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Abstract

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Keywords	SHM; Structural Health Monitoring; load testing; dynamic testing; bridge; FEM; Finite Element Model; reinforced concrete.
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Università degli Studi di Ferrara Dipartimento di Ingegneria – via Saragat 1

Object: STRUCTURAL HEALTH MONITORING OF AN OPERATIONAL BRIDGE: A CASE STUDY

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Dear Editor,

Dear Reviewer,

I am sorry to have omitted in the references the codes, guidelines and recommendations SHM Japanese: in the revised version I have cite they in the text, in the table and in the references.

With regard to the second observation, I would like to point out that I have chosen to identify the accelerometric recording positions (nodal positions) in the same positions occupied by the benchmarks (five): positions that were located along the longitudinal development of the bridge's central beam in order to make the most accurate comparison possible between the static and the dynamic load test.

This choice it is also congruent with the hypothesis of linear deformation of the central beam of the bridge, allowed me to assume the frequency response independent of the excitation technique used; for this the SIMO technique was used instead of the MIMO (Multi-Input–Multi-Output) technique, since the latter was impracticable on account of operational limitations.

In the revised text these corrections have been highlighted in yellow. Now the paper is composed of n. 19 pages.

Finally, on the third observation, I would like to reiterate that for the testing of a newly built bridge, the Italian Standard requires a static load test: therefore, the dynamic load test can be performed only in addition to the static load test. In the post-construction monitoring of operational bridges, as recommended by the SHM standard the decline in stiffness of the bridge can be ascertained in practice by estimating only the modes of vibration. An eventual deformation (deflection) can be calculated a posteriori from an updated finite element model (FEM): in this case, the dynamic load test is an alternative to the static load test.

Therefore for new bridges the static test is irreplaceable and the dynamic test can be used as supplement test given the advantages that emerged from the study.

Sincerily.

Ferrara, 24/5/2019.

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- Various structural health monitoring (SHM) codes, guidelines and recommendations available for engineering applications have been resumed in the appropriated summary table;
- A preliminary investigation evaluated the diffusion of the SHM dynamic load test of bridges in Italian regulation;
- Dynamic load test and static load test hare compared regarding the structural responses, performances and costs.

STRUCTURAL HEALTH MONITORING OF AN OPERATIONAL BRIDGE: A CASE STUDY

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ABSTRACT

During testing of the structural reliability of a prestressed reinforced concrete bridge built in the late 1960s, the author compared the structural responses, performances and costs of jointly conducted static and dynamic load tests. In the static load test, the precision spirit leveling technique was used to measure the deflections of the deck induced by four trucks weighing about 36 tonnes each. In the dynamic load test, accelerometers placed on the main beam were used to measure the vibration frequencies following an impulse produced by a 2-tonne truck. The dynamic load test resulted in a refined finite element model of the bridge. The comparison showed that the dynamic load test can supplement the static load test for the structural testing of new bridges or be an alternative to it for the monitoring of operational bridges.

Key word: SHM; Structural Health Monitoring; load testing; dynamic testing; bridge; FEM; Finite Element Model; reinforced concrete.

INTRODUCTION

Various structural health monitoring (SHM) codes, guidelines and recommendations have been developed abroad in recent decades to monitor the structural health of bridges. One of the first was published by the Intelligent Sensing for Innovative Structures (ISIS) research network of Canada in 2001 (Mufti 2001): it presents a summary of the SHM techniques known at that time, including static and dynamic load tests and periodic and continuous monitoring. Shortly thereafter, in the United States the Federal Highway Administration (FHWA) and the International Federation for Structural Concrete (FIB) published guidelines for the development of a SHM model for monitoring strategic bridges (Aktan and Catbas 2002) as well as for monitoring and evaluating the safety of concrete bridges (Bergmeister 2002). These guidelines include aspects of SHM engineering applications for bridges, including the concepts of monitoring, structures and materials, inspection technology, measurement methods, implementation and data acquisition problems, systems analysis, assessment of conditions, analysis of structural reliability and LRFR (load and resistance factor rating) methodology (TRB 2001). A few years later, the International Organization for Standardization (ISO 2003; ISO 2004-a; ISO 2004-b) presented new international standards for measuring and processing the responses to vibrations of bridges.

In 2006 the European Union issued guidelines (Rucker et al. 2006) with the aim of introducing, for both managers and civil engineering technicians, the SHM procedures and technologies for structural assessment, monitoring and control (SAMCO) of infrastructure systems. In 2010 the Russian Federation developed the GOST R 53778:2010 regulations (Russian Federation 2010), which introduced visual inspection, assessment technologies and classification schemes according to the operating conditions in various types of structures. Two years later, Germany issued an official guideline for monitoring bridges and other engineering structures (Österreichisches Forschungsgellschaft RVS 2012). In India, starting from 1965 (on the occasion of the publication of design criteria for prestressed normal and reinforced concrete road bridges), specific standards were issued for assessments based on stress during use, of which the latest versions were published between 2010 and 2015 (IRC 2010; IRC 2011; IRC 2015). Fujino and Siringoringo (2008) described the development of bridge SHM in Japan; subsequently, Fujino and Kawai (2016) listed the SHM Design Codes in Japan from 1950 to 2010 for concrete and steel bridges.

Yang et al. (2016 and 2017) published a complete review of the SHM codes and standards in China, in particular for codification of the technical norms for the monitoring of buildings and bridges (DB/T29-208-2011 2011; CECS 333-2012 2012; JGJ/T 302-2013 2013; GB 50982-2014 2014; JT/T 1037-2016 2016), describing some engineering application procedures and SHM technologies for many representative Chinese cases. Finally, existing SHM guidelines showed significant progress, on a broad scale and for all infrastructures, with AASHTO (2012) and Minnesota Department of Transportation (2017), which are now among the most frequently consulted standards for SHM technologies and methods available for engineering applications.

Therefore, at present, other countries have many authoritative and abundant codes and standards of SHM that can significantly promote its applications in engineering: some of these codes and standards are reported in Table 1. In contrast, Italian legislation for operational bridges (Min. LL.PP. 1962; Min. LL.PP. 1980; D.M. 02.08.1980 1980; D.M. 04.05.1990 1990; Min. LL.PP. 1991; Istruzione I/SC/PSOM/2298 1995) is lacking in the SHM sector, with the exception of UNI 10985:2002 (UNI 2002). However, the Morandi Bridge disaster in Genoa and a long series of collapses and failures (18 April 2017, viaduct of the Fossano Cuneo ring road; 9 March 2017, bridge 167 on the A14 motorway between Loreto and Ancona Sud; 29 October 2016, overpass on the SS 36 in the province of Lecco; 22 October 2013, the Carasco Bridge, above the Sturla River, in the Genoese hinterland) demonstrate the necessity of a review of the regulations and the urgent preparation of a national monitoring plan for the structural health of road infrastructures.

