13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3211

DYNAMIC RESPONSE AND SEISMIC VULNERABILITY OF A HISTORICAL BUILDING IN ITALY

D. RINALDIS[1], M. ÇELEBI[2], G. BUFFARINI[1], P. CLEMENTE[1]

SUMMARY

The CEDRAV building in Cerreto di Spoleto, originally a monastery, was built in the 14th century on the top of a rock ridge. The two events occurred on September 26th, 1997, with magnitude M_s=5.4 and M_s=6, respectively, caused damages to it. This study includes analyses mainly related to the part of the data acquired corresponding to tests and configurations using temporary deployments. Results from analyses of representative seismic response data acquired from the building specific permanent deployment are also included. The building is very complex and rigid. In fact, translational and torsional frequencies are close to one another, coupling occurs and damping ratio is low. Coupling of the frequencies and the low damping are two factors that cause beating effect when shaking is strong enough. In the case of this study, the shaking levels are not large but yet the building is affected by beating effect. For example, the approximate beating period is computed for the June 28th, 2000 earthquakes as (taking T_1 = 1/9.7 = 0.104 s, and T_2 = 1/10.4 = 0.096 s) T_b = 2.5 s, observable in the time history plots. Although analysed data clearly exhibits the dynamic behaviour of the complex and non-symmetric structural system of the CEDRAV building, additional analyses of the extensive data set would be very useful and is recommended.

INTRODUCTION

The purpose of this study is to describe a unique case of the complexity in assessing seismic behaviour of the historical built environment in Italy. The rich cultural heritage that has evolved in Italy over the centuries is spread throughout the rural as well as urban areas. Each case, while exhibiting a unique historical attraction, also brings the problem of their seismic vulnerability into focus. While seismic hazard for the historical buildings has always been a concern, it has been more so since San Francesco Church in Assisi was damaged during the 1997 Umbria-Marche earthquakes.

To completely understand all the vulnerability aspects of the cultural heritage, multidisciplinary studies are needed, including those involved with art, architecture, earth science and earthquake engineering. Such vulnerability analyses must include clear identification of the structural systems, structural dynamic characteristics and the knowledge of the characteristics and mechanical properties of the materials used to

[1] ENEA – Casaccia Research Centre, Rome, Italy, dario.rinaldis@casaccia.enea.it
[2] U.S. Geological Survey, Menlo Park, CA, USA, celebi@usgs.gov

construct the original historical buildings. Thus, given the particular difficulty in classifying and defining the characteristics of the structural systems of the historical buildings, the vulnerability study efforts appears very complex when compared to regular modern structural systems. Furthermore, in such cases, the particular building under investigation may have been altered repeatedly over time. This can be a critical issue because, for example, the building may be founded on older buildings that got buried over. Thus, considerable attention has to be given to assess which types of structural systems are the most dominant in the area under consideration and how these types of structures can be matched, if at all, with modern day structural classification for the sake of assessment of material characteristics. Therefore, the particular architectural and structural history of each structure adds complications to the assessment of its seismic vulnerability. In any case, an improved and better educated attempt in evaluating the vulnerability of the historical buildings, as well as finding strengthening methods to reduce their seismic risk, can be made if its dynamic response characteristics are more carefully estimated. In fact, what is aimed at is the evaluation of the seismic vulnerability and the assessment of the degree of damage that a structure with a specified typology could suffer, when subjected to a seismic action with specified characteristics. The evaluation of seismic vulnerability is then linked to the knowledge of the dynamic behaviour of buildings during a seismic event.

The performance of structural systems during seismic events can be better understood if arrays of seismic sensors can be deployed throughout the structures in order to record their responses during strong shaking events. Thus, it is essential that, parallel to establishing integrated arrays of instrumentation installed to assess the ground shaking level (free-field arrays) and the structural dynamic behaviour during significant seismic events, a series of ambient-vibration tests could be conducted. Generally speaking, the importance of ambient-vibration tests and consequential analyses is that it gives the basic elastic properties of the structure. During strong earthquakes, the structure may experience non-linear behaviour. Thus, if the parameters of linear behaviour are known beforehand, it may be easier to extrapolate the non-linear behaviour. This process is very difficult for old, slightly or severely damaged masonry or monumental buildings because it is quite difficult to establish their elastic properties. For such cases, even for very small excitation, non-linear behaviour may be experienced by the structure. However, it is possible to approximate their behaviour with a pseudo-linear approach.

THE BUILDING

The Centre for Anthropological Documentation and Research of Nerina Valley building [CEDRAV], in Cerreto di Spoleto, originally a monastery, was built in the 14th century on the top of the ridge a “scaglia rossa” rock formation. The building is irregular both horizontally and vertically (Figs. 1a-d). The first floor is partially embedded into ground and is mostly founded directly on rock. The N-W part of the building is not well defined. It is assumed that in that area, the second floor is partially founded on rock. This assumption is based on the discovery of a large cistern in the extreme South part of the building.

The walls of the building are stone masonry. The first level is divided into 3 small approximately square rooms and a larger rectangular room, from NE to SW, used for archiving documents. All rooms follow an irregular plan. The first level shows, more or less, the same subdivision (there is one small room missing and the remaining two are merged and the archive room is subdivided into two rooms). Then one more rectangular room in the NE top and 3 in the NW part have been added. The third level, where a new section in the NE part of the building has been added to a room distribution roughly similar to the second floor. The addition consists of a small church covered with a cross vault ceiling.

