

Investigation of traffic-induced vibrations on a historic swing bridge in Italy

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Abstract— This work presents a study on a very peculiar bridge, the “St. Francesco da Paola” swing bridge in Taranto, with the aim to investigate the problem of vertical traffic-induced vibrations and their effects on pedestrians. A wide monitoring ambient vibration testing has been conducted on the bridge, in order to obtain useful data for identification of modal parameters and analysis of vibration level. A detailed finite element 3D-model has been realized on the basis of survey and design data; then a model updating has been calibrated with experimental data. The vertical vibrations have been compared to reference values from technical standards/literature in order to estimate the vibration level, and a probabilistic approach has been adopted to evaluate the pedestrian comfort.

Keywords— dynamic monitoring, modal identification, pedestrian comfort, serviceability of bridges, St. Francesco da Paola bridge

I. INTRODUCTION

THE health and performance of bridges is an important topic because in the last years the development of heavy traffic on bridges, that are usually structurally deficient or functionally obsolete, has determined an increase of dynamic effects. The most common bridges are usually subjected to vertical, torsional and coupled mode vibrations which induce vertical vibrations on the deck [1,2] especially in absence of seismic forces [3]; wind-induced horizontal vibrations are more common in long span bridges [4]. Although vibrations rarely affect the global structural safety for the fatigue, they can lead to serviceability deficiencies and discomfort for the users. Human beings are very sensitive to vibrations, so their response to vibrations caused by dynamic loading should be regarded as a serviceability limit state [5].

The control of safety and comfort needs dynamic testing of bridges, an effective experimental technique that can provide useful information for calibrating numerical models, for

evaluating simulation strategies and for retrofitting and maintenance [6].

Structural Health Monitoring (SHM) is a non-destructive direct technique that allows a continuous or regular measurement of structural and ambient parameters, which includes input tests and ambient tests [7]. In general, tests with measured inputs are conducted on small bridges, while in other cases output-only test, based on ambient vibrations (generated by wind or traffic), are the only practical and economic means for exciting the structure without disturbing their normal operation. The main goal of SHM is often the experimental identification of modal parameters [8] to check and update numerical models, to evaluate the safety or the serviceability of existing structures, to characterize existent structures before the development of rehabilitation projects or to obtain a baseline characterization of an existent structure to check the evolution of its dynamic parameters during time as a consequence of a progressive damage.

In the present study output-only SHM is adopted for dynamic identification, and subsequently for model updating, and for the evaluation of vertical traffic-induced vibrations and their effect on pedestrians on a very peculiar case study, the “St. Francesco da Paola” swing bridge in Taranto, Italy.

After a preliminary study on a detailed numerical model to identify the theoretical modal parameters, a dynamic monitoring has been conducted on the bridge with the use of four force-balanced accelerometers in different configurations and the data have been elaborated to obtain experimental modal parameters. Secondly, literature studies and the principal international codes about vibrations have been analyzed, only to show how a deterministic approach is common and one or more comfort thresholds are usually proposed, regardless of how many times or how long the comfort is rejected. The different methods of evaluation of comfort have been compared to find the most severe one to use for this study and to further perfect it in probabilistic terms.

II. DESCRIPTION OF THE CASE STUDY AND FE MODEL

Taranto is a coastal city located in the southern part of Italy, in the Apulia region, and is characterized by two basins close to the Ionic coast: an inner, semi-enclosed basin with lagoon features – named “Mar Piccolo” – is connected with the outer basin (named “Mar Grande”) through two canals, namely the “Navigabile” canal and the “Porta Napoli” canal. The actual swing bridge over the “Navigabile” canal, the “St. Francesco

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da Paola” bridge (Figs. 1-2), was opened to traffic in 1958; it is considered a historical monument of the city and has a crucial role within the local transport network. The actual structural reliability and serviceability of the bridge are substantially unknown because the bridge has not been investigated previously by using modern numerical techniques and by monitoring dynamic properties.

The bridge has a total span equal to 89.52 m and accommodates two traffic lanes with a total 6.00 m roadway; two pedestrian lanes are on both sides of the bridge and the sidewalk span is equal to 1.50 m for each lane (Figs. 3-4). It was built with two equally armed movable portions with a steel truss structure and each of them rotates about one vertical axis; one rim bearing, consisting of a series of conical rollers which are loaded during the bridge movement for each movable portion of the bridge, is placed on the corresponding abutment. The two movable parts of the bridge are connected each other in four points located in the transversal section of the free ends. The steel truss structure of each movable portion of the bridge was realized with 4 longitudinal truss beams, 19 transverse braces, and horizontal braces on the lower and upper chord of the truss structure. Since 1983, a reinforced concrete plate was used for the bridge deck. Subsequently, it was replaced with an orthotropic steel plate-type deck with constant thickness equal to 10 mm in order to reduce the dead load over the bridge.

