Dynamic characterization of a five spans historical masonry arch-bridge

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ABSTRACT: This paper presents the studies carried out on a five spans masonry arch bridge, the Viaduct of Vara, inside the marble caves close to Carrara. The bridge was strengthened in recent time due to the failure of a pier. Two sets of dynamic tests were performed, the first before the strengthening, the second after the strengthening was carried out. A finite element model of the structure was made for preliminary studies. Dynamic tests were necessary to validate numerical results. After describing the way the tests were performed in situ and the instrumentation used for collecting the data, a comparison is made between numerical and experimental modal parameters (before and after the strengthening) of the structure. Signal processing techniques used for modal parameters extraction focus on the use of wavelet transforms, which are a very powerful tool in case the signals are non stationary and with a low signal to noise ratio.

1 INTRODUCTION

Scheduled dynamic tests are useful for structural safety monitoring and for checking serviceability conditions.

Dynamic tests have several advantages: at first they are carried out on the whole structure, thus giving information about its global behaviour. More dynamic tests are non destructive techniques, and they can be performed with limited suspensions to the use [Gentile].

Up to now experimental dynamic tests have been experienced in situ on reinforced concrete bridges or steel-concrete girder bridges [Fasana et al., Peters and De Roeck]. In masonry constructions structural safety monitoring via dynamic tests (e.g. via modal parameters checking) is much more complicated than in steel structures or reinforced concrete structures. Masonry structures are very massive and stiff, so it is more difficult to hold the structure vibrating in a way that is easy to measure by the instruments. This operating difficulties outcome in subsequent signal processing troubles. In fact the recorded time histories are non stationary, with low signal to noise ratio and often corrupted by noise.

Nevertheless operating and analytical difficulties, dynamic identification techniques give their very contribution for studying masonry structures, validating and supplementing numerical results achieved via finite element model. The anisotropy and the variety of the material used in the past for constructions, the fact that the quality of these material was not certified, the construction technology linked to local uses lead finally to a structure whose mechanical behaviour can be hardly summarized in a few parameters. For these reasons even the most refined finite element model needs to be validate and, eventually, updated.

2 HISTORICAL NEWS

This paper deals with the studies carried out on the big Vara Viaduct close to Carrara, Fig. 1. In the second half of XIX century inside the marble caves of Carrara many infrastructures were built for updating the transportation of marble blocks from the caves to the harbour.

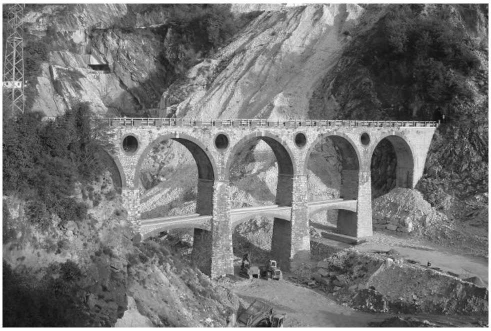


Figure 1: the big Vara Viaduct today

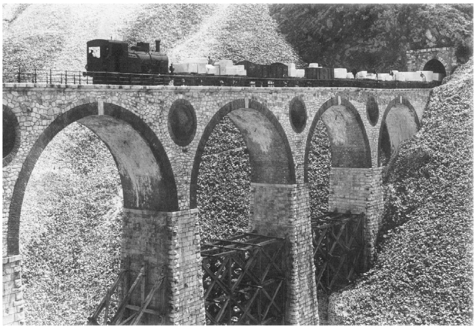


Figure 2: Pier propped up after failure in 1913 *(Historical Record Office Carrara)*

The Vara Viaduct was built between 1887 and 1890 and it became soon a symbol for its region. Born as a railway bridge it was changed to a road bridge about in 1960. The viaduct is a five spans masonry arch bridge. Each arch spans about 16m for a global length of about 100m. The deck is 40m high over the ground; it curves and it slopes about 7%. The lower arch in the middle spans were built in 1932 during the restoration works due to the failure of the fourth pier for replacing the temporary wooden props, see Fig.2 [Carboncini].