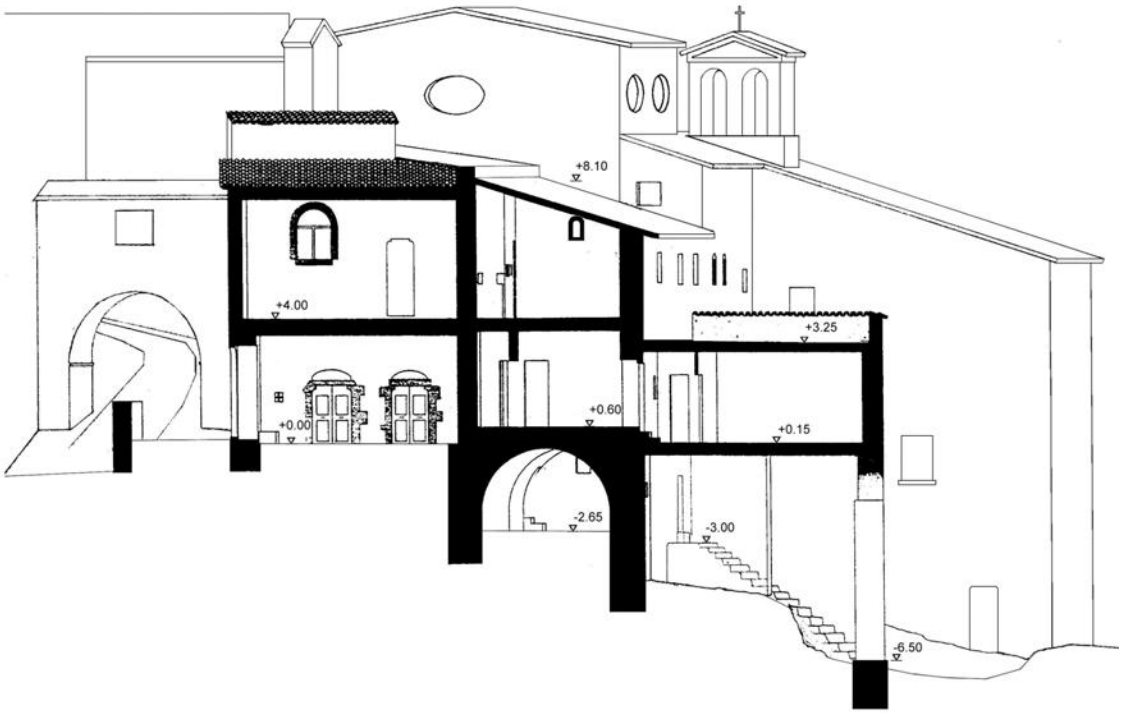

Fig. 1a. The vertical section of the building exhibits the complex structural system