A three-dimensional finite element model of the bridge was built by using SAP2000© (version 14); only structural elements were included in the model, whereas non-structural elements are considered as extra masses. The steel has elastic modulus 200000 N/mm^2 , Poisson’s ratio 0.30, density 7850 kg/m^3 . The soil-structure interaction is not considered and the rim bearing is replaced with an appropriate set of constraints. Beam-type elements were adopted to model the element of the truss structure. Thin shell elements were used to model steel orthotropic plate-type deck. The modal analysis has been performed by considering a linear elastic behavior. The first six numerical natural frequencies of the bridge are listed in Table I and the corresponding mode shapes are shown in Fig. 5.



Fig. 1 “St. Francesco da Paola” bridge.

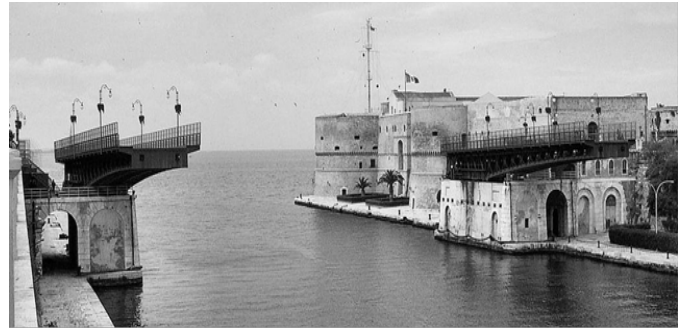


Fig. 2 “St. Francesco da Paola” bridge opened (from www.ressa.it).



Fig. 3 Photorealistic view of “St. Francesco da Paola” bridge.



Fig. 4 CAD based view of the orthotropic steel deck of the bridge.

Table I Natural frequencies of the bridge by FE analysis.

mode	frequency [Hz]
1	2.421
2	3.342
3	6.160
4	9.175
5	12.848
6	16.273

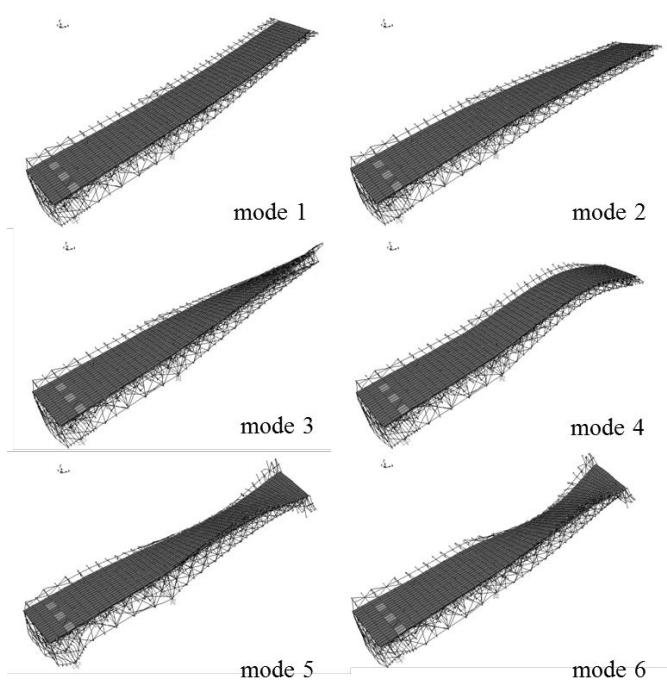


Fig. 5 First six mode shapes of the bridge.

III. DYNAMIC MONITORING

Dynamic tests were performed under ambient and traffic excitations. The bridge was instrumented with four uniaxial force-balance accelerometers, which belong to the category of passive transducers and are used in structural monitoring, seismic monitoring and aircraft navigational systems and are one of the most employed types of transducers especially for civil engineering applications to large flexible structures.

The instrumentation used for dynamic monitoring included a data acquisition system (named THOR, of Waveng society) [9] able to manage more distributed sensor networks with real-time acquisition and data processing for structural analyses. Data acquisition was driven by a software, which allows the acquisition of signals with sampling rate of 1000 Hz and the real time visualization of accelerograms and Fourier spectra.