The contribution of managers and testers is no better: in this regard, the results (section 1) of an investigation of whether the SHM dynamic load test is performed frequently on old but operational reinforced concrete road bridges were deeply disappointing.

Therefore, the author compared (in terms of structural responses, performances and costs) a static load test provided for by Italian law and a SHM dynamic load test performed jointly (at different times) to assess the structural reliability of a medium-length, prestressed reinforced concrete bridge constructed and tested at the end of the 1960s, in view of an evident state of deterioration caused by more intense vehicular traffic than that foreseen in the design of the bridge. In the static load test, the precision spirit leveling technique was used to measure deflections of the deck induced by four trucks weighing about 36 tonnes each. In the dynamic load test, the first three vibration frequencies of the beam were measured through the accelerations produced by vibrating the bridge via jumps of a 2-tonne truck. The dynamic load test resulted in a refined finite element model (FEM) of the bridge.

Regarding the structural responses, performances and costs, it was found that the dynamic load test can supplement the static load test for the structural testing of new bridges or be an alternative to it for the monitoring of operational bridges.

1. PRELIMINARY INVESTIGATION

In view of the rather patchy, deficient Italian regulations, a preliminary investigation was carried out to evaluate the diffusion of SHM dynamic load tests of bridges. It was conducted in the field via interviews of ten engineering companies (sources) involved in the testing and monitoring of bridges from 2005 to 2015. About 20 questions were asked concerning 100 structures, of which 29 in reinforced concrete, 35 in prestressed reinforced concrete, 22 in steel and 14 in mixed-steel and reinforced concrete:

a) the testing:
- number of dynamic load tests carried out per year and their increase;
- number of requests for dynamic load tests alone, dynamic and static load tests together, static load tests alone;
- subordination of the dynamic load test with respect to the static load test (complementary or alternative);
- costs and times of planning and execution of the dynamic load test with respect to the static load test;
- costs and times of processing of measurements in the dynamic load test with respect to the static load test;
- subjects commissioning the dynamic load test (public or private);
- dynamic load used (impulsive with impacting agent; induced with a vibrodyne or instrumented hammer; natural due to vehicular traffic or atmospheric agents);
- measurement sensors (accelerometers, geophones, displacement transducers);
- measured vibration modes (in the intervals 1 to 5, 6 to 10, or more than 10);

b) the investigated bridges:
- material (reinforced concrete, prestressed reinforced concrete, steel, mixed - steel and reinforced concrete);
- use status:
    - under construction - partial tests;
    - completed - final test;
    - in use - operational tests;
- health status shown by the dynamic tests for operational bridges;

c) knowledge of regulations:
- national;
- international (SHM).

Table 1. Summary of some SHM codes and standards divided by year, country, title, organization and language.
Italian legislation on bridges.

Country	Year	Title	Organization	Abbreviation	Language
Canada	2001	Guidelines for structural health monitoring	Intelligent Sensing for Innovative Structures	ISIS	English
USA	2001	Manual for Condition Evaluation and Load Rating of Highway Bridges Using Load and Resistance Factor Philosophy	Transportation Research Board - National Research Council	TRB	
USA	2002	Development of a model health monitoring guide for major bridges	Federal Highway Administration Research and Development	FHWA	
USA	2002	Monitoring and safety evaluation of existing concrete structures: state-of-the-art report	International Federation for Structural Concrete	FIB	
Washington USA	2012	LRFD bridge design specifications 6th Ed.	American Association of State and Highway Transportation Officials	AASHTO	
Oakdale USA	2017	LRFD bridge design manual 5-392	Minnesota Department of Transportation		
Switzerland	2003	ISO 14963 Mechanical vibration and shock - guidelines for dynamic tests and investigations on bridges and viaducts	International Organization for Standardization	ISO	
	2004	ISO 16587 Mechanical vibration and shock—performance parameters for condition monitoring of structures			
	2004	ISO 18649 Mechanical vibrations evaluation of measurement results from dynamic tests and investigations on bridges			
Berlin Germany	2006	Guideline for structural health monitoring. Final report	Structural Assessment, Monitoring and Control	SAMCO	
Germany	2012	Quality assurance for structural maintenance, surveillance, checking and assessment of bridges and tunnels, monitoring of bridges and other engineering structures	Österreichisches Forschungsgellschaft RVS	RVS	German
Russia	2010	GOST R 53778 Building and Structures, Technical Inspections and Monitoring Regulations	National Standard of the Russian Federation	GOST	English
New Delhi India	2010	IRC 6 Standard specifications and code of practice for road bridges. Section: II, Loads and Stresses	Indian Roads Congress	IRC	
	2011	IRC 112 Code of practice for concrete road bridges			
India	2015	IRC SP:51 Guidelines for load testing of bridges - 1st Revision			
Japan	1996	Second Recommendations about the Seismic Design Standards for Civil Engineering Structures	Japanese Society of Civil Engineers	JSCE	Japanese
	2007	Standard Specifications for Steel and Composite Structures (Performance-based Limit State Design)			
	2007	Standards for Test Methods and Material Quality			
	2013	Standard Specifications for Concrete Structures (Design-Material and Construction-Maintenance)			English
	2010	Standard Specifications for Hybrid Structures-2009	Japan Concrete Institute	JCI	Japanese
	2004	Highway Bridge Management Handbook	Japan Bridge Engineering Center	JBEC	Japanese

	2005	Collected Examples of Seismic Retrofit of Existing Bridges			
	2007	Calculation for Highway Bridge Rehabilitation/Strengthening			
	2004	Specifications for Highway Bridges: Part I Common Design Principles	Japan Road Association	JRA	English
	2012	Specifications for Highway Bridges: Part II Steel Bridges			Japanese
	2012	Specifications for Highway Bridges: Part III Concrete Bridges			English
	2012	Specifications for Highway Bridges: Part IV Substructures			English
	2002	Specifications for Highway Bridges: Part V Seismic Design			Japanese
	2002	Fatigue Design Manual for Steel Highway Bridges	Japan Association Steel Bridge Construction	JASBC	English
	2010	Development of Technique for Steel Bridge			Japanese
	2002	Specific. for Highway Bridges (Performance-Based Design, Endurance Design)	National Institute for Land and Infrastructure Management	NILIM	English
Tianjin China	2011	DB/T29-208-2011 Structural health monitoring system technical specification for bridge of Tianjin	Tianjin Municipal Government	TMG	Chinese
Beijing China	2012	CECS 333-2012 Design standard for structural health monitoring systems	China Association for Engineering Construction Standardization	CAECS	
China	2013	JGJ/T 302-2013 Technical code for construction process analyzing and monitoring of building engineering	China Building Industry Standard	CBIS	
	2014	GB 50982-2014 Technical code for monitoring of building and bridge structures	Chinese National Standards	CNS	
	2016	JT/T 1037-2016 Technical specification of safety monitoring system for highway bridge structure	China Building Industry Standard	CBIS	
Italy	1962	Regulations on loads for calculation of road bridges. Circolare n. 384 del 14 Febbraio 1962	Ministero dei Lavori Pubblici	M.LL.PP.	Italian
	1980	STC Instructions relating to the technical regulations on road bridges Circ. n. 220977 del 11/11/80			
	1980	General criteria and technical regulations for the planning, execution and testing of road bridges	Decreto Ministeriale	D.M.	
	1990	Update of technical regulations for the planning, execution and testing of road bridges		D.M.	
	1991	STC Instructions relating to the technical regulations on road bridges (D.M. 4.5.90) Circ. n. 34233 del 25/02/1991	Ministero dei Lavori Pubblici	M.LL.PP.	
	1995	Istruzione I/SC/PSOM/2298 Overloading for the assessment of railway bridges – Instructions for planning, execution and testing	Ferrovie dello Stato	FF.SS.	
	2002	UNI 10985:2002 Vibrations on bridges and viaducts – Guidelines for the execution of dynamic tests and surveys	Ente Nazionale Italiano di Unificazione	UNI	

