaining a value equal to 2.03% (Fig.s 10a and 10b).

IV. NUMERICAL MODEL

The numerical model was developed to study and justify the experimental results obtained by considering its dynamic effects before the restoration.

The finite element model used to study the dynamic effects produced by pedestrians on the footbridge was modeled with SAP2000 software [15], discretizing the structure into a 3D model composed of shell elements for the deck and for the columns (Fig. 11).

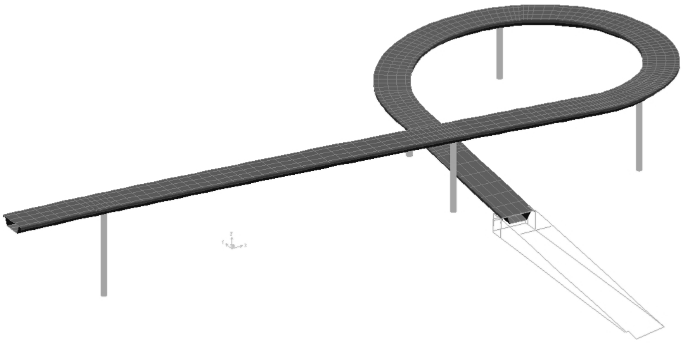

Fig. 11 Numerical model with SAP2000.

The definition of the geometrical model consists of 10838 nodes, 83 "Frame elements" and 10401 "Shell elements".

In this first approximation, with the aim of adapting the response of the model to the actual results, it was necessary to model the constraints of the columns with the ground with "spring elements" in the longitudinal, transversal and vertical directions to the walkway. Similarly, both ends (the mountain Benacantil side and the beach side of the footbridge) were considered simply supported.

All supports of the walkway on columns have been modeled with "frame elements" with a very low stiffness, in order to consider the existing elastomeric bearings.

Based on these requirements, the total weight of the deck and the sidewalk obtained from the numerical model was equal to 490 kN.

The overall results of the modal analysis, after an initial calibration of the model, are shown in Table VII. The values of the mode shapes experimentally observed, which corresponded to the modes with higher modal mass for each direction are also included. These experimental frequencies actually approximated the numerical values obtained with the finite element model as the ratios between both of them are lower than 1.13.

Table VII. Percentages of participating modal masses.

Numerical model					**Experimental**		
U_X %	U_Y %	U_Z %	Hz	mode classif.	Hz	Mode classif.	Numerical/ experimental ratio
69.5	14.3	0.0	2.01	longitudinal	1.77	longitudinal	1.13
11.0	21.7	1.3	2.81	transversal	2.84	transversal	0.99
6.6	3.0	2.6	4.00	longitudinal			
0.0	0.0	48.7	4.76	vertical	4.2	vertical	1.13
0.6	4.5	25.2	4.96	vertical	4.64	vertical	1.07
2.2	16.9	8.8	5.88	transversal			
1.1	5.8	0.7	7.24	transversal			
0.0	0.2	0.0	8.77	transversal			

Fig. 12 Mode 4 of vibration: 4.76 Hz.

The vertical natural frequencies obtained are close to those excited by the passage of pedestrians, not directly in its first harmonic, but in the second or third ones, especially with regard to mode 4 (Fig. 12), which is the first that has a vertical component and is very close to the frequencies excited by the passage of pedestrians, e.g. the passage of pedestrians at 135 steps/min presents its first three harmonics at frequencies 2.25 Hz, 4.5 Hz, 6.75 Hz. Bending vibration modes, in fact, have been calculated for 4.76 Hz in the numerical mode, and have been detected experimentally at 4.64 Hz. Actually both frequencies are rather close to the second harmonic induced by the walk of pedestrians at 135 steps/min.