The monitoring program went from October 2012 through April 2013, and finally the data collected during 10th of April were selected for this study. The measurement nodes were located under the bridge deck and the setups have been chosen according to optimization criteria in Marano et al [10] and according to the configuration that allow underlining the principal mode shapes, as previously found with FE model. In total 21 tests of 5 minutes each, divided in three setups, were performed. In the first setup (9 tests) and second setup (6 tests) all vertical accelerometers were adopted (Fig. 6a-6b); in the third setup (6 tests) the central accelerometer is horizontal (Fig. 6c). In Fig. 7 one typical acceleration time-history recorded by the vertical accelerometer A0 in test 1 is reported with the corresponding Fast Fourier Transform (FFT, Fig. 8), both elaborated with the software MATLAB.

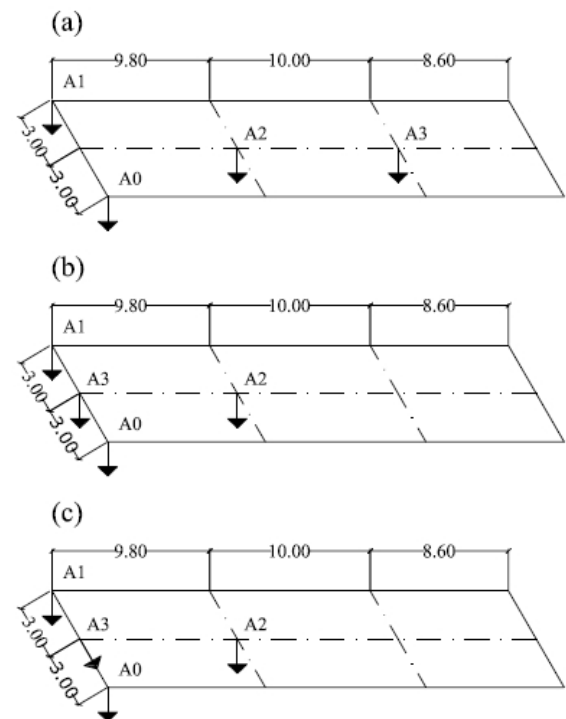


Fig. 6 Setups of the accelerometers.

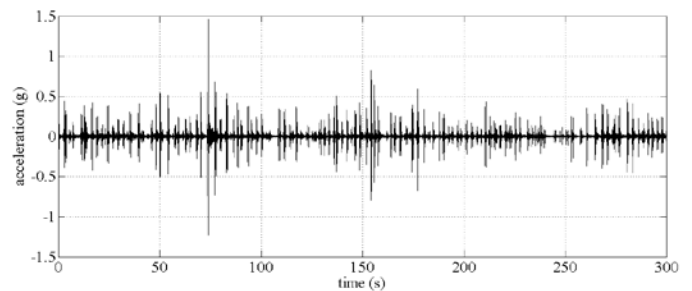


Fig. 7 Time-history of the accelerometer A0 during the first five minutes of test 1.

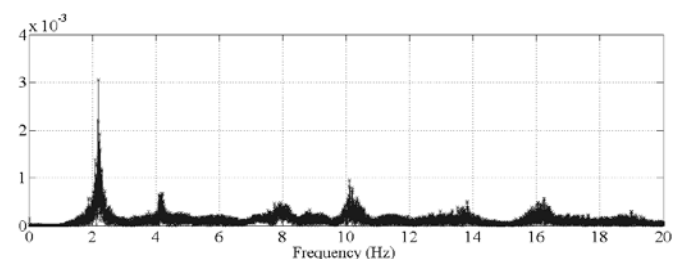


Fig. 8 Fast-Fourier Transform of the accelerometer A0 during the first five minutes of test 1.

IV. DATA PROCESSING AND OPERATIONAL MODAL ANALYSIS

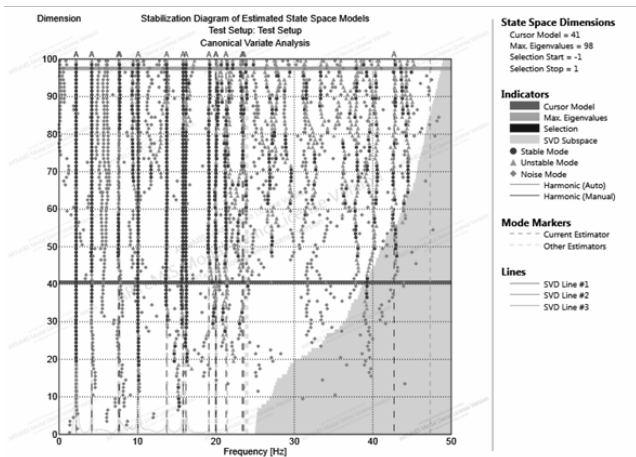
Experimental information about the modal parameters of a structure can be obtained from Operational Modal Analysis (OMA), without requiring the knowledge of input forces: this allows testing structures under operating conditions and with the unknown input of ambient forces (wind and/or traffic). The output is a time-history that gives the possibility to obtain

the experimental modal parameters, related to the actual properties of the structure, that can be compared to predicted values from numerical models.