The following data were extrapolated from the responses (in anonymous form):

a) the mean annual number of dynamic load tests and their increase (as a percentage);
b) the mean annual number of requests (percentage) of dynamic load tests or static load tests or both together;
c) the percentage of subordination of the dynamic load test with respect to the static load test (complementary or alternative);
d) the percentage savings in costs and times of planning and execution of the dynamic load test compared to the static load test;
e) the percentage increase in costs and processing times of the dynamic load test compared to the static load test;
f) the percentage of public and private subjects commissioning the dynamic load test;
g) the type of load used in the dynamic load test (percentage);
h) the type of sensor used in the dynamic load test (percentage);
i) the vibration modes measured in the dynamic load test (percentage);
j) the construction material of the investigated bridges;
k) the percentage of use status of the investigated bridges;
l) the percentage of health status of the bridges investigated with the dynamic load test;
m) the knowledge of national and international regulations (SHM) (percentage).

The results are shown in Figure 1-a, 1-b and 1-c.

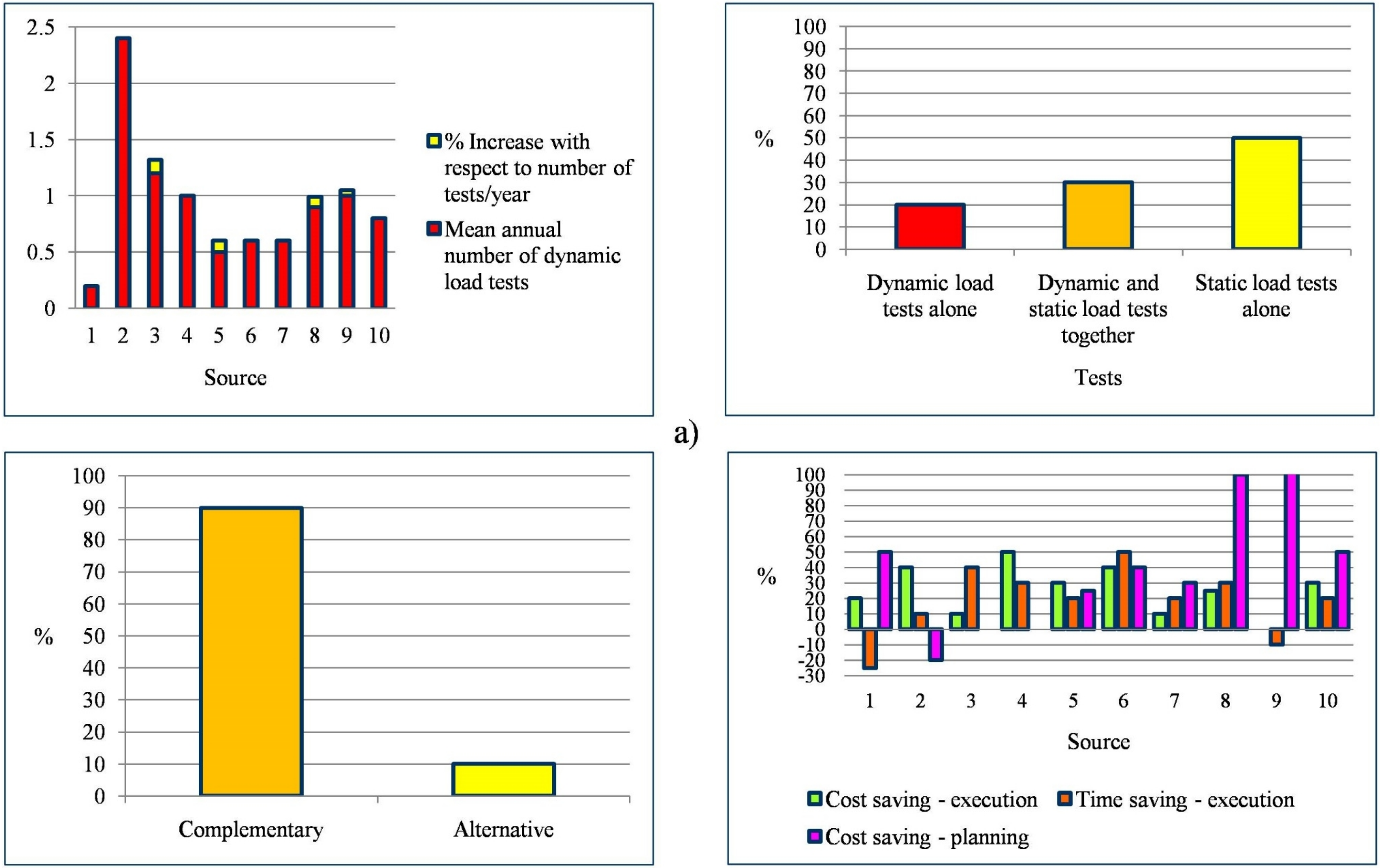
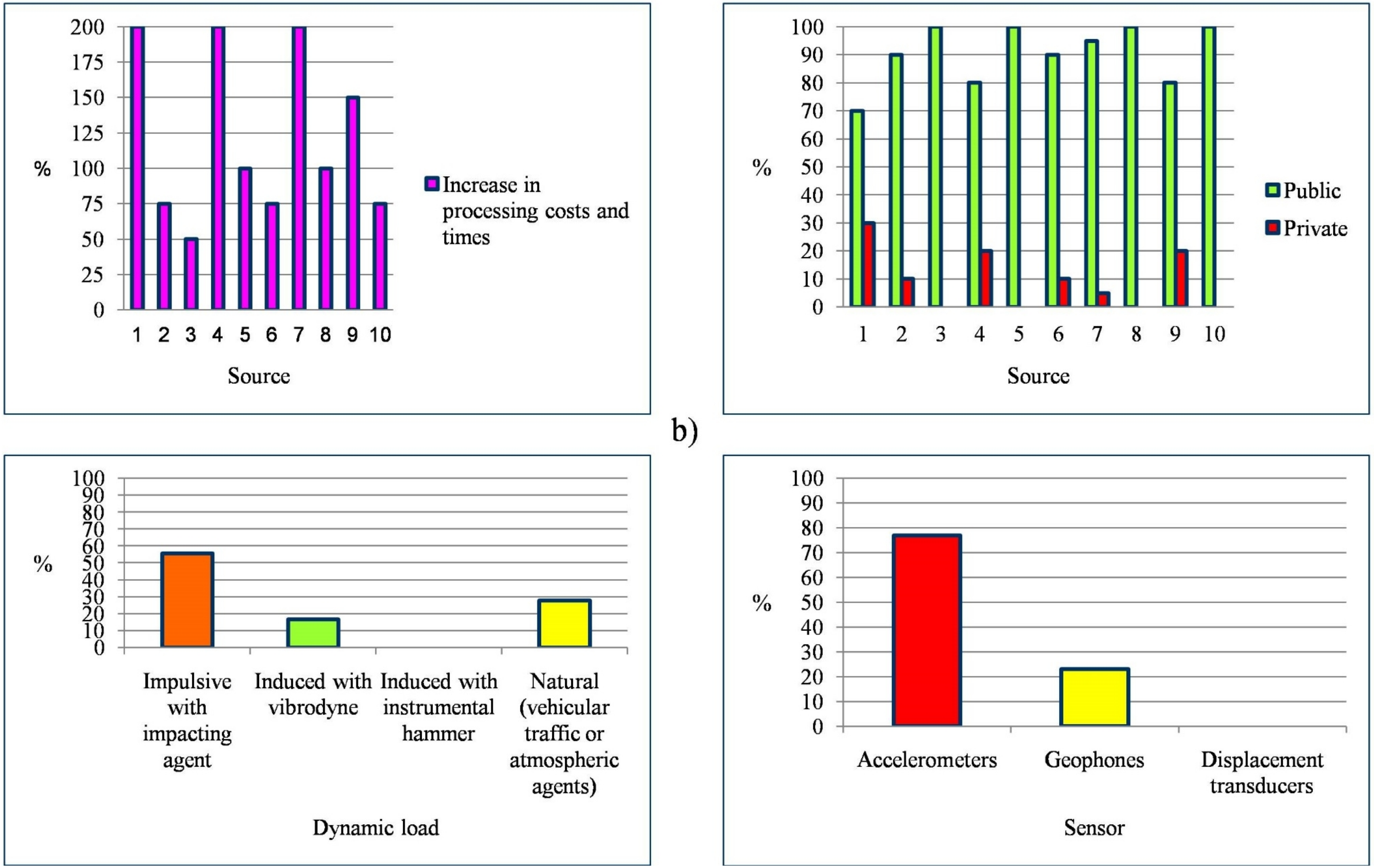


