RESEARCH ACTIVITY ON EXPERIMENTAL ASSESSMENT OF SEISMIC RESPONSE OF MASONRY ARCADES

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ABSTRACT :

The analysis of seismic vulnerability of old masonry structures is very hard, especially when already damaged by earthquakes. Modelling of the structure is often very hard and the numerical analysis does not give any realistic information. Therefore the experimental analysis is not only advisable but represent the unique way to improve the understanding of the structural behaviour. Seismic actions cause cracks in the masonry, and as a result the reduction of the stiffness, which implies changes in the dynamic characteristics and apparent non-linear behaviour. These effects can be pointed out by analysing seismic recordings or by means of shake table. In this paper the preliminary results of the analysis of shake table tests are shown, and technical limits and technological failures are discussed.

KEYWORDS: Shake-table tests, Masonry Barrel Vaults, Seismic vulnerability

1 INTRODUCTION

The analysis of seismic vulnerability of old masonry structures is very hard, especially when already damaged by earthquakes. In this case, in fact, they show lower and lower resistance to seismic events. The seismic sequence that interested Umbria and Marche in Italy, in 1997-1998, pointed out that a structure can be subjected to a series of shocks of medium intensity with a short time interval between them, so that repair works cannot be done. In such cases the modelling of the structure is very hard and the numerical analysis does not give any realistic information, so the experimental analysis is not only advisable but represent the unique way to improve the understanding of the structural behaviour. Seismic actions cause cracks in the masonry and as a result the reduction of the stiffness, which implies changes in the dynamic characteristics and an apparent non-linear behaviour. Direct recordings of seismic events and shake table tests represent the unique tool where linear and non-linear behavior of structures can be studied.

Shaking table tests as a tool for better understanding the dynamic behavior of structures under seismic loads, received considerable attention in recent years. The limits of this technique are connected to its high cost and to the relatively low value of the pay-load (i.e. the weight of the specimen to be tested on the shake-table). Of course, due to the reduced shake-table payload, the weight of specimens does not allow full-scale tests of very large buildings, so tests on reduced scale specimens have been conceived. The Buckingham theorem suggests that reduced-scale structures require, to preserve the similitude, a material characterized by values of damping and density difficult to match simultaneously or even singularly. In many cases, the weight of full-scale structures requires unrealistic scale factor (lower than 1:5).

Another limit is related to the peak displacement. At the ENEA facility it is ± 12.5 *cm*, so if the design earthquake is characterized by peak ground displacement (PGD) > 12.5 *cm*, two solutions are possible in order to have comparable results of tests and numerical analysis: i) specimens on shake-table are full-scale and time-histories are filtered to match PGD < 12.5 *cm*; ii) specimens are reduced-scale and spectra shifted in frequency for the mechanical similitude.