A lot of researches developed OMA for civil engineering applications [11]. The two best known identification methods are the enhanced frequency domain decomposition (EFDD) in frequency domain and the stochastic subspace identification (SSI) in time domain. The idea of the EFDD method is to perform an approximate decomposition of the system response into a set of independent single degree of freedom systems, one for each mode. In the SSI method the order of the model is characterized by the state space dimension. SSI is an output/only time domain method that directly works with time data, without the need to convert them to correlation or spectra [12].

In this study the extraction of the modal parameters from ambient vibration data was carried out using the ARTeMIS Modal 3.0 software. System identification was performed using the SSI algorithm, considering only modes below 10 Hz, as these are of most interest for ambient excitation and human induced vibrations. Fig. 9 shows the experimental results with reference to the 1th and 2th setups.

Setup 1



Setup 2

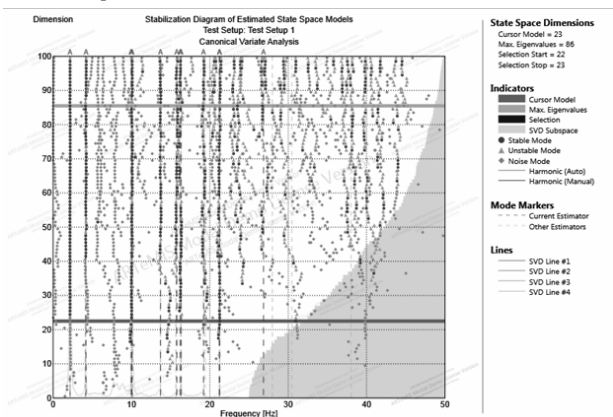


Fig. 9 Fast-Fourier Transform of the accelerometer A0 during the first five minutes of test 1.

setups and the FE model is shown in Table II, where the first six estimated experimental frequencies are compared to the first six FE theoretical frequencies; the percentage errors are reported. The results show that the frequencies are close to the experimental ones, but there are some differences, possibly due to the partial loss of stiffness during time for the oxidation of steel trusses. So a model updating procedure [13] has been done to consider the loss of stiffness by the progressive reduction of the truss sections until a factor of 0.8. Table III shows a comparison between the experimental frequencies and the new frequencies obtained after a model updating.

This first investigation shows that a linear finite element model appears to be capable of capturing the dynamic behavior of the bridge with a good accuracy. It is worth noticing that only the first frequency shows a significant improvement after the model updating due to the complexity of the FE model. Moreover the horizontal experimental frequencies (modes 2 and 5) have been poorly investigated because only one accelerometer in one setup has been set horizontally; in fact the main aim of this paper is to investigate vertical vibrations. At the end, the detailed FE modeling of the bridge is resulted useful to obtain a validation of the experimental measurements.

Table II. Comparison between experimental and theoretical frequencies.

mode	experimental frequency [Hz]	theoretical frequency [Hz]	error [%]
1	2.173	2.421	10.23
2	2.658	3.342	20.46
3	4.962	6.160	19.45
4	7.725	9.175	15.80
5	10.086	12.848	21.50
6	16.060	16.273	1.31

Table III. Comparison between experimental and theoretical frequencies.

mode	experimental frequency [Hz]	updated model frequency [Hz]	error [%]
1	2.173	2.213	1.81
2	2.658	3.045	12.71
3	4.962	5.660	12.33
4	7.725	8.588	10.05
5	10.086	12.124	16.81
6	16.060	16.731	4.01

The comparison between the experimental data of the three

V. HUMAN PERCEPTIBILITY TO TRAFFIC-INDUCED BRIDGE VIBRATIONS

People have a high sensitivity to vibrations, so human response to vibrations due to dynamic loads should be considered as a serviceability limit state. Several factors influence human sensitivity and perception of vibration: position of the human body, health condition, age, type of activity, excitation source characteristics, exposure time, direction of motion, floor and deck system characteristics, level of expectancy [14]-[15].