Figure 1a. Preliminary investigation results.
Mean annual number of dynamic load tests and their increase (upper left box).
Mean annual number of requests of dynamic load tests or static load tests or both together (upper right box).
Subordination (complementary or alternative) of the dynamic load test with respect to the static load test (lower left box).
Savings in costs and times of planning and execution of the dynamic load test compared to the static load test (lower right box).



b)

Figure 1b. Preliminary investigation results.
Increase in costs and processing times of the dynamic load test compared to the static load test (upper left box).
Public and private subjects commissioning the dynamic load test (upper right box).
Type of load used in the dynamic load test (lower left box).
Sensors used in the dynamic load test (lower left box).

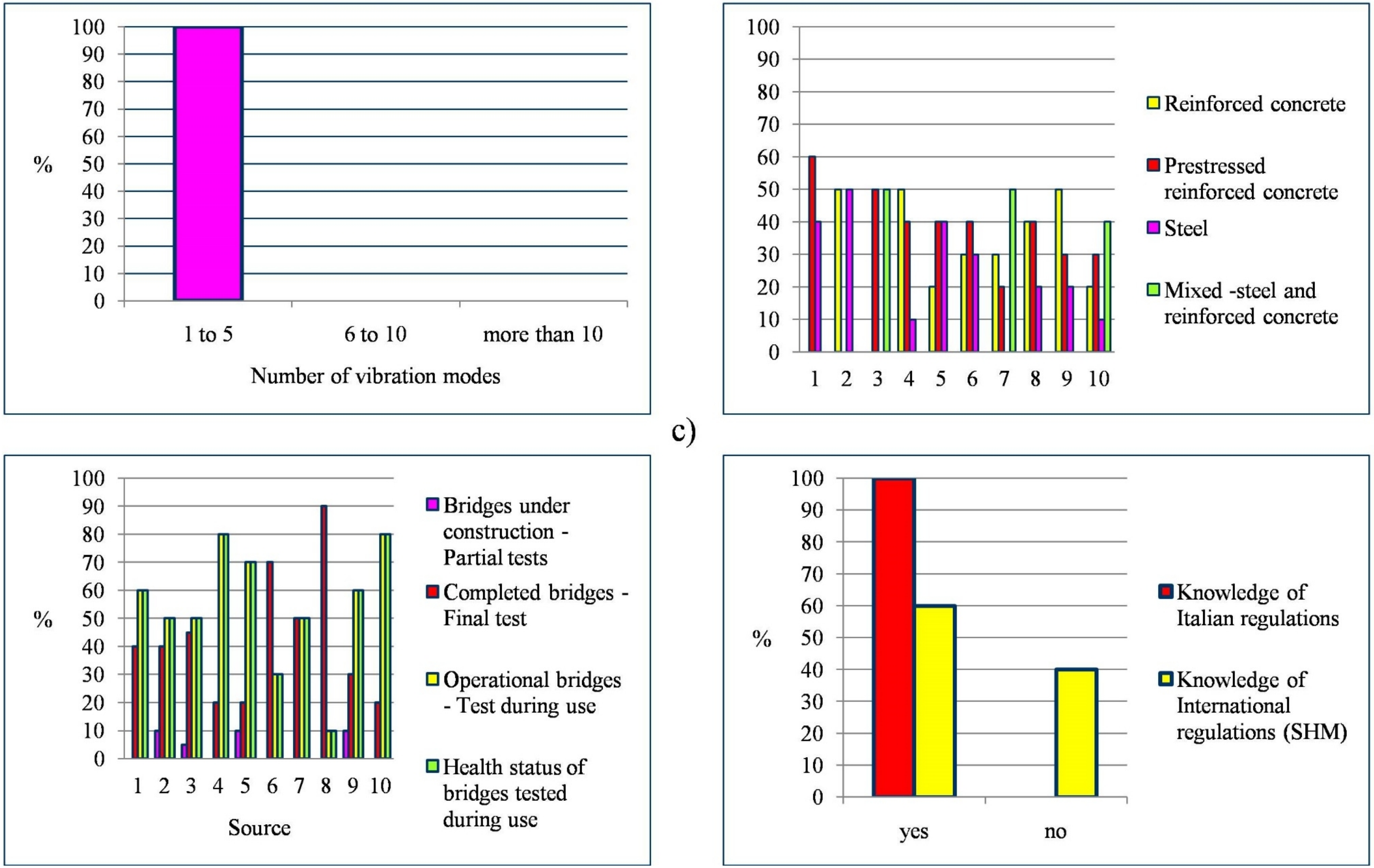


Figure 1c. Preliminary investigation results.
Vibration modes measured in the dynamic load test (upper left box).
Construction materials of the investigated bridges (upper right box).
Use status and health status of the bridges investigated with the dynamic load test (lower left box).
Knowledge of national and international regulations (SHM) (lower right box).

2. THE INVESTIGATED BRIDGE

The bridge, located in a seaside town in the province of Ferrara near a state highway (S.S. Romea), supports particularly intense local traffic in the summer or even deviation of vehicles from the aforementioned highway in the most critical moments. It was built in the late 1960s and is one of the first applications of prestressed reinforced concrete technology for medium-length bridges (D.M. 04.05.1990 1990). The bridge's original design reports and drawings from the 1960s, as well as the final test documents, were recovered (Perricone 1960-a-b; Prebeton 1960).

Geometrically it has a length of 5500 cm divided into three spans, each of which, simply supported, is ca. 1800 cm long (Figure 2). The central part consists of two lanes used for vehicular traffic while the lateral parts, overhanging the supports, constitute the pedestrian sidewalks (Figure 3).

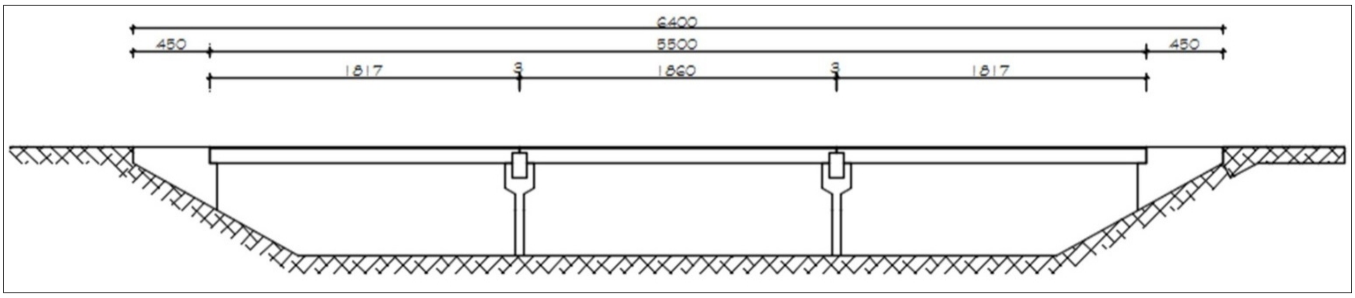


Figure 2. Longitudinal section of the bridge. Dimensions in centimeters.

The spans consist of three reinforced concrete beams, with rectangular section bxh 740x84 cm, connected by T-joints. The beams have been lightened by the inclusion at mid-thickness of nine longitudinal pipes of circular cross-section (ϕ 50 cm) arranged at regular intervals of 30 cm. The beams are prestressed with post-tensioned sliding-wire tendons, consisting of strands of 42 wires each (ϕ wire 6 mm), set in the ribs between the pipes.