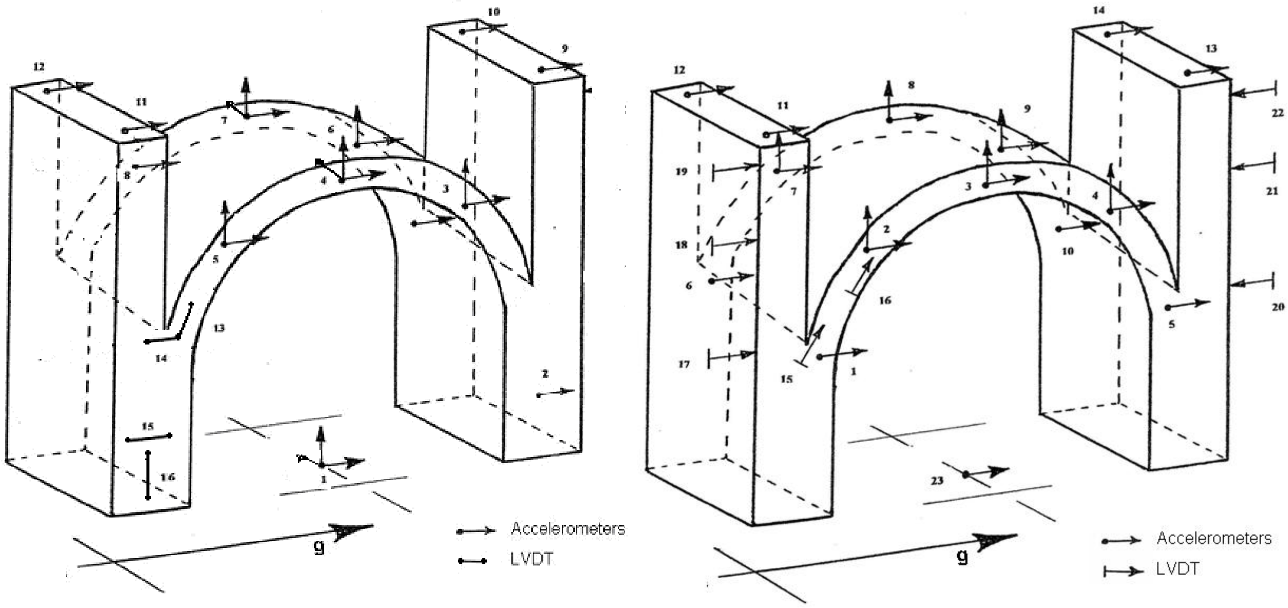
The scope of the present study is to correlate the results from experimental campaign to the vulnerability of real buildings also testing consolidation techniques. In order to do that is necessary to characterize the dynamic characteristics of existing structures and to correlate the theoretical results to in situ dynamic identification and to the laboratory tests that have been performed.

2 THE RESEARCH PROJECT

ENEA, the Federico II University of Naples and the Superintendent to Cultural Heritage of Caserta and Benevento, Italy, cooperate since the early ’90s to study consolidation techniques to improve the seismic bahaviour of the church of San Rocco in Guardia Sanframondi and the tower bell of the San Francesco church in Montesarchio. In particular, experimental tests on a shake-table, sited at the Casaccia research center of ENEA, were scheduled. The tested specimens were 2 masonry arches made of yellow tuff, typical of Campania, and poor mortar. The research activity was subdivided in the following steps:

a) Seismic tests and characterizations of the first tested specimen up to the collapse;
b) Seismic tests and characterizations of the second tested specimen up to a fixed damage level (b1); to consolidate the structure (b2); repeat the test up to the collapse(b3);
c) Tests and devices to scaled specimens of the arches;
d) Adapt designed tests and devices to scaled specimens of the monuments.

As a starting test an experimental program consisting on a series of shake table tests carried out on the masonry arch, by using real acceleration time histories having the same shape but with increasing amplitude, has been set up. Up to now only steps a) and b) were completed.
The first specimen was tested on November, 1993. Tests on specimen 2, scheduled a few months later, were instead executed almost 3 years later, on May 1996. Unfortunately, the original electronic recordings were lost and only paper shits and images documented the recorded time-histories of the acceleration obtained for the first specimen. All the diagrams were digitized (Rinaldis et al., 2008) and time-histories at the measurment points were recovered.



a) b)

Figure 1 Sensors layout in masonry barrel vault specimens 1 (a) and 2 (b).

The tested specimens are shown in Figure 1. The semicircular intrados of the arches had a radius of 200 *cm*. The depth of the ring was 20 *cm*. The arches were supported by two walls, whose height and thickness under the springing were 70 *cm* and 50 *cm*, respectively. The walls continued above the springing in order to contain the back-fill, with a thickness of 35 *cm*. The effective angle of embrace was 120°. The width of the structure was equal to 150 *cm*. Spandrel walls were not present, this specimen representing the central portion of a barrel vault. The masonry was composed by yellow tuff and poor mortar, and reproduced the most common masonry tyoe used in South Italy, especially in Campania. The back-fill was composed by bags filled with material deriving from the crushing of tuff blocks. The weight of the first specimen was 51.0 *kN* while the back-fill weighted 14.1 *kN*. The specimen was constrained to the shake table by means of a steel frame, composed by C bars placed around the wall basement and bolted to the shake table. The total weight of this additional elements was of 5.0 *kN*, so the total weight on the table was equal to 70.1 *kN*. The weight of the second structure was inizially lower, the back-fill weighting only 8.5 *kN*. Then, after some tests, the back-fill was increases up to 14.1 *kN* and the total weight was the same of the first specimen (Tab.1).