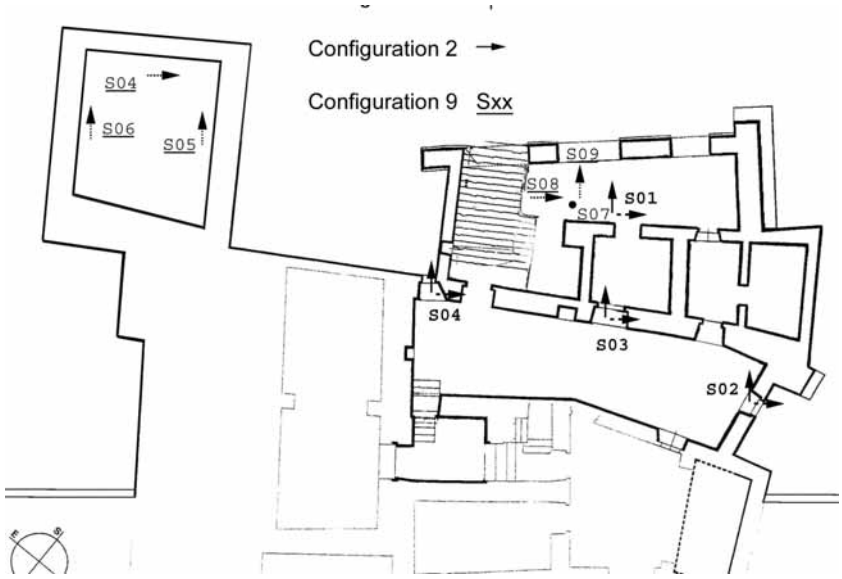

Fig. 1b. Plan view of Level 1 and layout of the temporary array

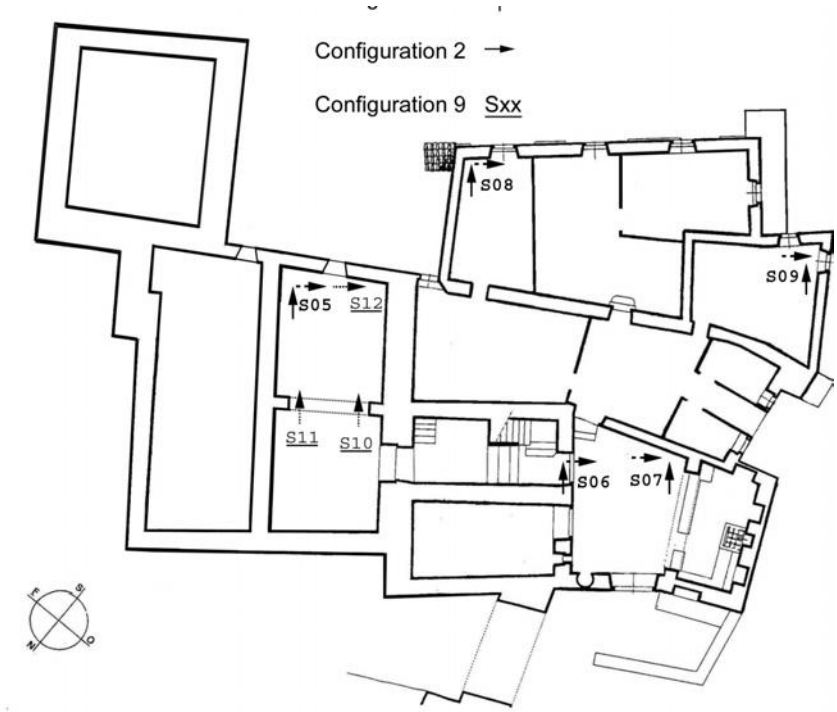

Fig. 1c. Plan view of Level 2 and layout of the temporary array

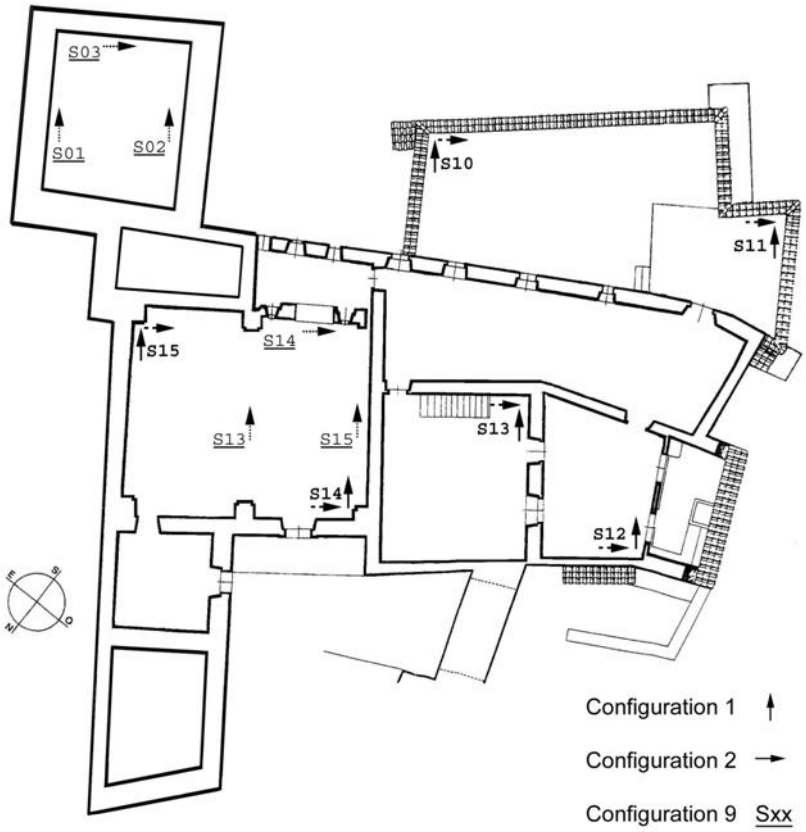

Fig. 1d. Plan view of Level 3 and layout of the temporary array

The building was damaged during the Umbria-Marche seismic sequences, especially during the two earthquakes occurred on September 26th, 1997, at 00:33 (Epicentre 43°01'00'' N, 12°55'00''E, M=5.6), and at 9:40 GMT (43°05'00'' N , 12°48'00'' E, M_s=6). An additional event occurred on October 14th, 1997 at 15:23 GMT (42°58'00'' N 12°55'00'' E, M_s= 5.4). By observation, it was determined that the building suffered some damage during the main shock of September 26th although the epicentre of the earthquake was 30 km away from the building. Then, the 14 October event, the epicentre of which was approximately 8-10 km away from the building, caused most of the damage. Following these two earthquakes, the structure was evaluated to characterise its dynamic properties by using natural and man-made excitation, as shown in this paper.

THE EXPERIMENTAL TESTS USING TEMPORARY DEPLOYMENT

The sensor configurations used to record the responses of CEDRAV building, using temporary deployment, are summarized in Table 1. For each configuration, different number of tests were performed. Each configuration refers to the instrumentation scheme and orientation. For each configuration, several tests were carried out using different kinds of excitation (Tab. 1). For example, for Configuration 1, only the NS oriented sensors (solid arrows in Figure 1b-d) were used. For Configuration 2, only the EW oriented sensors (dashed arrows in Figure 1b-d) were used. For Configuration 9, only sensors underlined in Figure 1b-d were used. In Table 1 are also shown the different kinds of excitation used in the acquisition of the data. Essentially the following sources of excitation were used:

A. Ambient (e.g., Configuration 1, Test 6),
B. Man-induced (lifting a caterpillar tractor arm and dropping - e.g. Configuration 1, Test 7),
C. Seismic events using temporary deployment (e.g., Configuration 1, Test 1)
D. Seismic events using permanent deployment.