A. Dynamic effects induced by pedestrians

To analyze the worst situation experimentally recorded a vertical load generated by the nine pedestrians who walk at speeds of 135 steps/min and 198 steps/min was simulated, resulting in a time-history for a variable load distributed over 4 nodes in the area in curve of the walkway for 10 s (Fig. 13). Following the recommendations of Bachmann [3], three

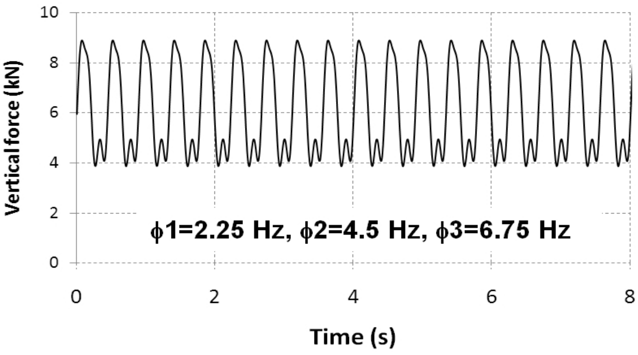

Fig. 13 Time history plot of the vertical force generated by pedestrians at 135 steps/min speed.

harmonics of the vertical component of the force generated by the passage of pedestrians have been examined.

With the aim to justify the dynamic interaction of pedestrians at 135 steps/min (harmonics 2.25 Hz, 4.5 Hz, 6.75 Hz) compared to the passage at 198 steps/min (harmonics 3.3 Hz, 6.6 Hz and 9.9 Hz), Figures 14a and 14b show the time-history of the maximum vertical accelerations recorded in the central part of the straight section of the walkway when the pedestrians pass in the curved area for 10 s. Even though the applied load is higher for the case of 198 steps/min (Fig. 14a), in these plots it can be noticed how the time-history in the middle of the central part shows much higher values for pedestrians at 135 steps/min. The accelerations recorded in this last case were almost twice as much. In the plots of Figure 13, from 10 seconds onwards, the time load introduced in the curved area is removed and the central part tends to fade.

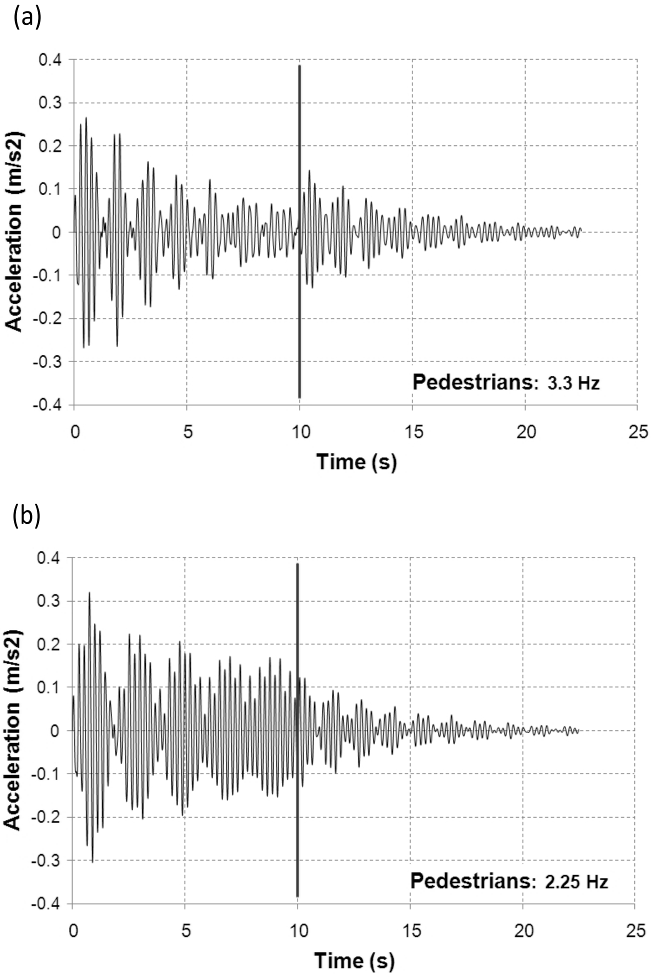

Fig. 14 Time-history of the vertical displacement in the central area of the straight section of the footbridge when pedestrians are in the curved area at a speed of a) 198 steps/min , b) 135 steps/min.