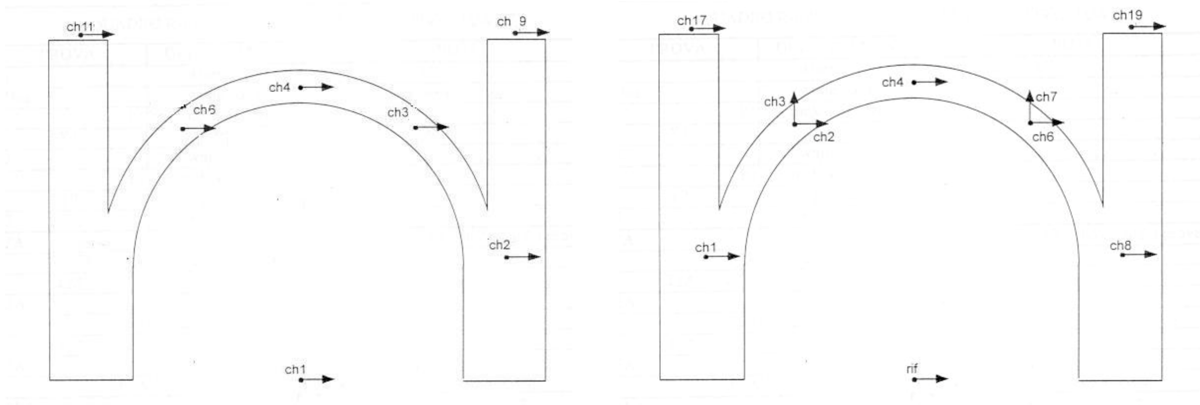


Figure 2 Sensors layout on the arch surface for specimen 1 (a) and specimen 2 (b).

Table 1 Tests scheduling and results of the dynamic analysis

FIRST ARCH				SECOND ARCH	
Char. and PGA Value of the previous test (Lateral)	Mode I Hz	Mode II Hz	Mode III Hz	Mode I Hz	Char. and PGA Value of the previuos test
Unloaded arch	10.0	17.2	19.1	6.1	C1 Loaded (d. l. 0.85 *t*)
C 1 loaded arch (1,41 ton)	8.7	13.2	20.6	6.1	C1bis
C 2 – 0.03g	8.0	12.7	20.0	4.9	C2 pink1 – 0.1g
C 3	7.7	12.0	20.5	4.9	C3 pink2 – 0.2g
C 4	7.8	12.0	20.8	4.7	C1a Loaded (d. l. 1.41 *t*)
C 5	7.9	12.1	21.1	4.2	C2a pink1 – 0.1g
C 6 – 0.06g	7.7	12.1	20.4	3.8	C3a pink2 – 0.2 g
C 7	7.8	12.2	20.6	4.0	C1r Arch repaired
C 8	7.7	12.2	20.4	4.0	C2r 0.1g
C 9	7.7	12.0	20.0	4.0	C3r 0.2g
C 10 – 0.09g	7.6	12.1	20.0	3.6	C4r 0.3g
C 11	7.25	12.3	-	3.6	C5r 0.4g
C 12 – 0.12g	7.6	12.3	21.2	3.2	C6r 0.5g
C 13	7.5	12.4	21.0	2.9	C7r 0.6g
C 14 – 0.15g	7.3	12.3	21.0	2.9	C8r 0.7g
C 15	7.4	12.5	21.3	2.9	C8rb 0.7g
C 16 – 0.18g	6.14	12.8	20.5	2.7	C8ratt 0.7g
C 17	5.8	12.6	20.2	2.2	C9r 0.7g
C 18 – 0.21g	5.6	12.6	20.0		
C 19	5.5	12.4	19.7		
C 20 – 0.24g	5.18	13.5	19.8		
C 21	5.3	13.6	20.5		
C 22 – 0.27g	5.0	14.0	19.7		
C 22a	5.0	14.2	19.2		
C 22b – 0.30g	4.9	14.2	-		