The acceptable level of vibration also depends on the kind of structure: for instance a higher level is acceptable on bridges, with respect to residential buildings, due to the awareness of the presence of wind and traffic and for the exposure limited in time [16].

A survey in the USA [17] indicated that pedestrians are more sensitive than drivers or passengers to disturbing vibrations, because people inside the vehicles seldom notice the oscillations of bridges, perhaps because their vehicle's normal vibration obscures these. Moreover pedestrians are less susceptible to the vertical component of vibration when walking than when standing and accept a higher threshold after a period of acclimatization, even with an upper limit.

A limited number of studies proposing acceptable human levels for bridge vibrations are available in technical standards/literature.

The first analyses on human response to vibration (HRV) were made by Mallock [18] who underlined the acceleration as the main parameter that influences comfort and fixed 1% of gravity acceleration as a threshold. Various studies were carried out that usually resulted in sensitivity curves, usually relating acceleration or displacement with frequency, with different levels of comfort.

Smith [17] presents the work of Irwin, who suggested a base curve for acceptable human response to the vibration of a bridge under frequent forms of loading.

Bachmann et al. [19] illustrate the main factors affecting human sensitivity to vibrations and for vertical vibrations propose the human perceptibility thresholds reported in Table IV.

British standard for bridge design, BS 5400 [20], contains recommendations on this topic valid exclusively in the case of footbridges. This standard is reasonably close to Irwin's suggested curve for storm conditions. Also EN 1990 furnishes indications exclusively for footbridges. EN 1990 states that the pedestrian comfort criteria for serviceability has to be defined in terms of maximum acceptable acceleration of any part of the deck. The acceptable values of acceleration are 0.7 and 0.2 m/s² in the vertical and the horizontal directions respectively [21].

ISO 2631 [22] proposes similar base curves just for residential and office places under transition vibration, without any indications for bridges.

Spanish standard [23], similarly to Bachmann study, fixes more thresholds for each level of comfort, as shown in Table V.

In the majority of the standards previously described it has been generally accepted that the acceleration is the vibration parameter which should be used to describe the exposure condition.

The main researches and standard previously exposed are compared in Fig. 10.

Table IV. Human perceptibility thresholds according to Bachmann.

description	threshold
just perceptible	0.0034g
clearly perceptible	0.01g
disturbing	0.055g
intolerable	0.18g

Table V. Human perceptibility thresholds according to Spanish standard.

description	threshold
easily perceptible	0.025g
clearly perceptible/disturbing	0.075g
very disturbing	0.125g

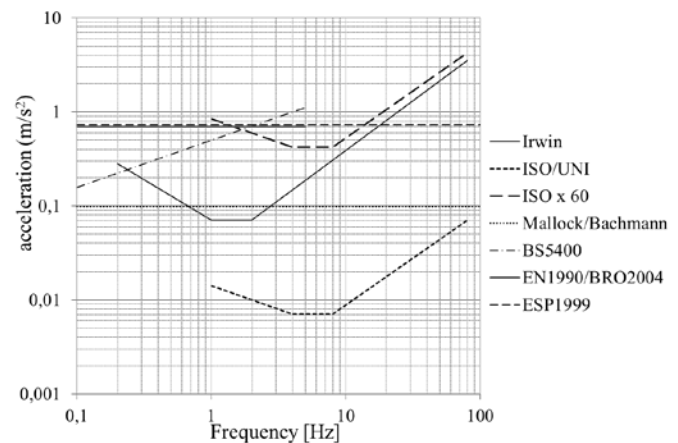


Fig. 10 Comparison of the different literature/standard thresholds.

The showed approaches for the vibration serviceability assessment are all characterized by thresholds fixed in a deterministic way, although many uncertainties exist in monitoring systems and in describing the disturbing degree of pedestrians. A probabilistic methodology appears more reasonable and is here proposed. From the comparison between the different thresholds, the ones proposed by Bachmann et al. appear the most severe and the most immediate to use as base reference limit for the vertical component of vibration; they also allow distinguishing among just perceptible, clearly perceptible, disturbing and intolerable vibration effects. Fig. 11 shows the four degrees of discomfort according to Bachmann referred to the first test (first 5

minutes).

One can note how often the maximum threshold (0.18 g, corresponding to an intolerable value) is overcome, especially in accelerometer A0 and A1, placed in the middle of the bridge.

In addition, the probability that the monitored data exceed the predefined limits is assumed a reliability measure. At this aim suitable histograms are adopted (Fig. 12); it is worth notice that in both the cases of accelerometers A0 and A1 the mean value of acceleration exceeds the threshold “clearly perceptible”. At the end all the data referred to each setup have been reunited in a diagram relating each acceleration with the probability that its value is exceeded (Fig. 13).