The two piers in the riverbed have a solid reinforced concrete section: to these must be added the risers, also with solid section. The section of the main body of the pier has a depth equal to the base of the beam and a width of 168.5 cm. The two abutments have a height of 272 cm outside the riverbed, up to 345 cm including the foundation base, which has a thickness of 50 cm, and a ballast wall of height 78 cm, both also raised about 70 cm, and having the thickness of the main body of 60 cm. The foundation slab is supported by poles.

The geometries and dimensions are shown in Figure 3.

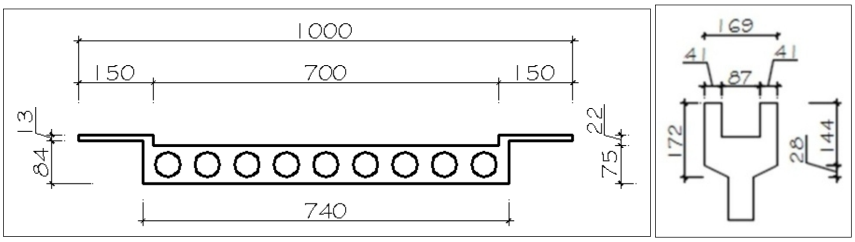


Figure 3. Cross section of the bridge and detail of the pier. Dimensions in centimeters.

3. STATIC LOAD TEST

To measure the deflections of the bridge, loading and unloading sessions were carried out with four trucks, each with a total weight of ca. 36 tonnes (Figure 4).

Figure 4. Trucks in operation during the static load test.

The measurement was based on the precision spirit leveling technique, the only one utilizable under the operational conditions: precision of the flexure measurement of ±0.1 mm. During the sessions the deflections were measured at significant points identified as eleven benchmarks (Figure 5) fixed rigidly to the upper surface of the beam slab: given the geometry of the deck, the measurements were limited to the central span only.
The measuring station consisted of a Topcon DL101-C digital level on a tripod, with the following characteristics: objective aperture 45 mm; magnification 32x; separator resolving power 3”; reading accuracy at the leveling staff 0.1 mm; compensator sensitivity 0.3”, equipped with an invar barcode staff of fixed length of 3 m. The station was located at one of the two ends of the carriageway in three different vertices (A, B and C) outside the area of the beams (Figure 5). Measurements were carried out for each loading and unloading session by performing the readings on the staffs on the deck benchmarks and on an external benchmark (CS) positioned near the vertices of the station.
During the readings the level was moved onto each of the three station vertices, thus allowing both collimation to the staff (even in the presence of the obstacles caused by the trucks) and redundancy of the measurements. The readings were digitally recorded but also transcribed in a field notebook.