To compare results obtained at some test on the two different specimens, Fig. 2 shows the channel numbering at the walls (top and bottom), and arch springing and key. The specimens were tested at the shake table laboratory of ENEA Casaccia Research Centre. The table used is 4.0*4.0 *m* size, has six degrees of freedom and is driven by means of a control system (LMS) in the frequency range]0, 50[*Hz*. The maximum absolute values of acceleration, velocity and displacement are 3*g*, 5 *m/s* and 12.5 *cm*, respectively.

The masonry barrel vaults were instrumented by using 20 accelerometers ENDEVCO 224C with a frequency passing band between 2.0 and 15000 *Hz*, and sensitivity equal to 10 *pC/g*. Eight LVDTs (displacement transducers) with a maximum displacement of 2.54 *cm*, a sensitivity of 0.2 *V/mm*, and a frequency passing band up to 50 *Hz*, were also used (Buffarini & al., 1997). Two main differences are noticeable in the two configurations (Fig. 1). First of all, specimen 2 was monitored mainly in the lateral direction while specimen 1 was instrumented with triaxial sensors both at the reference point (position 1) and on the arch; this was because of the tests plan (see Tab. 1 for the first arch) that provided tests in all spatial directions (lateral, longitudinal and vertical) as well as the possibility to measure energy dissipation in directions different from that of the input. Secondly, on specimen 2 LVDTs were positioned to measure the displacements of the two walls supporting the arch.

3 PRELIMINARY PHASE

As already said, the recorded measuements contained in the images were digitized (Rinaldis & al., 2008) and time-histories recovered at the measurment points. Furthermore, records were processed to obtain power spectral density (PSD) and the cross spectral density (CSD) for each significant couple of sensors. Tests were organized in such a way that each of them was followed by a white noise test, of 0.05 *rms* peak, to characterize the dynamic behavior of the structure (Tab. 1). From PSDs and CSDs, still available as print out, the changes in the first three frequencies, modal shapes and damping were pointed out.
The tests on the second vault were instead recorded on the computer and a backup of the all files (input and recordings of all channels – accelerometers and LVDT) was immediately made. Unfortunately, the input record on the shake table had not the same time origin of the other channels. To solve this problem all time-histories were processed and time-shifted to maximize the cross-correlation function and the measured coherence (Rinaldis et al., 2008). All the time histories were recorded at the sampling time of 0.02 *s*. Each record have been analysed in time and frequency domain, computing the PSDs S_{ii}, and the CSDs, the coherence function and the transfer function.
The purpose of building two similar specimens was also to verify the repeatability of the experimental procedure. Actually, the obtained results show that just the building the specimens positioning procedure on the shake-table provides arches with very different dynamic characteristics (Tab. 1 and Fig. 3), even though the arches had been built at same time, by the same workers and using the same materials.

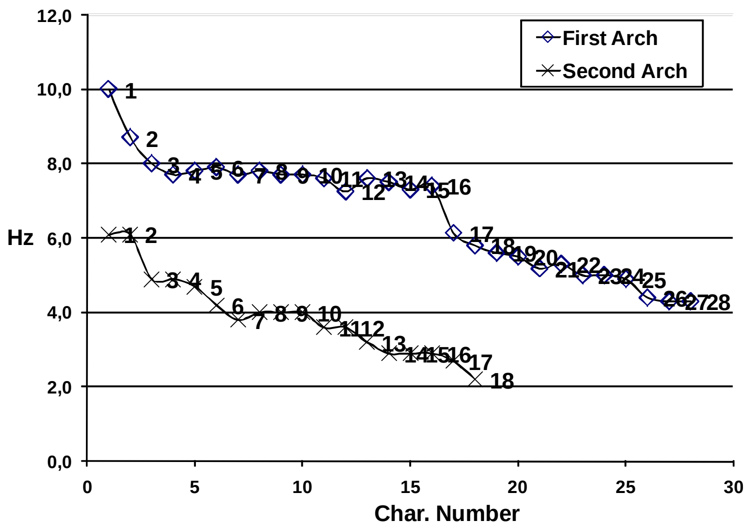


Figure 3 Variation of the first resonance frequency.