Considering all the acquired data, the mean curves referred to each setup are clearly superimposable and an a further mean curve can be considered to calculate the probability that vertical vibrations exceed the thresholds. In particular the probability that vibrations exceed the disturbing thresholds is 4.9%; similarly the mean exceedance probability for clearly perceptible and just perceptible thresholds are resulted equal to 38.7% and 77.13% respectively.

The above exposure conditions will be accepted if the following inequality holds: $P_f \leq P_f^*$, where P_f is the occurrence probability obtained by experimental results and P_f^* is the maximum probability value.

According to serviceability requirements, a structure during its intended life should remain fit for the use for which it is required with appropriate degrees of reliability and in an economic way. If human response to traffic-induced vibrations is regarded as a serviceability limit state, on considering the current European standards [21], it seems acceptable to set the value of P_f^* equal to about 10^{-2} .

So vertical vibrations due to traffic on “St. Francesco da Paola” bridge exceed all the three predefined limits describing with different intensity the human sensitivity to structural oscillations (disturbing, clearly perceptible, just perceptible). This means that this bridge has a serious problem of serviceability and suitable maintenance interventions should be planned in order to reduce the perceptible vertical vibrations of the deck.

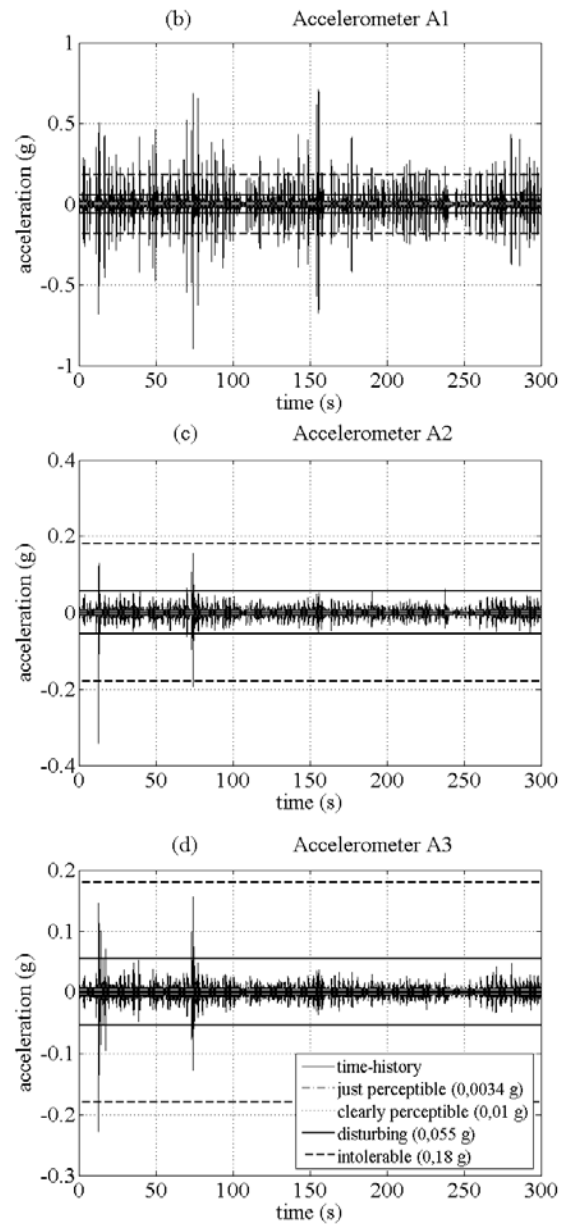
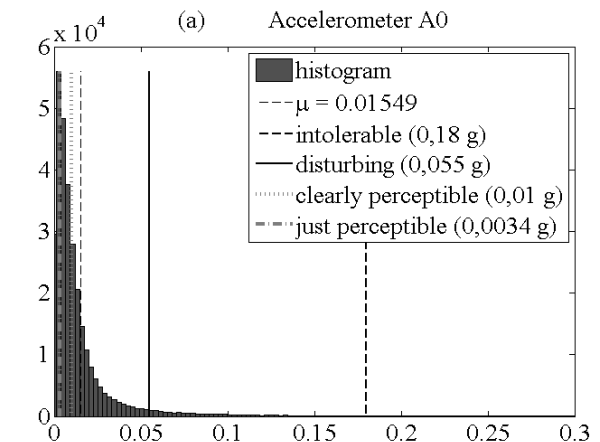
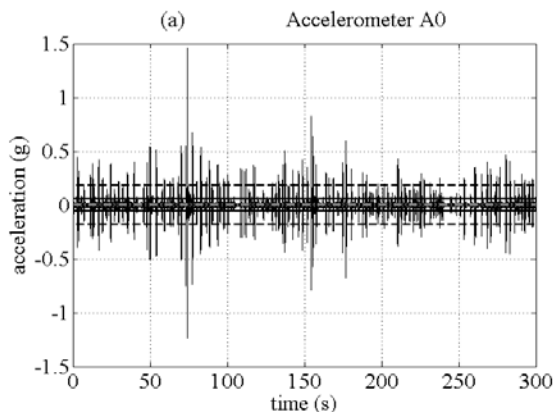