Vibration tests (ambient and man-induced)

The ambient vibration measurements were performed by using fifteen SS-1[3] uniaxial velocity sensors (natural frequency 1.0 Hz) connected to five K-2[4] recorders. Measurements were carried out between May 6th and 15th, 2000. Sensors were deployed in 9 different configurations. For the first configuration (Figs. 1b, 1c, 1d) velocity time-histories each lasting 30 s, have been obtained from small seismic events. Then two vibration responses of 300 s were recorded using both ambient excitation and sequence of shocks generated by an operating tractor-caterpillar. This was done to check repeatability of the vibration characteristics and to get average values of the characteristics. Sample time-histories of responses due to ambient as well as man-induced excitation are shown in Figures 2 and 3, respectively.

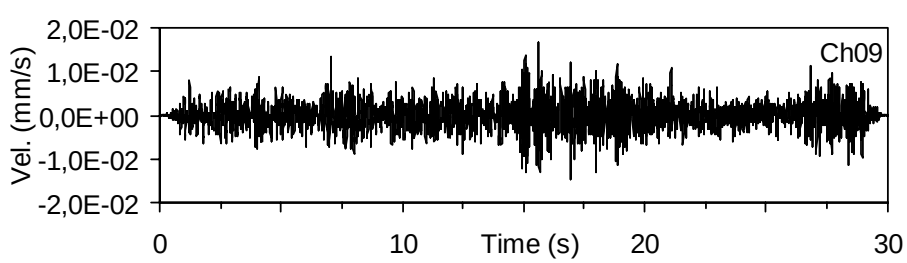

Fig. 2. Example of sample record of ambient excitation.

[3] Kinemetrics product. The use of commercial names is for information only and does not constitute endorsement of the products.
[4] ibid

Recorded Seismic Events by Temporary Deployment

While the temporary deployment was active, several sets of seismic events were recorded. A sample time-history of response of the building (Ch9) is shown in Figure 4 and exhibits beating effect of the building.

Tab. 1. Configurations and Tests Used in the Analysis

Configuration	Test Number	Input	Test Name
1	01	Earthquake	CDRV101
Note: Only NS sensors in Fig. 1b-d are recorded	02	Earthquake	CDRV102
	03	Earthquake	CDRV103
	04	Earthquake	CDRV104
	05	Earthquake	CDRV105
	06	Ambient	CDRV106
	07	Ambient + Man-induced	CDRV107
2	08	Ambient	CDRV201
Note : Only EW sensors in Fig. 1b-d are recorded	09	Ambient + Man-induced	CDRV202
	33	Earthquake	CDRV809
	34	Earthquake	CDRV810
9	35	Ambient	CDRV901
Note : Sensors are on the floor of top level of the church and the neighbouring buildings	36	Ambient + Man-induced	CDRV902
	37	Earthquake	CDRV903
	38	Earthquake	CDRV904

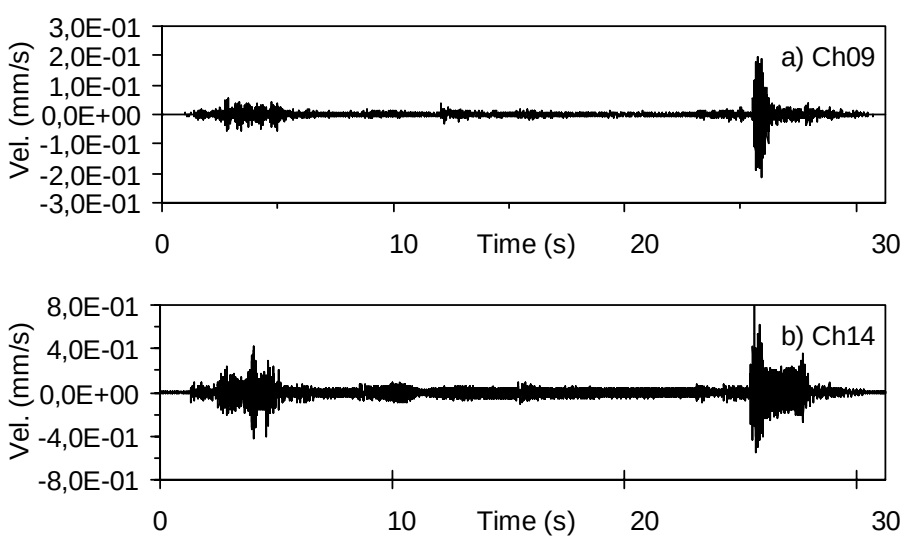

Fig. 3. Two examples of sample records of human-induced vibration.

Analyses of Data from Temporary Deployment

General remarks

For each record, data processing was performed in the frequency domain by calculating and plotting the power spectral density (PSD) function, S_{ii}, and for each selected couple of records, the cross spectral density (CSD) function, S_{ij}, with the corresponding phase factor and coherence function. The resulting plots of time-histories, PSD and CSD are reported in [1] for analyses and interpretation. For each considered configuration, the respective plots corresponding to ambient vibration test and to a seismic events are provided. For each considered test the time histories recorded by the 15 sensors, the power spectral densities of all the records and the cross spectral density of all the significant couples of records with the phase factor and the coherence function, were plotted. The range of interest [0, 30] *Hz* was considered both for PSD and CSD. In this paper selected events have been analyzed to recover the main dynamic features of the building.