Then the effect of increasing dead load (8.5 to 14.1 *kN*) has been analysed by subjecting the specimen to a selected pink noise (0.1-0.2 *g rms*, 8-16 *Hz*). The results are shown in Fig. 4, where PSDs, CSDs, transfer functions and coherences of channel 1 and the reference point are compared. As expected as the test proceeds PSD and CSD show peaks at lower and lower frequencies when the frequency interval were measurements coherence is suitable decreases. This interval is [2-7] Hz for C1, C2 and C3 and reaches [2-4] Hz for C3A.

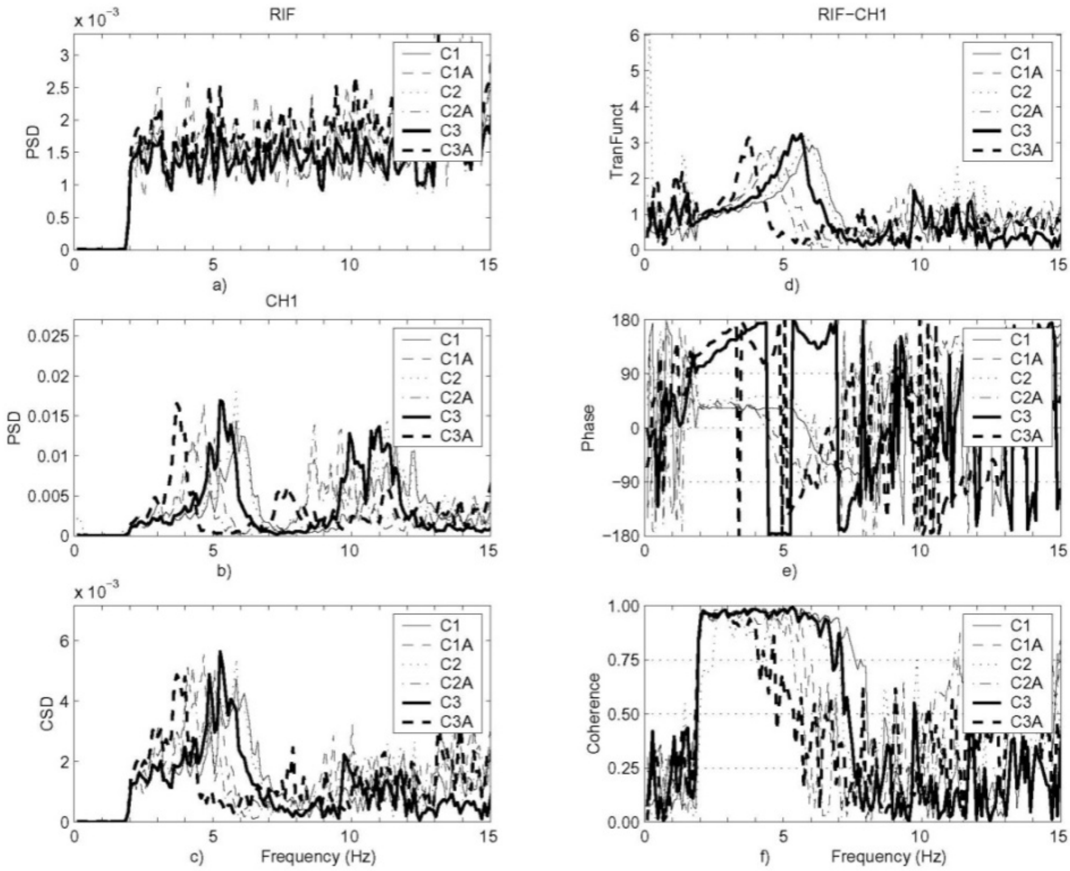


Figure 4 Comparison between characterization obtained during the preliminary phases (light load and pink noise) of specimen 2 test