V. POST-REINFORCEMENT TESTS

The bridge repair procedure consisted of the following steps: the structure was first of all taken apart; each part was sent to a specialized workshop afterwards in order to fix them; moreover the metallic parts which were heavily corroded were completely removed; finally the new components – composite shells and glass balustrades – were attached to the cleaned structure, with the consequent increase in the weight; all the supports of the structure have been repaired, neoprene supports on columns have been replaced and connections at both ends have been improved. A new wooden deck has been superimposed over the older steel one. This repairing process has produced big changes on the structural dynamic characteristics of this footbridge.

After upgrading the footbridge a new dynamic test was developed in order to analyze the response of the footbridge and get its free vibration frequencies. Ambient vibrations have been recorded for 30 min.

The frequency analysis of the signals recorded under ambient vibration is shown in Table VIII.

It can be concluded that the frequency of 3.027 Hz is a frequency where vertical and lateral vibration phenomena are coupled.

Table VIII. Frequency analysis. Free vibration.

Accelerometer		Recorded frequency (Hz)
3	Vertical	3.027
4	Vertical	3.027
5	Transversal	3.027
9	Vertical	3.027

In order to determine the new structural damping factors the footbridge has been excited by two pedestrians located at the position of accelerometer 9, at an excitation frequency of 198 steps/min for 30 s (Fig. 15). From the plots of free vibrations generated by this excitement using the logarithmic decrement procedure, and filtering it between 3 and 4 Hz, a value around 4% for the damping factor is obtained. Moreover, during the tests it was observed that damping is a nonlinear characteristic of the structure very dependent of the introduced load.