Fig. 11 Time histories of the first test with the thresholds fixed by Bachmann.



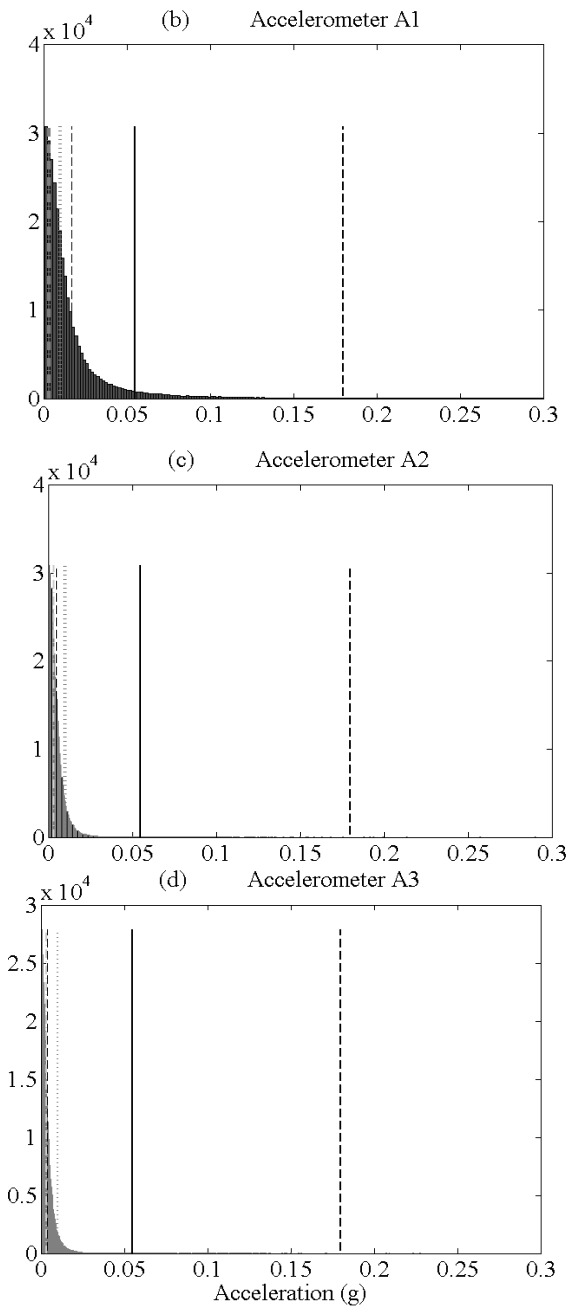
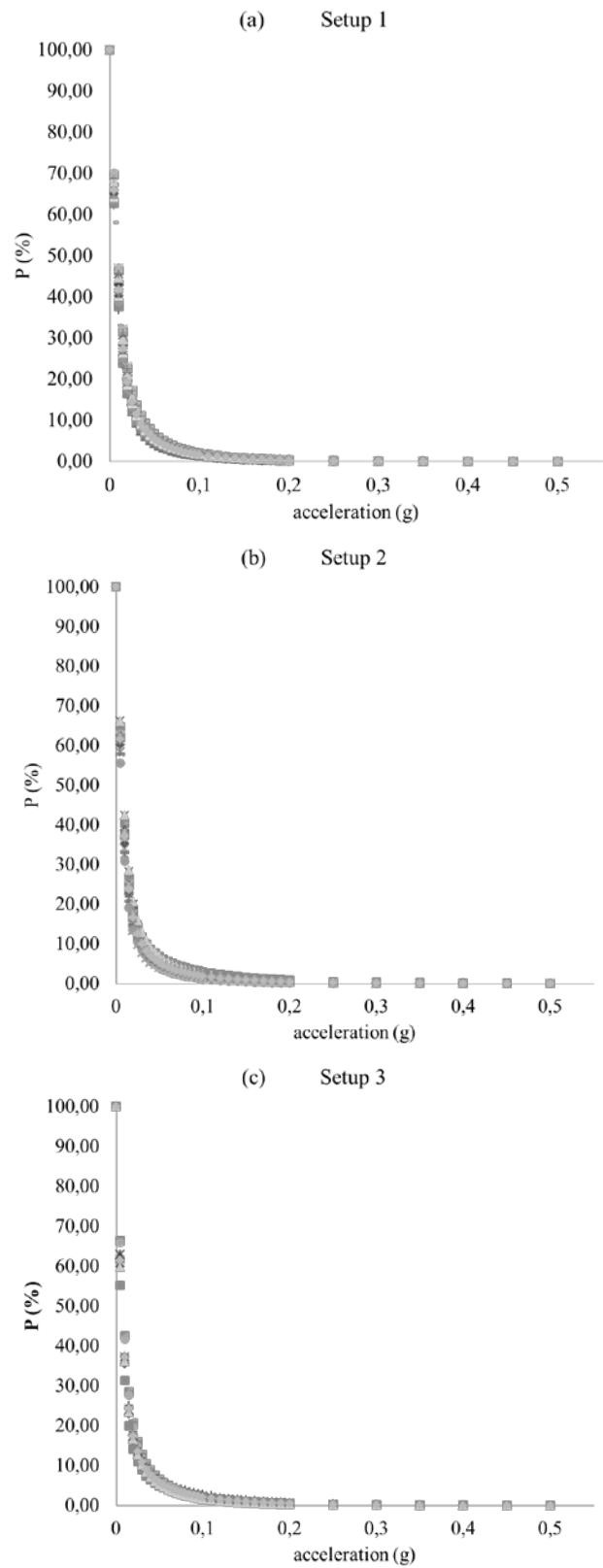