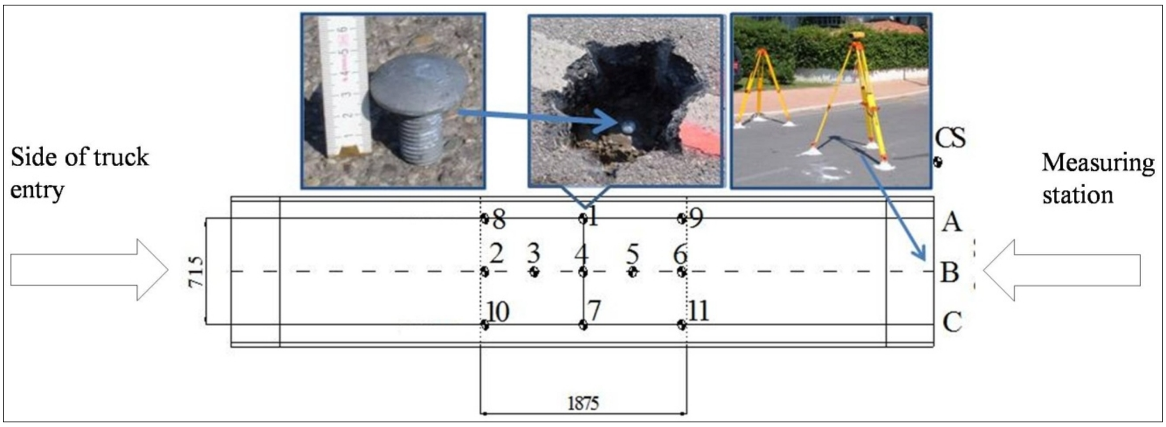


Figure 5. Positioning of the benchmarks. Level at the measuring station.

All the measurements were carried out in a single day. There were 16 sessions, each of them with conditions of unloaded bridge (subject to its own weight alone) and loaded bridge (subject to the weight of one or more operational trucks); in the latter case, the trucks were arranged on one side of the deck or on the whole structure, so as to create the most severe combinations imposed by law. At the end of a generic measurement session, a first check was performed to compare the numerical value of the measured deflection with the expected theoretical value. The measured and theoretical deflections of the benchmarks positioned at the center of the beam during the maximum load session are shown in Figure 6. The maximum deflection measured at the center (benchmark 4) was 10 mm compared with the expected theoretical 18 mm.

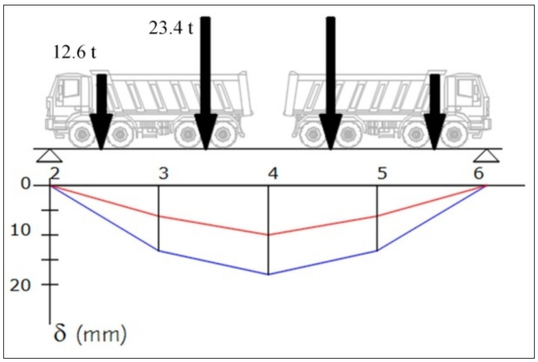


Figure 6. Measured (red) and theoretical (blue) deflections during the maximum load session.

4. DYNAMIC LOAD TEST

The dynamic load test was conducted using the impulse excitation method (Bien and Zwolski 2011), according to the specifications reported in the UNI 10985:2002 standard (UNI 2002), to acquire the frequency response function (FRF) of the first three vibration modes of the central beam. At the middle of the carriageway on this span, five nodal positions were identified in the longitudinal direction (Figure 7) for the installation of five piezoelectric accelerometers (numbered 1 to 5).

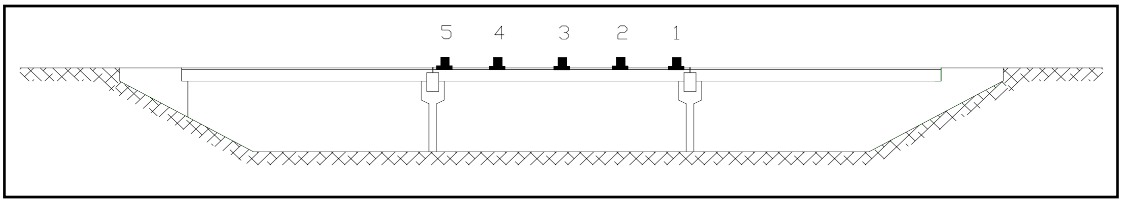


Figure 7. Measurement points and numbering of piezoelectric accelerometers.

This set-up was sufficient to reconstruct the dynamic response of the main span along the longitudinal axis since sensors 1 and 5, positioned over the supports (piers), allowed us to verify the existence of a constraint with the adjacent spans, the one in the center (3) to evaluate the first vibration mode and the other two at 1/4 and 1/3 of the span length to evaluate the second and third vibration modes: in total, five piezoelectric accelerometers with sensitivity between 1 and 0.1 V/g and peak-to-peak from ±5 to ±50 g. To complete the dynamic study of the structure in the transverse direction, two other nodal positions were chosen on the carriageway in correspondence of which were positioned two capacitive accelerometers, with sensitivity 1 V/g and peak-to-peak ±3 g. The measurement chain was completed by a portable PC, 16-bit digital analogue card (16 channels and 200 kS/s), ICP NI SCXI-1531 8-channel signal conditioning module, programmable gain and low-pass filter. The code for recording was created in the LabVIEW^{TM} rel.7.0 environment in Windows. The accelerometers were fixed to the structure with two-component epoxy glue (UNI 2007) applied to metal bases fixed to the extrados of the load-bearing structure of the span or on the head of the benchmarks used for the static load test.

The load was produced by the impulse of a two-axle truck with a total weight of 2 tonnes. Moving on the deck at a speed of ca. 30 km/h, it impacted on the upper part of the deck, causing it to vibrate, following a jump obtained with a 10-cm high artificial speed bump (Figure 8).

During the measurement, the speed bump was moved along the axis of the carriageway: in this way the impact zone could be positioned at one of the five recording positions so that, for each measurement session, one of the five accelerometers recorded the impulse and the others the vibrations of the structure (SIMO technique: Single-Input–Multi-Output; Allen and Ginsberg 2006) with "rowing hammer" arrangement (Cleland et al. 2013) extended to the structures. The SIMO technique was used instead of the MIMO (Multi-Input–Multi-Output) technique, since the latter was impracticable on account of operational limitations.

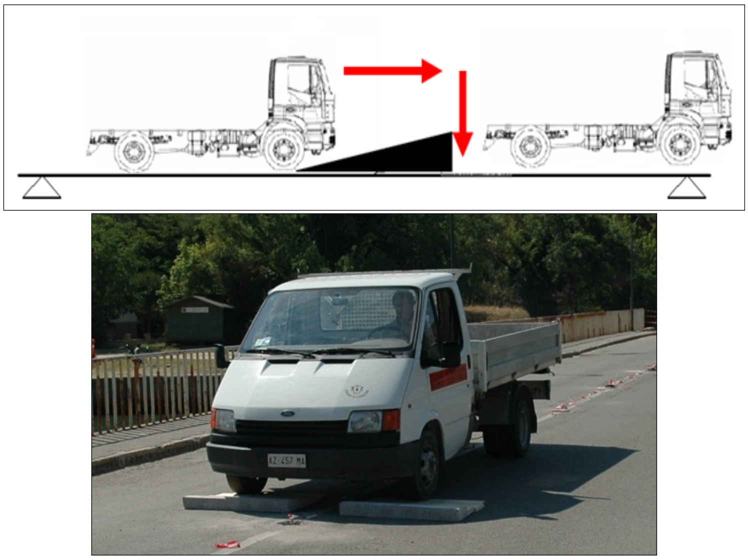


Figure 8. Application of the impulsive load.