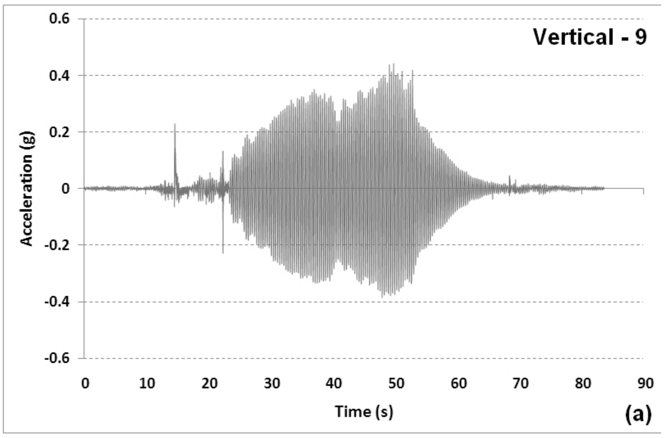

Fig. 15 Response at a force excitation in position 9. a) values recorded in 9

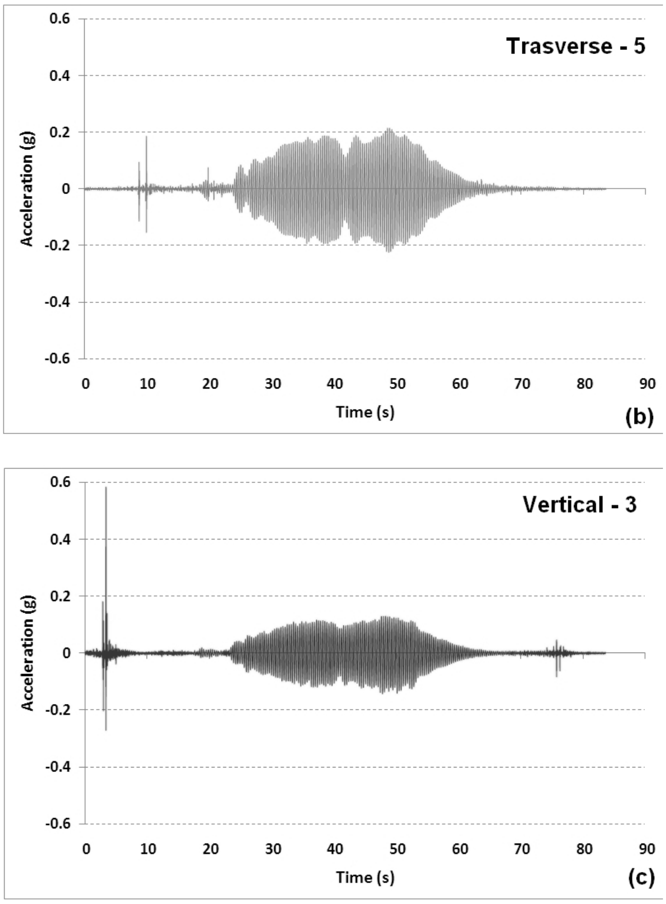

Fig. 15 Response at a force excitation in position 9 b) values recorded in 5 – transversal; c) values recorded in 3 – vertical.

This new damping ratio for the reinforced footbridge is justified by the use of wood on the repaired deck and the new elastomeric supports.

Moreover, also after the upgrade another dynamic load test has been performed. A group of six pedestrians of about 5 kN of total weight was used as a source of excitement for the test. Pedestrians crossed the footbridge in the same direction as in the pre-retrofit tests at 90, 135 and 198 steps/min. Fig. 16 shows the group of the six pedestrians at 90 steps/min. The location of the accelerometers was the same as in the preceding test (Fig. 6).

The analysis of the accelerations recorded by each sensor shows that a dynamic interaction still exists, but in this case for excitation frequencies different from the ones obtained for the un-restored footbridge. Fig. 17 shows the temporal variation of the vertical accelerations at position 3. This figure shows that resonance phenomena occurred for a speed of 198 steps/min. In fact, when the pedestrians pass on the area in curve at this frequency, the center of the straight span was vertically excited (Figure 16c). In all cases when pedestrians passed next to accelerometer 3, the levels of acceleration showed specific peaks.

Fig. 16 Group of 6 pedestrians walking on the footbridge

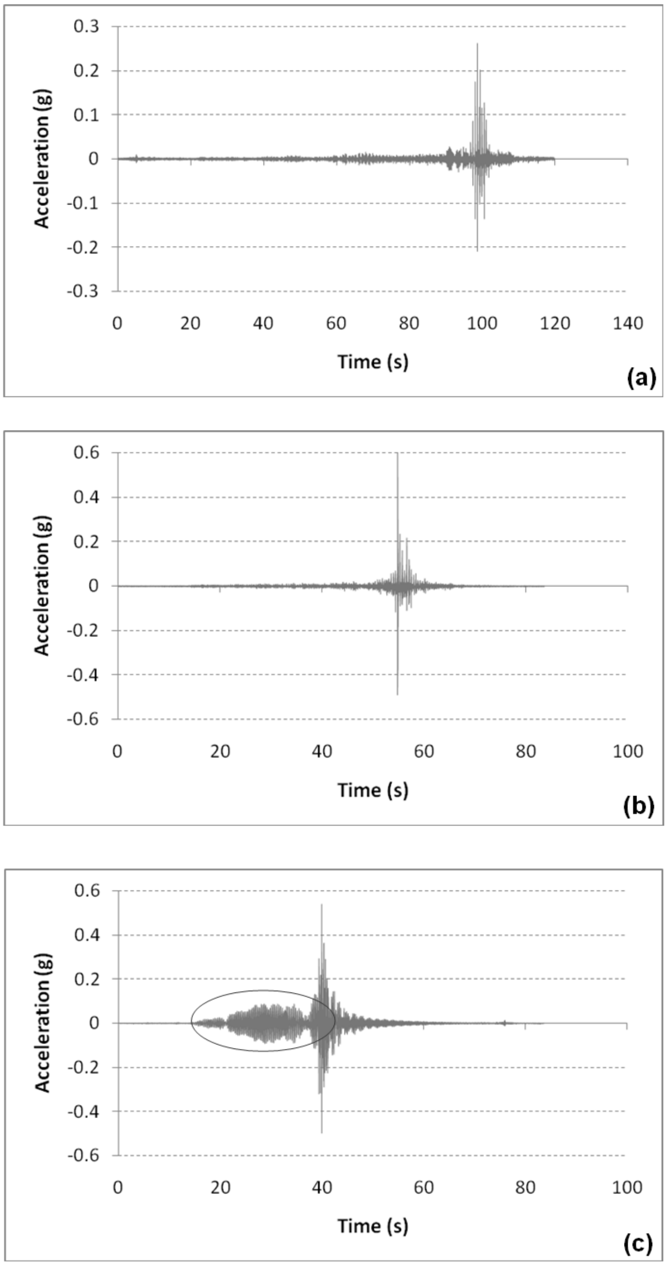

Fig. 17 Vertical accelerations at a) 90 steps/min, b) 135 steps/min and c)198 steps/min recorded at accelerometer 3