In recent years the fourth pier failed again and it was necessary to close the bridge to the traffic for allowing new restoration works. In this occasion the behaviour of the bridge under a seismic load was studied. For this goal the knowledge of the bridge's modal parameters is crucial but easy at all to achieve due to the structural complexity. In fact the material used for the construction do not have homogeneous mechanical properties. It is not known what was used to fill the hangings. Moreover the geometry is complex (curved and sloped). For all these reasons even the results obtained by the most careful numerical models need to be checked experimentally. For this purpose the dynamic test described in paragraph 3 were performed.

3 EXPERIMENTAL TESTS

Two sets of experimental dynamic tests were performed, the first before the bridge was strengthened (January 2002), the second after the strengthening has been carried out (October 2006).

The proof were outlined both as shown in Fig.3, so that a meaningful comparison of the results was possible.

Dynamic loads were produced by a weighted lorry driving on a transversal step and impacting on the deck, see Fig.4. The truck axis weighted 7100 kg (the front one) and 18680 kg (the rear one). the transversal step is shown in Fig.5.

During the experimental tests the bridge was dynamically excited in different positions, moving the step as shown in Fig.3 (positions denoted by letters A to I). For each test the time histories were recorded simultaneously in three sections (denoted with numbers 1 to 19 in Fig.3) in three directions (Vertical, Transversal and Longitudinal referred to the roadway axis).

Eight HBM inductive accelerometers (frequency range 0 to 100 Hz, measure range 200 m/s^2 and resolution 0.02 m/s^2) were used both the times for detecting vibrations, see Fig.. The time histories were recorded by an eight channel HBM MGC Plus data logger and a laptop.

During the tests in 2006 two seismometers HBM B21 and B2 and six PCB 393C pre-amplified piezoelectric accelerometers were used as well (accelerometers frequency range 0.025 to 800 Hz, resolution 1000 mV/g), see Fig.7.

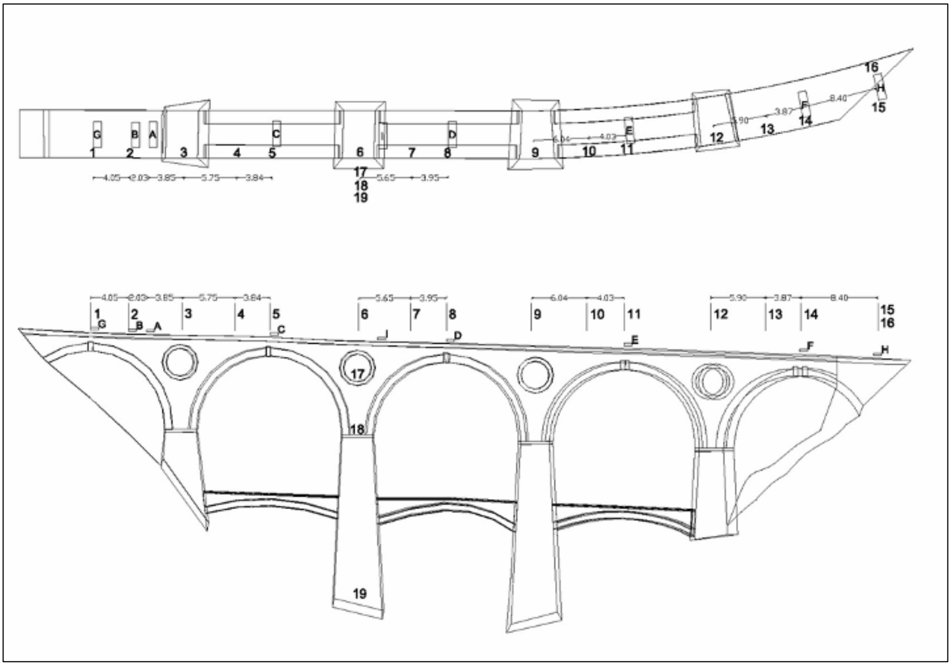


Figure 3: Outline of the way the instruments were placed. Letters denote the step position, numbers denote the accelerometers positions.