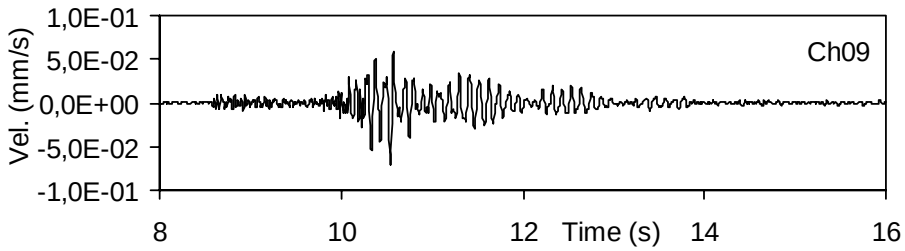

Fig. 4. Example of record from seismic event recorded by temporary deployment.

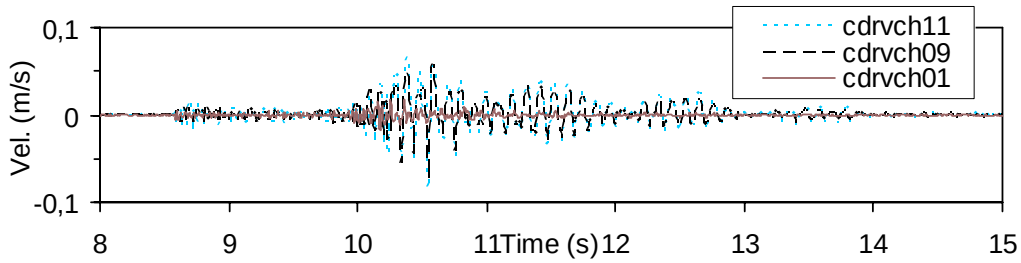

Fig. 5. Velocity responses recorded at three different levels (Ch11 (3rd floor), Ch9 (2nd floor), Ch1 (Basement)).

Long Duration Response (Time-history)

Ch9, Ch11, Ch12 and Ch13 shows unusual long duration velocity time-histories with particular low frequency content that is not visible in the input record (Ch1) (Fig. 5). This trend is most likely due to the closely-coupled torsional-translational mode that causes beating phenomenon. Normally, such beating occurs when the system has low damping in addition to closely-coupled translational-torsional modes. Such effects have been observed in response data from instrumented structures in the United States. The PSD of Ch11 shows the two peaks at very close frequencies, 8.80 Hz and 9.75 Hz (Fig. 6a). Thus, it is seen that all channels show significant long response duration effects (Ch9, Ch11, Ch12, Ch13) and contain both of the above mentioned peaks in the PSDs (Figs. 6a, 7a, 7b and 8c, respectively). Peak at 8.80 Hz is particularly relevant for Ch13, while Ch12 shows larger peaks at 8.80 Hz and 9.75 Hz. Peaks in the PSD are very sharp indicating that, even thought the building was old and damaged at some locations, damping value is small. Thus, the calculated damping for the mode corresponding to the peak at 8.8 HZ is approximately 0.5% for Ch9, Ch11 and Ch12. Damping in this case is evaluated using half-power band method. Because PSD functions for Ch8 and Ch10 do not show evidence of the 8.80 Hz peak, it is possible to assume that this frequency content should be linked to a physic phenomenon mainly connected

to the wall instrumented by Ch9 and Ch11. By means what is in Ch9 and Ch11 (PSD peak at 8.8 Hz) is not in Ch8 and Ch10, which are connected to a more rigid wall that does not have this torsion (probably the rotation axis is positioned on a parallel plane and very close to the wall). The CSDs Ch8-Ch10 and Ch9-Ch11 (Figs. 9a and 9b) indicate that the peak at 8.80 Hz appears only from the motion of the wall instrumented by Ch9 and Ch11 (Ch12 and Ch13 as well). Peak at that frequency is very large at the input level as well (Fig. 6b). In fact the analysis of Ch8-Ch9 and Ch10-Ch11 CSDs (Figs. 9d and 9c) confirms that the mode at 9.75 Hz has more energy at the third floor (Ch10-Ch11) than the second one (Ch8-Ch9) and they are 180 degrees out of phase with high coherence, which is a clear indication of torsional mode. This indication is confirmed by the analysis of the phase factor and coherence function of the difference between Ch8-Ch9 and Ch10-Ch11.

The cross-spectra CSD of Ch10-Ch8 and CSD of Ch9-Ch11 show as well a spectral peak at 9.75 Hz. A phase angle of zero degrees confirms that this frequency peak is associated to a traslational movement of the walls in the NW-SE direction (Figs. 10a and 10b).