Regarding the plots in Fig. 18, it has been noticed that the horizontal response of the footbridge was influenced by the excitement generated by pedestrians. Fig. 18 shows the temporal variation of the transverse accelerations recorded at accelerometer 5. Figs. 18a and 18c show a significant dynamic interaction between the excitation frequencies and modes of lateral vibration of the walkway itself. The passage of pedestrians in the area of the cantilever - position 9 - generates a significant lateral acceleration at the center of the bay located at position 5.

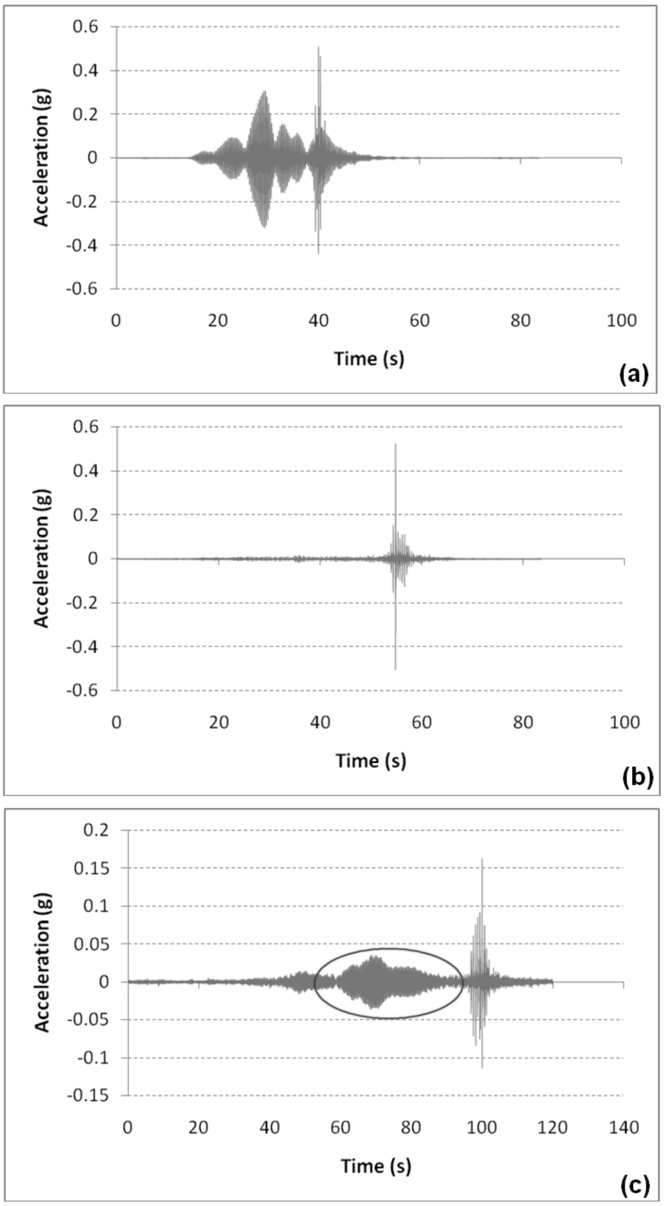

Fig. 18 Transversal accelerations at a) 90 steps/min, b) 135 steps/min and c) 198 steps/min, recorded in position 5

Moreover, the values of the maximum accelerations at the passage of pedestrians on the footbridge at different excitation frequencies have been recorded (Table IX). It can be concluded that all recorded values, both vertical and transversal exceed those recommended by the Spanish code. It has also been studied the effect of a pedestrian of 110 kg of weight passing at a speed of 135 steps/min all along the walkway. Figures 19a and 19b represent the vertical accelerations recorded respectively, at accelerometers 7 and 4, marking the limits recommended by the Spanish code. In the case of the cantilever curved beam - position 7 - this value exceeds the thresholds of both vibration perception and vibration annoying.