4 DYNAMIC TEST PROCEDURE

A study of the arches dynamic characterisation was performed between each test and the next in order to evaluate the changes in the dynamic properties and to analyse the effects of the damages. Changes in the dynamic properties, such as resonance frequencies, modal shapes and damping were analysed (Tab. 1). The structure was subjected to the acceleration time history recorded at Sturno (all components for specimen 1 and the WE component specimen 2 and Bisaccia – specimen 1 – on November 23rd, 1980, during the main shock of the Campano-Lucano Earthquake, Italy. A preliminary filtering at low frequencies up to 2.0 *Hz* was necessary to avoid displacements larger than the maximum allowable for the shake table. During the test of specimen 1 a three-dimensional excitation was applied; so soon after the first test by means of the scaled record of Sturno (TA11) three characterization were performed (one to each axes) followed by the scaled record of Bisaccia (TA11b).
The second specimen was tested in two steps. In step 1 the cumulative effect of an increasing pink noise excitation, charging the arch with different dead loads, was studied. Fig. 4 shows how the increasing in the table excitation affects the dynamic parameters of the specimen. It is worth pointing out the difference in the specimen payload (8.5 *kN* on the second specimen, 14.1 *kN* on the first one); pink noise tests with peaks of 0.1*g* and 0.2*g* *rms* were repeated after changing the payload (up to 14.1 *kN*). In step 2 the structural dynamic behaviour was analyze, subjecting the arch to successive base acceleration time histories, having the same shape but increasing intensity. The idea was to excite the specimen with a known pink noise and to study the increase of damaging of the structure, then to repair it and to repeat the test. The excitation was applied in the longitudinal direction in order to have a plane stress state. First of all, the dynamic characterisation of the undamaged structure was performed (Cr1). Then a series of tests with increasing intensity was carried out. In

the first test (Tr1) the acceleration time history was scaled in order to have 0.03*g* (Specimen 1) and 0.1*g* peak (Specimen 2 – Clemente et al. 1999), respectively. Specimen 2 was also testing after repairing, in this case (Tr2) the peak was 0.2*g* and so on up to a maximum peak value of 0.7*g*, about twice the effective peak acceleration recorded at Sturno, which was equal to 0.34*g*. The test with a peak of 0.7*g* (Tr7) was interrupted because of the fall of some stones and was repeated (Tr8).
Each test was followed by the dynamic characterisation, in order to evaluate the changes in the properties and to analyse the effects of the damages. The characterisations were performed by soliciting the structure with a white noise input. The appearance of the cracks was pointed out during the tests. As usual, the arches went to collapse by forming pin joints at cracked sections, i.e., by turning into a mechanism (Clemente, 1998). During the test of Specimen 2 the experimental analysis was interrupted before the collapse, while the test of Specimen 1 was continued up to the collapse. The first resonance frequency is plotted, against the characterisation number. As one can see, its reduction was not progressive but concentrated in some phases of the experimental analysis.