The sampling frequency was set at 8192 Hz and at least three accelerometer recordings were made for each sampling session: this number, in relation to the intrinsic low-pass characteristics of the structure, made it possible to avoid the use of hardware filters without incurring aliasing.

The recordings made during the measurement campaign were analyzed in the time domain with a 6th-grade Chebyshev bandpass filter and 0.4-80 Hz cutoff frequencies: among those filtered, the pairs with coherence function greater than 0.9 were selected. The FRF obtained in the frequency domain consisted of a 5x5 matrix of "inertance or accelerance", ratio between the amplitudes of the ordinates of the fast Fourier transform (FFT) of the acceleration measurements and the external force: the latter was obtained by multiplying the acceleration of the sensor closest to the impact point by 50% of the mass of the truck.

The reliability of the "inertances" was assessed by comparing the equality of the symmetrical elements of the previous matrix. Finally, the single degree of freedom (SDOF) method was used to search for the modal parameters (Fu and He 2001). The results (Table 2) provided a first experimental vibration mode at 5.2 Hz and the following ones at 12.0 and 16.1 Hz. The deflections were measured in correspondence of the first frequency, reaching at node 3 a maximum amplitude of ca. 1 mm and a peak-to-peak of ca. 2 mm. The displacements transverse to the longitudinal axis measured at the edge of the carriageway had, again in correspondence of the frequency of 5.2 Hz, a maximum amplitude of 0.2 mm (and a peak-peak of 0.4 mm).

Table 2. Vibration frequencies of the bridge (in Hz).

f_1	f_2	f_3
5.2	12.0	16.1

5. FINITE ELEMENT MODELS

Three distinct finite element models for the central span of the bridge were created before the execution of the tests and after the dynamic load test. The first was for planning of the static load test, the second for planning of the dynamic load test and the third to refine the first two after the dynamic load test. To this end, the historical analysis and the geometric and material elements of the bridge, necessary for the realization of the FEM, were acquired in part through the original projects (Perricone 1960-a; Prebeton 1960) and partly through topographic surveys, on-site inspections, tests and verifications. For the model realized for execution of the static load test, a scheme consisting of "shell"-type elements both for the beam slab and for the sidewalks was adopted; a geometric configuration was imposed such as to ensure equivalence with the moment of inertia calculated at the time of the original design (0.2449 m^4 - Perricone 1960-a). The load conditions were those provided for by the latest Italian legislation (Min. LL.PP. 1980): each truck had a weight of 36 tonnes, 35% of which on the front axle and 65% on the back one. It should be specified that at the time of the initial testing the maximum deflection in the center was 8.95 mm (Perricone 1960-b). For the FEM realized for execution of the dynamic load test the beam slab of the span was modeled by means of a "mesh" of "shell" elements (with shell behavior), with height of 84 cm, connected to the sidewalks, also represented by "shell"-type elements of the same type and thickness of 12 cm. In the space between the supports a slab thickness of 20 cm was assumed. Standard characteristics of the materials were associated with these first two models; to the second was added a combination of seismic load (dynamic tremor alpha=0.0) associated with its own weight. The data processing of the second model provided a value of 8.07 Hz for the structure's first vibration mode.

Refinement of the finite element model of the bridge's central span was carried out based on knowledge of the FRF and on confirmation that the three spans were free of a joint constraint (simple hinge-support). Since the structure behaves like a slab inside which are inserted 50-cm diameter tubes to lessen the weight, the FEM was adjusted by flanking 9 hollow square-section "beam"-type elements with a 15-cm thick overlying base consisting of "shell"-type elements. The modeling of the sidewalk remained unchanged. The following equivalent characteristic values were attributed to the materials:

- Concrete: Elasticity module 312200 Kg/cm^2, Poisson coefficient 0.12, Transverse elastic modulus 139400 Kg/cm^2, Specific weight γ= 2500 Kg/m^3, α (coefficient of linear thermal expansion for temperatures up to ca. 100 °C) 1^{-5} $°C^{-1}$;
- Steel: Young's modulus 2100000 Kg/cm^2, Poisson coefficient 0.30, Transverse elastic modulus 807700 Kg/cm^2, specific weight γ = 7850 Kg/m^3, α (coefficient of linear thermal expansion for temperatures up to ca. 100 °C) 1^{-5} $°C^{-1}$, f_t (fracture tensile strength) 4300 Kg/cm^2, f_y (yield strength) 2750 Kg/cm^2, f_d (design strength = f_y/γ_m, γ_m=1) 2750, f_{dt} (design strength for thickness>40 mm) 2500 Kg/cm^2, σ_{adm} (allowable tension) 1900 Kg/cm^2, σ_{admt} (allowable tension for thicknesses>40 mm) 1700 Kg/cm^2.

The geometry remained unchanged. Five load combinations were considered: combination 1) unperturbed structure subjected to its own weight and prestressing; combinations 2) and 3) tremors propagating in the longitudinal and transverse directions; combination 4) verification of the results of the dynamic load test; combination 5) structure subjected to its own weight, prestressing and weight of the trucks of the static load test. The deflection at the center obtained with the refined FEM following application of the maximum test load (the four trucks) on the deck was 9.3 mm for the central benchmark; the value measured in the static load test was 10.0 mm (Table 3).

Table 3. Comparison of deflections at the center of the deck.

Deflection max	δ (mm)
Testing of bridge 1960s	8.95
FEM raw	18.0
FEM refined by the dynamic load test	9.8
Static load test	10.0

The frequency (5.23 Hz) of the first vibration mode obtained from the refined FEM following application of a tremor propagating longitudinally was equal to the experimental one calculated in the dynamic load test (5.2 Hz) (Table 4). The vibration amplitude along the direction orthogonal to the plane of the deck in the former case was 1.5 mm, while the one measured in the dynamic test at the same node was 1 mm.

Table 4. Vibration frequencies at the center of the deck.

First vibration mode	f (Hz)
FEM raw	8.07
FEM refined by the dynamic load test	5.23
Dynamic load test	5.2

6. COMPARISONS

The comparison between the static and dynamic load tests was extended to the performances and costs, taking into consideration the following aspects:

a) planning of the tests;
b) number and installation of sensors;
c) loads, times of execution;
d) closure of the bridge;
e) processing of the measurements;
f) cost of the equipment,

and attributing to each of them a score from 0 to 10, increasing with the inconveniences and difficulties: the higher total score, expressed in sixtieths, indicated the more penalizing of the two tests.