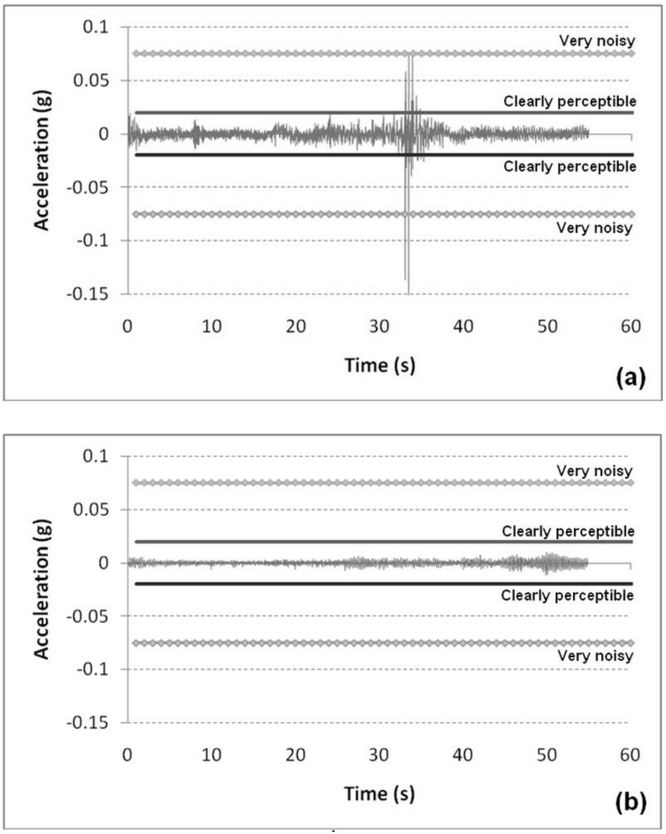

Fig. 19 A person of 110 kg of weight walking on the runway at 135 steps/min. The plots also report the limits of acceptability following the Spanish code (0.025g). a) Accelerometer 7 located on the cantilever. b) Accelerometer 4 located in the center span, vertical.

Table IX. Maximum recorded accelerations [g].

Frequency (Steps/min)	Nº Pedestrians	Accelerometer			
		4	5	6	9
90	9	0.2	0.35	0.07	0.16
135	9	0.25	0.18	0.1	0.29
198	1	0.35	0.12	0.23	0.59

VI. CONCLUSION

The footbridge of Postiguet Beach in Alicante, Spain, is a typical example of a structure particularly sensitive to vertical vibrations and, to a lesser extent, to horizontal vibrations. In this study the dynamic behavior of this walkway was investigated in detail with the aim of establishing its deficiencies from a dynamic point of view.

In this context the natural frequencies of vibration were determined and it was identified a wide range of frequencies capable of excitation during the flow of pedestrians, especially for low excitation frequencies (90 steps/min, 135 steps/min), at which the response of the structure was greatly amplified, resulting in values well above the recommended ones. Moreover, it was determined the modal damping factors for the main modes of bending vibrations.

The dynamic interaction with the passage of pedestrians does not happen at the first harmonic of the excitation induced by the motion of the pedestrians at 135 steps/min (2.25 Hz), but it appears with the second harmonic, around 4.5 Hz.

The numerical model calibrated with the experimental results allows predicting the influence of the pedestrians on the dynamic behavior of the walkway. During the calibration phase it was changed some boundary conditions at the supports that were originally designed as fixed and, probably, considerably changed their stiffness as a result of the deterioration due to corrosion of the same footbridge.

With the results obtained from this analysis it is possible to determine the best technique to apply for the restoration of Postiguet footbridge to improve both its durability to weathering and dynamic behavior.

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