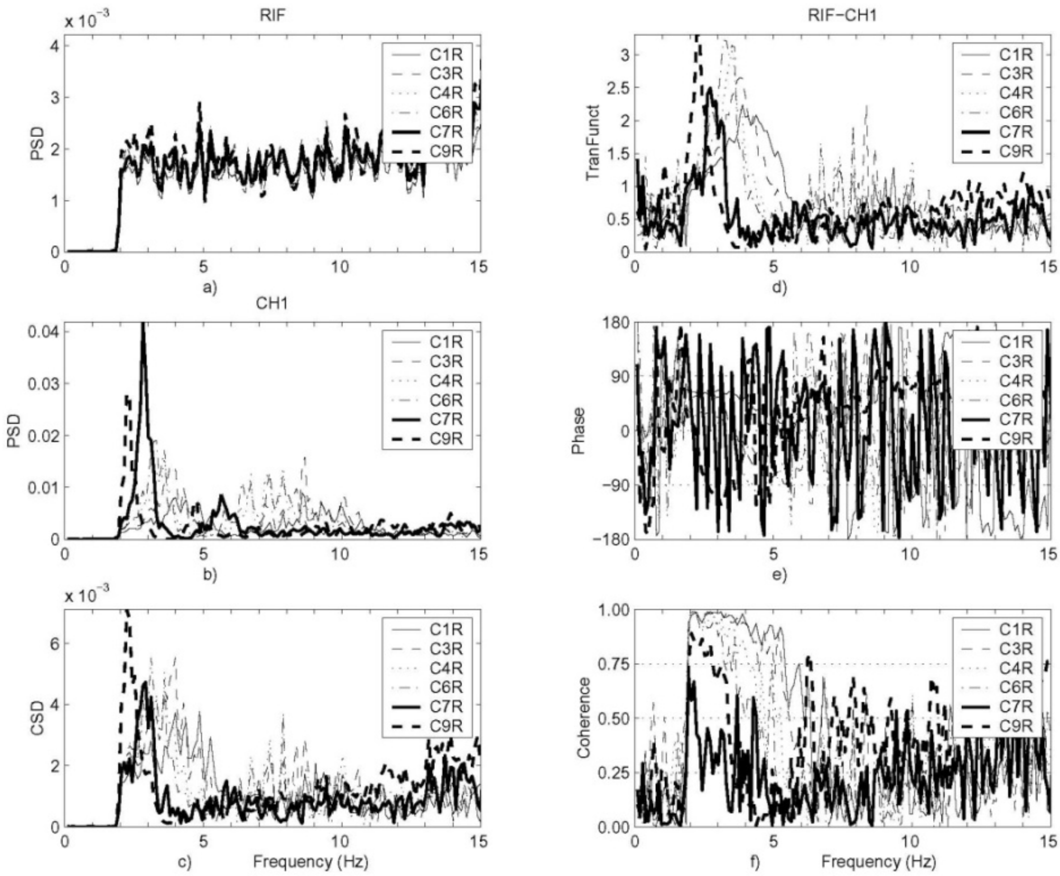


Figure 5 Comparison between characterization obtained during Specimen 2 test after repairing (r) REF-CH1

In more details, with reference to Specimen 2, tests Tr3, Tr6 and Tr8 determined very important reductions of the first resonance frequency, while no significant changes were found after any other test. The final value was about half the initial value. The changes identified in the dynamic properties were related to the appearance and the increasing of damages in the structure (Clemente et al., 1999) . Spectra relative to Cr1 show structural amplifications in the frequency intervals 4 to 5 Hz and 9 to 10 Hz (Fig. 5b). The coherence function is almost unitary (in the analyzed frequency interval), the phase factor is not always significant for all the couples of sensors. Fig. 5 shows that for the couple ch1–reference the phase factor is effectively not suitable. Anyway from the analysis of the cross-spectra relative to sensors ch1 and ch8 we deduce that the modal shapes associated to the first frequency is anti-symmetric while the second modal shape is symmetric (see coherence function in Fig. 6).
The laboratory tests have drawn the attention to some evidences between the two arches. Both the arches show a typical behavior where the trend of the recorded frequencies decreases with respect to the seismic intensity

(the coefficient "*c = ap/g*") the arch has been subjected approximately according to an exponential curve. Nevertheless the dynamic curve of the first arch decreases more quickly than the curve of the second arch. Probably this effect is due to the different program of the shaking sequences to which the arches have been subjected during the tests: in the tests of the second arch an in-creasing pink noise has been coupled to the Sturno input, with the result to anticipate the damage of the arch (Baratta et al., 2008).