Figure 4: the lorry “launched” for the jump

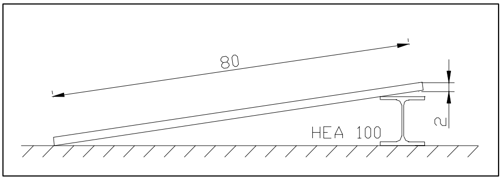


Figure 5: step geometrical features

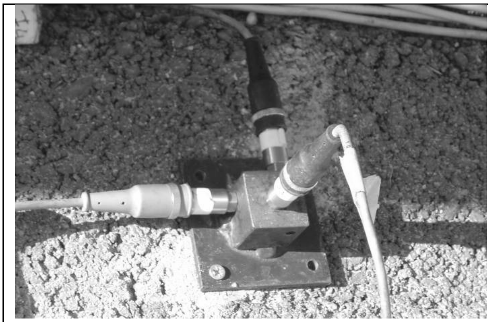


Figure 6: HBM inductive accelerometers

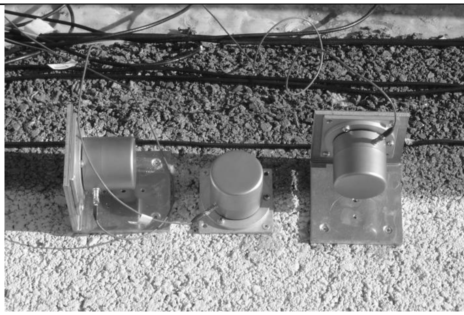


Figure 7: PCB piezoelectric accelerometers

4 SIGNAL PROCESSING TECHNIQUES

The dynamic time histories recorded during experimental tests can be analyzed with different techniques. Classical techniques in structural dynamic are mostly based on Fourier transform, nevertheless, in the last years, some interesting alternative techniques, borrowed from other sectors of the engineering, have been suggested, like the ones based on wavelet transform, considered in the present work.

The way Fourier transform is got is reminded in the following.

Let *f(t)* be a periodical function and let *T* be its period. If *f(t)* is n-derivative *f(t)* can be expanded as a Fourier series:

$$f(t) = \sum_{-\infty}^{+\infty} c_n e^{i\omega_n t} \tag{1}$$

and c_n is given below:

$$c_n = \frac{1}{T}\int_0^T f(t) e^{-i\omega_n t} dt \tag{2}$$

$$\omega_n = \frac{2\pi}{T} \tag{3}$$

The calculation of the Fourier coefficient c_n is an integral transformation joining *f(t)* to a series of complex numbers (*finite Fourier transform)*.

If *f(t)* is a non periodic function defined in the range (a,b) it could be treated as a periodic function whose period is *T* = *b-a* and matching in the range (a,b) with the original function. In this way the finite Fourier transform may be extended to non-periodic functions.

For the non periodic functions defined on an infinite range another approach is necessary. The approach is the *integral Fourier transform, F(ω)* obtained from Fourier series when the period T tends to infinity.

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-i\omega t} dt \tag{4}$$

Finally many discrete efficient formulations stands for numerical calculation of Fourier transform *(fast Fourier transform)*.

As previously stated in the last years wavelet transforms have become more and more used.

Wavelet transforms are systematically used in various scientific fields, like analysis of climatic data, analysis of financial indexes, cardiac monitoring, identification of statistic fluctuations in turbulent motions, characterization of fracture surfaces, compression of images and so on.

The wavelet analysis uses compact (*let*) oscillatory functions (*wave*), deriving their name from the form of a fundamental function Ψ, the mother wavelet, used to build such functions (fig. 8).

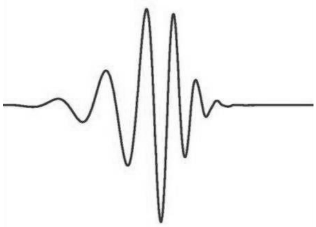


Fig.8: Daubechies mother wavelet.