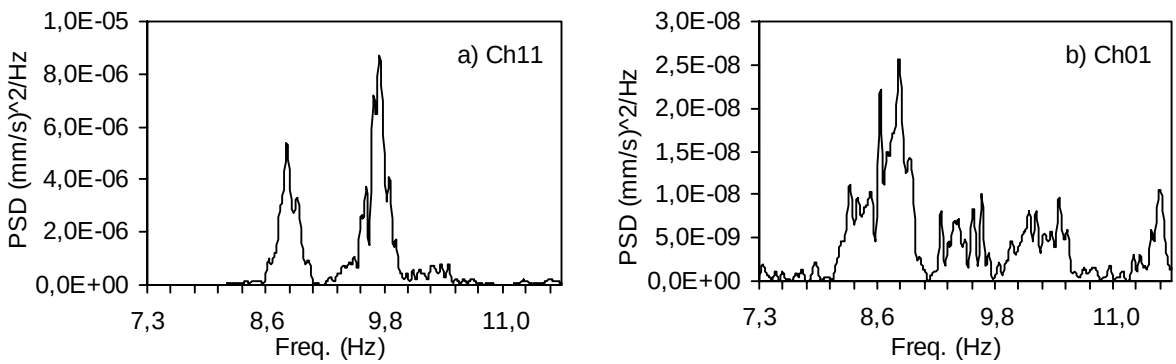

Figure 6. PSD of Ch11 and Ch1

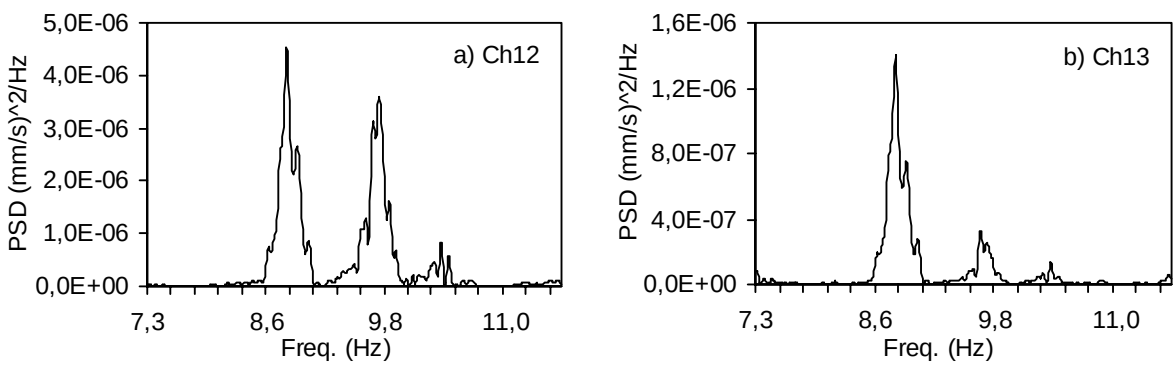

Fig. 7. PSD of Ch12 and Ch13

In summary, the spectral analysis shows a superposition of spectral amplification connected to the dynamic characteristic of the building (see Fig. 6b to the evidence on the PSD of Ch11 at 8.80 Hz with very low damping value). This may be linked, for some reasons, with the position of the centre of mass and rigidity of the building. Therefore, the response is larger at the perimeter walls in the NW-SE direction due to the contribution of the torsional component of the motions whereby the frequency of the torsional mode (Fig. 8c and Fig 6a – PSD of Ch9 and Ch11 at 9.75 Hz) is very close to the frequency of some other modes (i.e., there are several peaks in a very small frequency interval, 9-10 Hz, that could be related to modes of the structure –Figs. 8a and 8b – and, e.g., Ch8 and Ch12 for a very close peak at 9.63 Hz). The mode associated with this second peak seems to have, as for the peak at 8.8 Hz, a very small damping (very sharp frequency peak). On the other hand all spectral peaks at frequencies larger than 9.0 Hz seem to be associated only to torsional modes (Figs. 11a and 11b for CSD phase of CSD of Ch10-

Ch11 and Ch8-Ch9, respectively). The CSD phase of differences between time-histories of Ch8 and Ch9 and Ch10 and Ch11 seem to confirm this result (Fig. 11c).