Fig. 12 Histograms of the first test with the thresholds fixed by Bachmann.



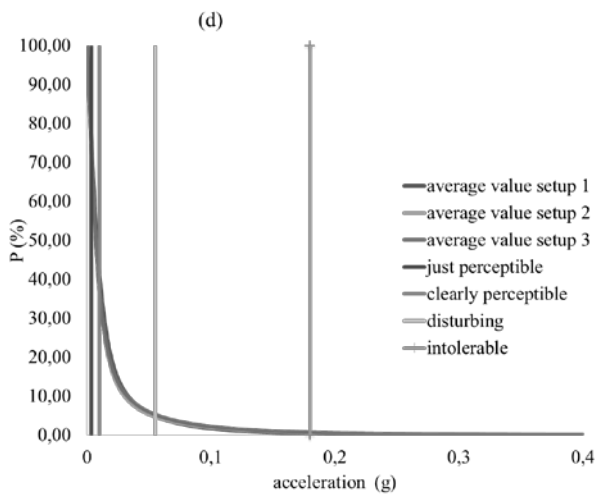


Fig. 13 Relation between acceleration values and the corresponding exceeding probability P : a) setup 1; b) setup 2; c) setup 3. d) average curves of the previous graphs and comparison with Bachmann's thresholds.

VI. CONCLUSIONS

This study has dealt with an experimental dynamic monitoring of a very particular and strategic bridge in Italy. For each direction traffic-induced vibrations were recorded by accelerometers located in suitable positions under the deck of the bridge and shown by accelerograms. Modal identification procedure was applied to ambient vibration data to extract the modal parameters adopting the SSI method, by means of the ARTeMIS software. The experimental modal frequencies of the bridge were compared with the ones identified by a very detailed FE model. Some exiguous differences were observed, but after a model updating by the reduction of the sections (due to oxidation) a good agreement was observed; so a linear finite element model appears to be capable of capturing the dynamic behavior of the bridge with a good accuracy.

Secondly the influence of traffic-induced vibration in terms of human perceptibility was investigated. A practical probabilistic approach to assess bridge reliabilities was presented, based on the use of histograms and the literature threshold proposed by Bachmann. It was shown that histograms provide useful estimates of the exceedance probability associated to sensitivity limits. Human response to traffic-induced vibrations was regarded as a serviceability limit state. The analysis showed that "St. Francesco da Paola" bridge is subjected to significant vertical motions and requires interventions. More detailed probabilistic descriptions associated with different time periods of a day, a week and a year (seasonal) should be considered in future studies, to provide more reliable probabilistic values.

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