The wavelets are basis functions, of a real or complex variable, produced by translation and expansion of the mother wavelet, Ψ, which is a regular function, defined on a limited interval and equal to zero outside the interval, characterised by null average and finite energy [Addison 2002]. These mathematical properties make the wavelets particularly effective in the analysis of non periodic, intermittent, transitory or noisy signals.

In analogy to Fourier transform, they exist continuous (CWT) and discreet (DWT) wavelet transform and the relative inverse transform. Moreover, unlike Fourier transforms,, that associates to a temporal impulse an infinite spectrum in the frequency domain, wavelet transform associates to a function defined in a short time interval, a function defined in an analogously short time interval in the transformed domain.

The continuous wavelet transform of a function $f(t)$ is defined as

$$T(a,b) = w(a)\int_{-\infty}^{+\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{5}$$

where a is a scale parameter, b represents the translation on the time axis, $w(a)$ a normalization function that assures that the wavelets have the same energy for every value of the scale parameter and the star means conjugate complex. The scale parameter has a meaning analogous to the cartographic scale: high values of the parameter give global information on the signal, associated with low frequencies, while small values give local information on the signal, associated with the high frequencies.

5 NUMERICAL ANALYSIS

Before the first sets of dynamic tests the bridge was studied via a sophisticated finite element model realized with *Cosmos/M v. 2.7* software. The model, shown in Fig.9 is made up of 13160 nodes and 8895 solid elements.

The first six modes of vibrations were calculated together with their respective modal participating factors. Fig. 10 shows as an example the second mode of vibration.

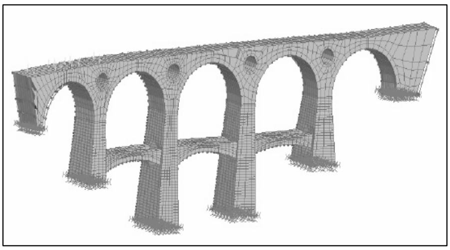


Figure 9: the finite element model of the bridge

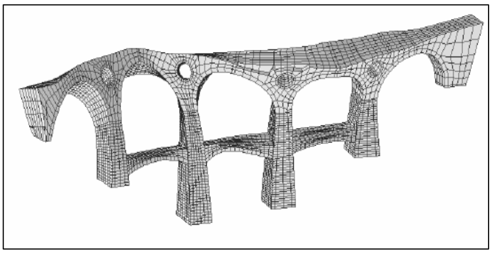


Figure 10: the second mode of vibration

The numerical model used for the studies carried out before the strengthening was validated with experimental results achieved after the first experimental tests.

6 EXPERIMENTAL RESULTS

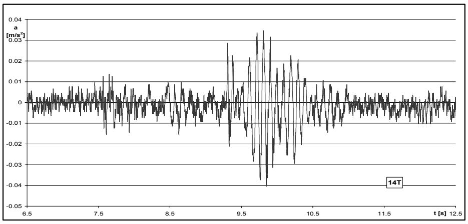
The choice of the wavelet function to be used for the analysis depends upon the peculiarity of the problem to be solved. The presence of noise and the need of signal featuring selection at low frequencies suggested the wavelet has these properties:

- a band pass spectra with a low frequencies range
- a scale function with very narrow low-pass spectra

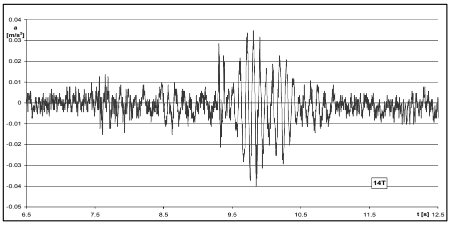
The Daubechies function satisfies both these properties.