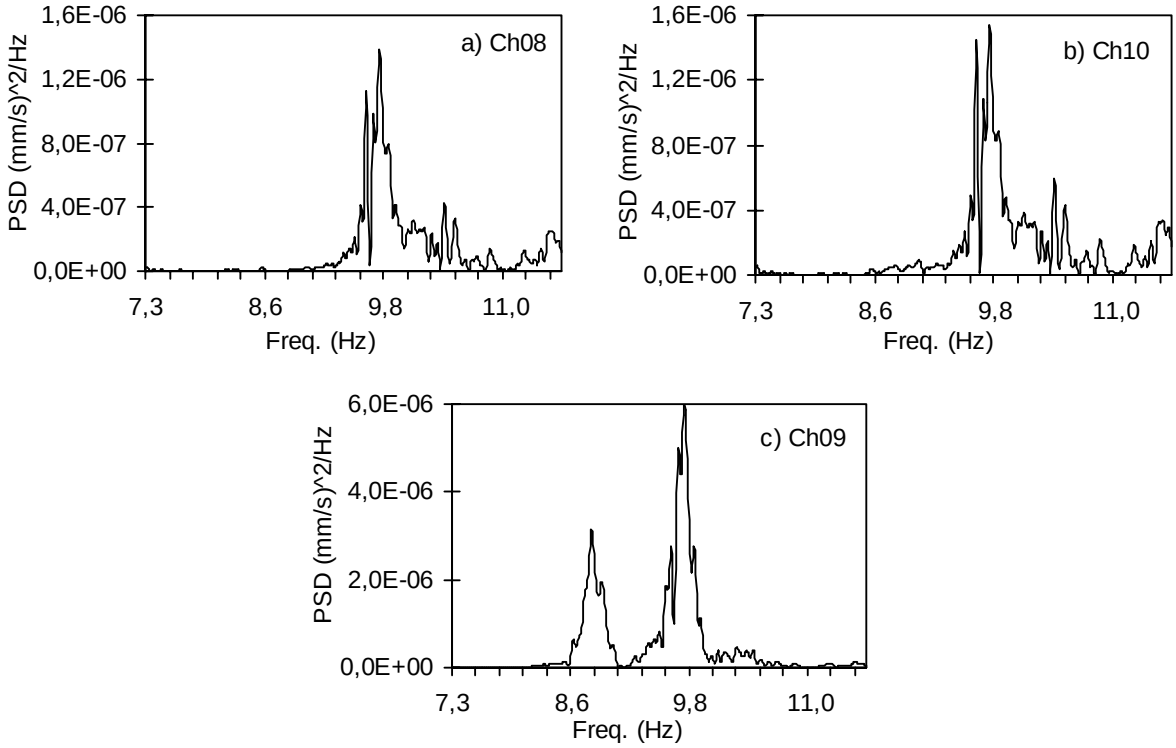

Fig. 8. PSD of Ch8, Ch9 and Ch10

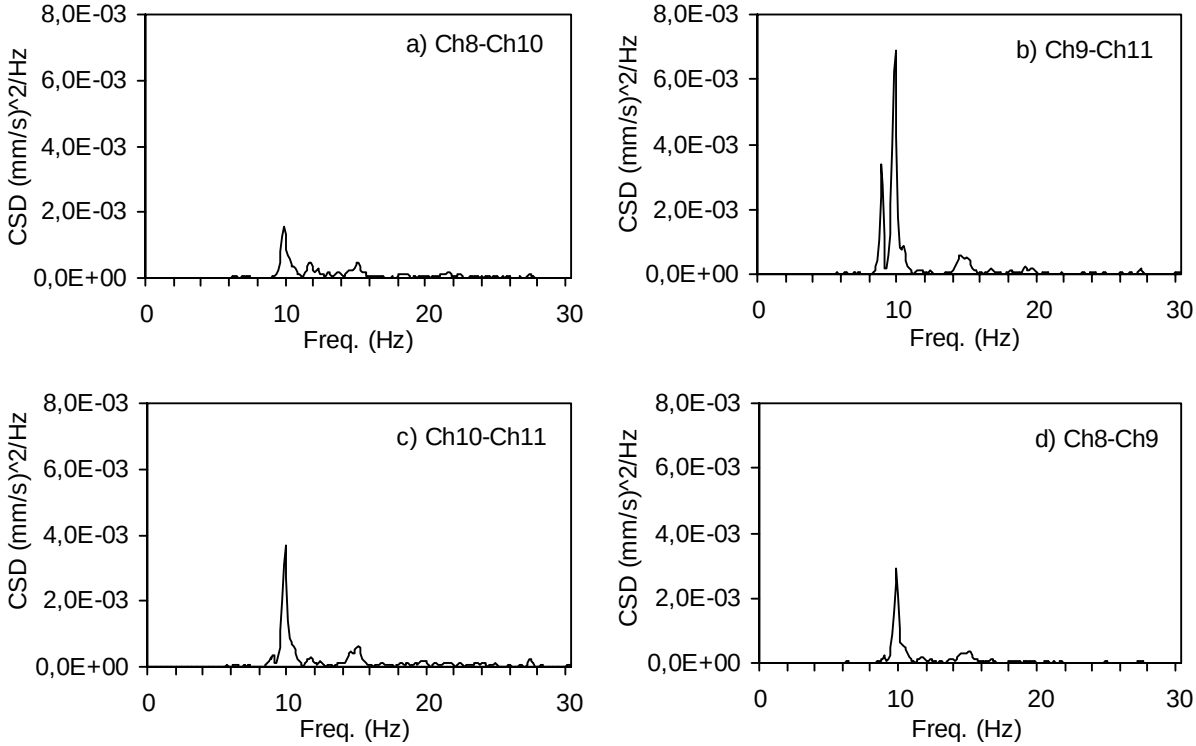

Fig. 9a-d. CSD of (a) Ch8-Ch10, (b) Ch9-Ch11, (c) Ch10-Ch11 and (d) Ch8-Ch9.

Detailed Look at Closely Couple Modes

The CSD analysis of Ch8-Ch9 and the PSD of Ch9 in a very narrow frequency band (9.18-10.47 Hz) shows two main clusters of peaks that is very difficult to differentiate. These are centred approximately at 9.60 and 9.75 Hz (Fig. 12). All the peaks (at least 5) appear to be associated with torsional modes because of the phase factor (Fig. 11b). In particular the couple of peaks P1, P3 (9.49 and 9.55 Hz) and P2, P4 (9.63 and 9.70 Hz) are associated with modes of opposite phase. Finally, plotting in the same graph the CSD magnitude and phase, enlarging it as maximum as possible, give us the doubt to the phase value of peak P3 (Fig. 13: there is a discontinuity in the phase factor at P3).