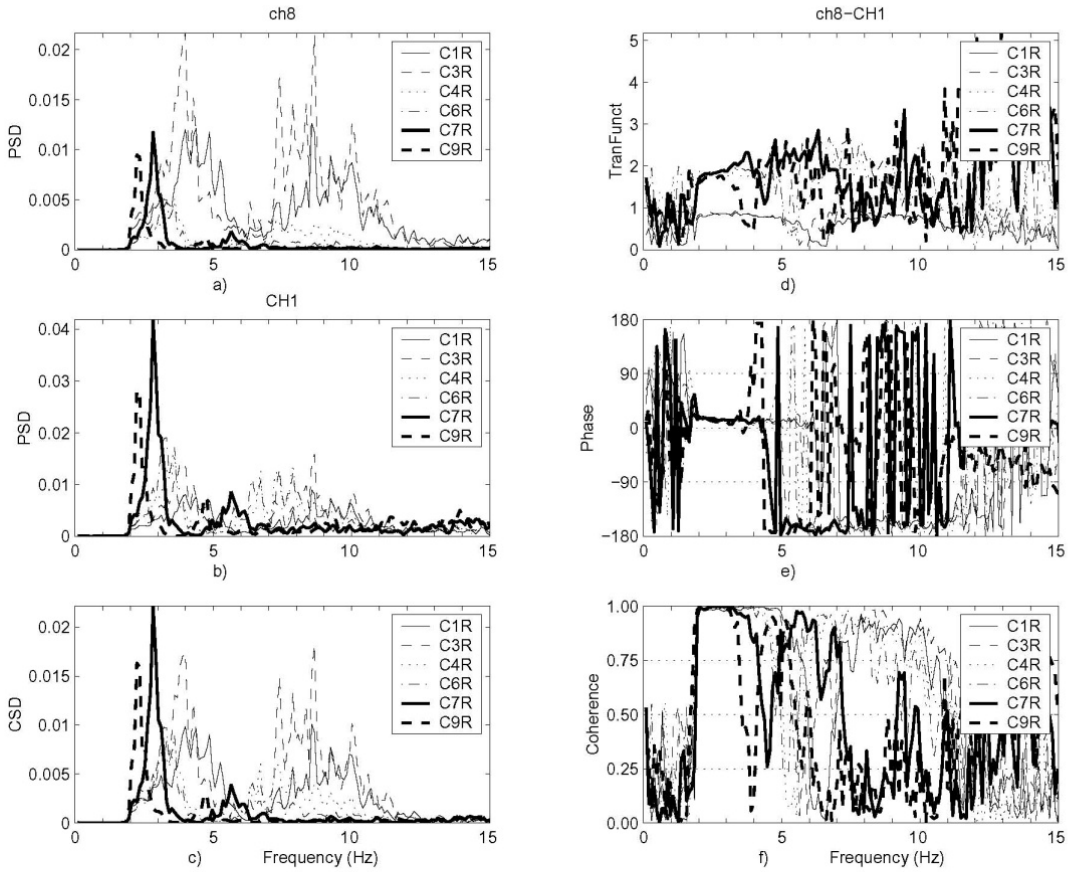


Figure 6 Comparison between characterization obtained during Specimen 2 test after repairing (r) CH8-CH1

The laboratory tests have drawn the attention to some evidences between the two arches. Both the arches show a typical behavior where the estimated frequencies decrease with reference to the seismic intensity (the coefficient "*c = ap/g*" – Baratta et al. 2008). Nevertheless the dynamic curve of the first arch decreases more quickly than the curve of the second arch. Probably this effect is due to the different program of the shaking sequences followed in the two cases: in the tests of the second arch an increasing pink noise has been coupled to the Sturno input, with the result to anticipate the damage of the arch.

5 CONCLUSIONS

The dynamic tests of two masonry barrel vaults subjected to successive base acceleration time histories, having the same shape but with increasing amplitude, were analysed.
The analysis on the first structure seems to indicate that differences between the mechanical parameters of the Specimens, probably due to the time lasting between the two experiments, largely influenced their dynamic behaviour. In preliminary analysis of single test results CSD of records obtained at the same position (channel 4 for both Specimens and channel 1 and reference respectively for Specimen 1 and 2) seem to indicate that different mode are excited. Of course much more detailed and complete analysis are needed to confirm these results.

The results obtained pointed out that the decrease of the first resonance frequency was not progressive but concentrated in three phases. On the second structure the first cracks corresponded to a reduction of 18% in the first frequency, while the final frequency was almost half the initial value. Changes in damping were also significant. A more detailed analysis of this aspect is needed.

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