6.1 Analysis after first experimental dynamic tests

The time histories collected during the first set of dynamic tests (in 2002 before the bridge was strengthened) were low amplitude, short time lasting and deeply corrupted by noise (see Fig.11)



a)



b)

Figure 11: example of two time histories recorded in 2002. a) transversal acceleration, b) longitudinal acceleration

For each time recorded history resonance frequencies were identified. Only the values pointed out in more than 70% of the whole accelerograms were selected as natural frequencies, while the ones pointed out in a less percentage were ascribed to operating working conditions.

In Fig.12 the Fourier spectra and the wavelet spectra of the same signal are compared. Wavelet spectra emphasize low frequencies much more than Fourier spectra, thus allowing an easier detection of the resonance frequencies.

In Table 1 numerical and experimental resonance frequencies are compared. The comparison is summarized by the index E_ω settled by expression (6)

$$E_\omega = \frac{\left|\omega_{n_{num}i} - \omega_{n_{\exp}i}\right|}{\omega_{n_{num}i}} \tag{6}$$

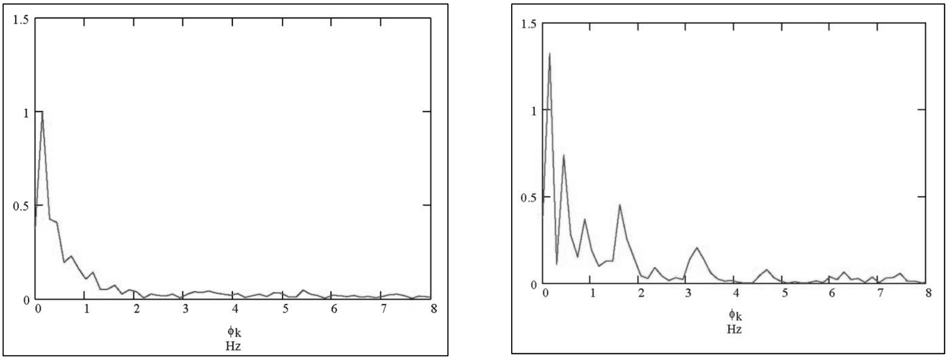


Figure 12:Fourier spectra (left) and wavelet spectra (right) of a same signal. Wavelet spectra allow an easier detection of resonance frequencies

Table 1:comparison between numerical and experimental resonance frequencies. The vibrating direction refers to the road axis.(Transversal and Longitudinal)

Mode n°	Vibrating direction	frequencies (Hz)		$E_{\omega i}$ (%)
		numerical	experimental	
1	T	3.53	3.55	0.57
2	L	4.75	4.88	2.74
3	T	5.54	5.51	0.54
4	T	5.86	5.92	1.02
5	L	6.26	6.54	4.47
6	T	7.16	6.97	2.65

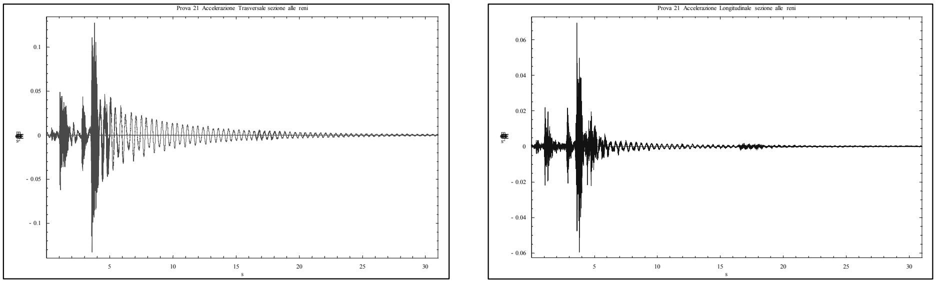
The comparison shows a very good agreement between numerical and experimental values. In particular, the index E_{ω} minor than 5% means that the finite element model do not need any updating at all.