6.1 Planning of the tests

Both tests required a preliminary phase of measurement planning to identify the number and location of the benchmarks and sensors, for preparation of the equipment, for planning of the times and modes of execution. For the static load test the theoretical deflections were calculated a priori according to the loads, number of trucks and weight per axle of the individual truck. In the dynamic load test, an initial finite element model (FEM raw) was created to approximately estimate the vibration frequencies. The planning was carried out by specialized personnel who participated in the measurement operations and subsequent data processing. For these reasons it was decided to assign an almost equivalent score to the planning of both tests.

6.2 Number and installation of sensors

Execution of the tests required choosing a different type and number of sensors:
- 12 benchmarks for the static load test;
- 7 accelerometers for the dynamic load test.

Installation of the benchmarks required removal of part of the road surface, perforation of the slab, injection of the resins, fixing of the benchmark and waiting for the resins to harden. At the end of the test the road surface was repaired with consequent loss of the benchmarks as they were covered with asphalt.

The accelerometers were fixed by means of two-component epoxy glue either to metal bases attached to the extrados of the load-bearing structure of the span or to the head of the benchmarks used for the static load test: thus, no additional costs were required. Hence, a higher score was assigned to the static load test.

6.3 Loads, times of execution and closure of the bridge

In the static load test, four fully loaded trucks weighing 36 tonnes each were used. For safety reasons, since the maximum load condition was exceptional for the structure, the four trucks were made to enter and exit the bridge from one side only and at different times. Moreover, the elastic deformation of the deck subjected to the static load was not immediate: to eliminate the risk of permanent plastic deformations, the measurement times were lengthened to allow assessment of the return of the deflections to zero (unloaded bridge condition). In the dynamic load test a single truck (weighing 2 tonnes) was used without maneuvers and the accelerometers directly recorded the vibrations of the deck: thus, there were no forced delays during the measurements. Both tests required that the bridge be closed to both vehicular and boat traffic: the static load test for a whole day, the dynamic load test for only half a day. Thus, a high score was assigned to the static load test and a low one to the dynamic load test.

6.4. Processing of the measurements

The measurements collected during the two tests were post-processed. In the static load test, the leveling data were processed easily and quickly even though a careful statistical analysis was required due to the presence of redundant measures. In the dynamic load test, the accelerometric measurements required a longer, more demanding analysis: thus, a higher score was attributed to it.

6.5. Cost of the equipment

Both the equipment used in the static load test (Topcon DL101 level and three-meter invar staff) and that used in the dynamic load test (piezoelectric and capacitive accelerometers, 16-bit digital analogue card, signal conditioning module and recording software) had comparable purchase and maintenance costs: for this reason, the same score was attributed to both tests.

A summary of the aspects of the comparison and of the assigned scores is shown in Table 5.

Table 5. Summary of aspects of the comparison, scores and calculations.

Aspects	Score (out of 10)	
	Static load test	Dynamic load test
Planning	6.5	7
Number and installation of sensors	6	2.25
Loads and execution times	9	2
Closure of the bridge	8	4
Measurement processing	3	10
Equipment costs	5	5
Total (out of 60)	37.5	30.25

CONCLUSIONS

The preliminary survey revealed that the mean annual number of dynamic load tests performed over ten years was one, with a maximum of two, obviously without any significant increase. The highest percentage of test requests (50%) referred to static load tests alone; indeed, nine out of ten sources stated that the two tests are complementary: only one source declared the dynamic load test alternative to the static load test. For the execution and design costs and for the times, the sources indicated that the dynamic load test gave an average saving of 30%, which reached 40% for the planning costs: only three reported an average reduction of less than 20%. The negative aspect regards the costs of processing the data recorded in the dynamic load test, which doubled for some sources. In the rare cases where a dynamic load test was required, the client was a public subject (90%). From an operational point of view, the sources opted mainly for an impulsive (60%) or natural (30%) dynamic load; the sensors used were usually accelerometers (in 70% of cases), “limited” to measuring up to 5 vibration frequencies. The bridges monitored with the dynamic load test were made of prestressed (35%) or normal (30%) concrete, in operation for years (54%) or to be tested at the end of construction (42%): the test results showed just over 50% healthy bridges. Finally, all the sources declared that they knew the Italian regulations on the testing of bridges while less than half (40%) also knew the international ones.

Regarding the results of the two tests, the maximum deflections measured in the static load test and those deduced from the finite element model refined by the dynamic load test showed the same value (10 mm deflection in the static load test vs. 9.8 mm in the dynamic load test). However, in terms of structural response, only the dynamic load test allowed identification of the bridge’s dynamic properties, i.e. the first three vibration modes (5.2, 12 and 16.1 Hz) and the constraint conditions.

The performance and cost comparisons showed practically equivalent costs for the planning of the measurements while the static load test required a larger number of sensors, load trucks, personnel (both on site and for planning) and a longer duration. The dynamic load test was disadvantageous only for the processing of the measurements while the equipment costs were practically the same. For the case under study, the dynamic load test was less expensive than the static load test.

We conclude by pointing out that bridges currently in operation were designed to withstand static loads and thus are still assessed with static load tests. In reality, a bridge is a structure subjected exclusively to dynamic loads in the course of its working life and thus should be tested and then monitored with dynamic loads. It should not be surprising then that, together with the SHM technique presented in this study, other methods integrating geodetic measurements and accelerometric measurements (Xu et al. 2002; Roberts et al. 2004-a; Moschas and Stiros 2011; Moschas and Stiros 2013; Xiong et al. 2017) or geodetic measures with LVDT-linear variable differential transformer

measurements (Chung et al., 2018; Liu et al., 2018) or optical and LVTD methods of real-time displacement comparative measurements of bridges (Lee et al., 2006; Busca et al., 2014) or only geodetic measurements via total robotic stations with high sampling rates (Li et al. 2004; Stiros and Moschas 2014; Yu et al. 2017) are becoming more common for testing or monitoring particular bridges, such as stayed or rigid ones (Roberts et al. 2004-b), of high (Vazquez et al. 2017) and medium capacity (Yu et al. 2014). Such methods offer accuracies comparable with those of precision spirit leveling (Moschas and Stiros 2015), as well as real-time monitoring (Yu et al. 2016).
For the testing of a newly built bridge, the Italian Standard requires a static load test: therefore, the dynamic load test can be performed only in addition to the static load test. In the post-construction monitoring of operational bridges, as recommended by the SHM standard the decline in stiffness of the bridge can be ascertained in practice by estimating only the modes of vibration. An eventual deformation (deflection) can be calculated a posteriori from an updated finite element model (FEM): in this case, the dynamic load test is an alternative to the static load test.

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