6.2 Analysis after second experimental dynamic tests

The time histories recorded during the second experimental tests in 2006 are of better quality (see Fig. 13) due to:

- piezoelectric accelerometers have a better sensitivity than inductive ones
- the signals were amplified before the data logger collected them so that the signal to noise ratio was increased

Fourier analysis has been performed. Spectra results of good quality allowing an easy selection of resonance frequencies (see Fig.14). Finally in Table 2 are summarized the identified resonance frequencies.



a) *b)*

Figure 13: example of two time histories recorded in 2006. a) transversal acceleration, b) longitudinal acceleration

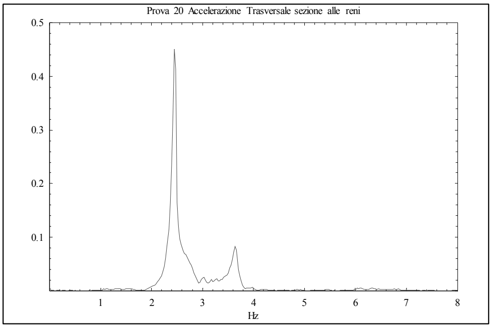


Figure 14: Fourier spectra of a transversal accelerogram

Table 2: Resonance frequencies detected after the 2006 dynamic tests.
The vibrating direction refers to the road axis. (Transversal and Longitudinal)

Mode n°	Vibrating direction	frequencies (Hz)
1	T	2.45
2	T	3.65
3	L	5.89
4	L	6.22

7 CONCLUSIONS AND FURTHER DEVELOPMENTS

At this step of the research some important conclusions can be drawn as for the combined use of wavelet transform and Fourier transform for modal parameters detection.

The good agreement between theoretical and experimental data, resulting in values of error index E_ω lesser than 5% for all the detected modes, confirms the correctness of the proposed methodology, stressing also that cross check of the results is quite unavoidable, especially when geometrical, physical and mechanical parameters governing the structural responses need to be calibrated.

Fourier transform is very effective technique in dynamic structural identification, provided that the structural response is clear. On the contrary, when the recorded signals are weak or contaminated by noise, the ability of modal identification of the wavelet transform give much more satisfactory results than the Fourier transform.

Although sometimes used for dynamic identification of r.c. bridges (Fasana et al., 1999; Lardies et al., 2004), wavelet transform represents, in consideration of its high sensibility in the low frequency range, of its effectiveness in demodulation, of its accuracy in manipulation of transitory and aperiodic signals, a very powerful tool also in the field of the dynamic identification of stiff structures, like historical masonry constructions.

The following phases of the research will be finalized to improve the proposed method, using wavelet transform to evaluate modal damping and modal deflection shape. Moreover the finite element model will be updated to take into account changes in dynamic behaviour due to the reinforcement works.

REFERENCES

Addison Paul S. (2002) "*The Illustrated Wavelet Transform Handbook Introductory Theory and Applications in Science, Engineering, Medicine and Finance"* IoP

Fasana, L. Garibaldi, E. Giorcelli, S. Marchesiello, M. Ruzzene *"A Road Bridge Dinamic Response Analysis by Wavelet and Other Estimation Techniques"* XVII IMAC Orlando (Florida), USA, 8 − 11 Febbraio 1999

C. Gentile, "Ponti e Viadotti: Concezione, Progetto, Analisi, Gestione", *Centro per la Formazione Permanente del Politecnico di Milano, Dipartimento di Ingegneria Strutturale, atti dei corsi di aggiornamento* 29 giugno - 3 luglio 1998, 28 giugno – 2 luglio 1999, Pitagora Editrice Bologna

Nuno Manuel Mendes Maia, Júlio Montalvão e Silva *"Theoretical and Experimental Modal Analysis"*, Research Studies Press LTD, Baldock, Hertfordshire, England 1997

B. Peeters, G. De Roeck *"One year monitoring of the Z24-Bridge: environmental effects versus damage events"* Earthquake Engeneering and Structural Dynamics, 30: 149 − 171, 2001

Seppälä O. "From Fourier Transform to Wavelets", Aprile 2001

Staszewski W.J. (1998) "*Wavelet based compression and feature selection for vibration analysis"* Journal of Sound and Vibration 211(5): 735 − 760

Valens C. *"A Really Friendly Guide to Wavelets"* c.valens@mindless.com 1999