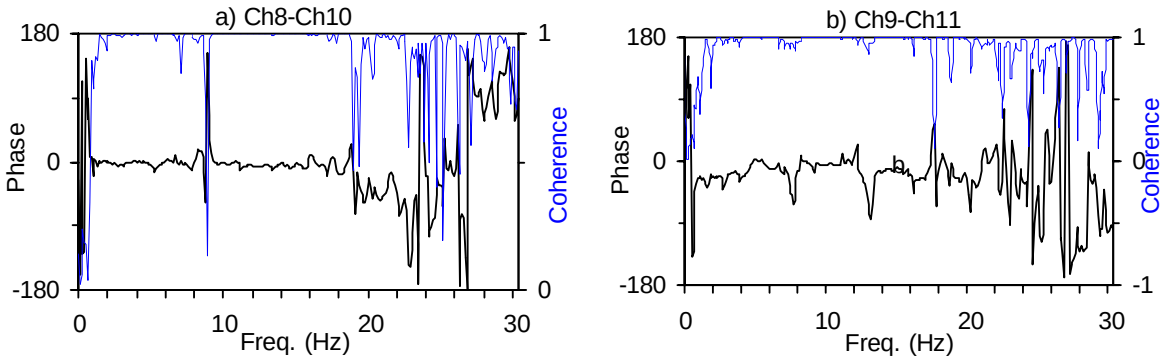

Fig. 10. Phase and Coherence for (a) Ch8-Ch10 and (b) Ch9-Ch11

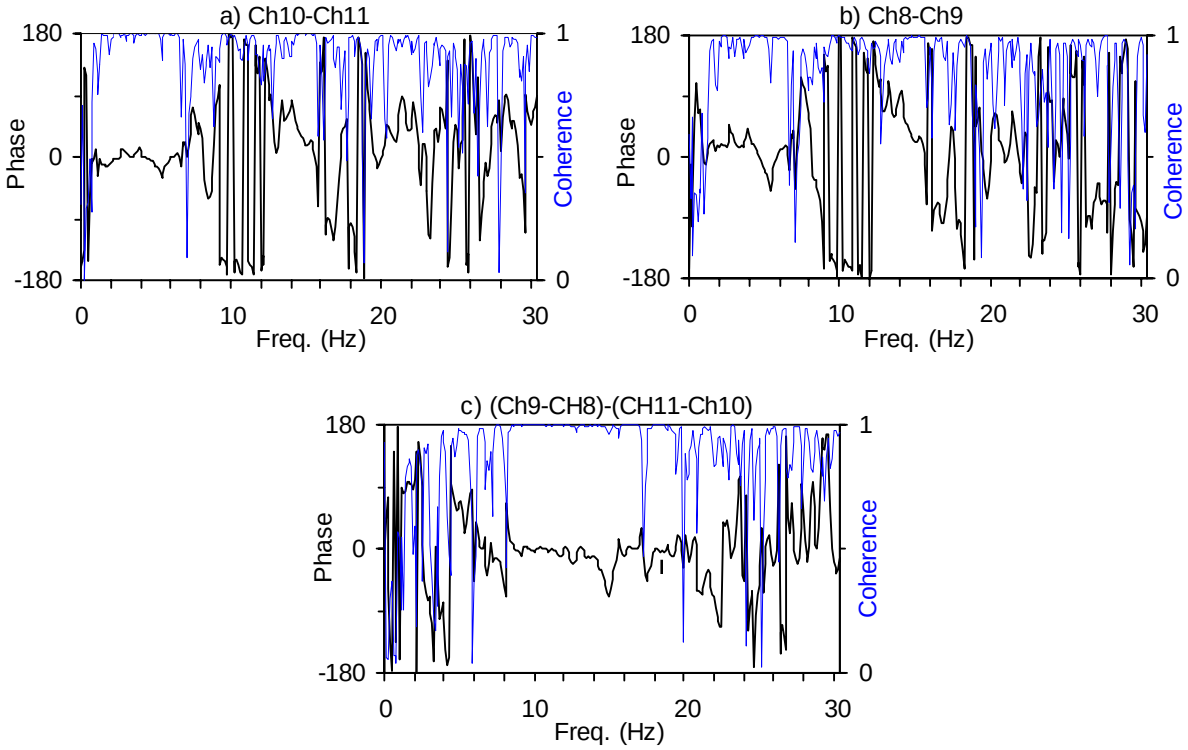

Fig. 11. Phase and Coherence (a) Ch10-Ch11, (b) Ch8-Ch9, (c) (Ch 9-Ch8) and (Ch11-Ch10)

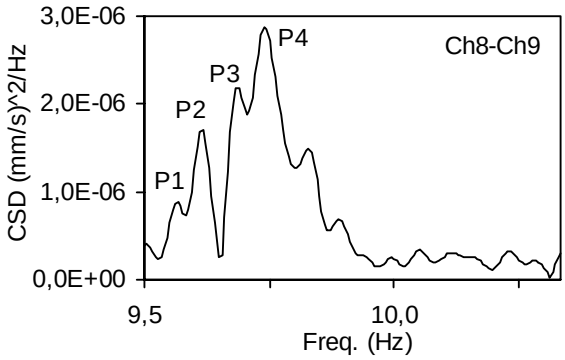

Fig. 12. CSD Ch8-Ch9

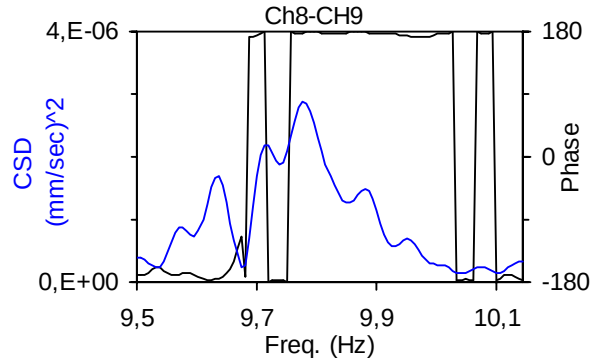

Fig. 13. CSD Ch8-Ch9

RECORDED RESPONSES USING PERMANENT DEPLOYMENT

The building was permanently instrumented in June 2000 by using 36 accelerometer channels. Schematics showing of the locations of the permanent instruments are provided in Figures 14 which is rearranged from Figure 1. Following the permanent deployment, several seismic events were recorded.

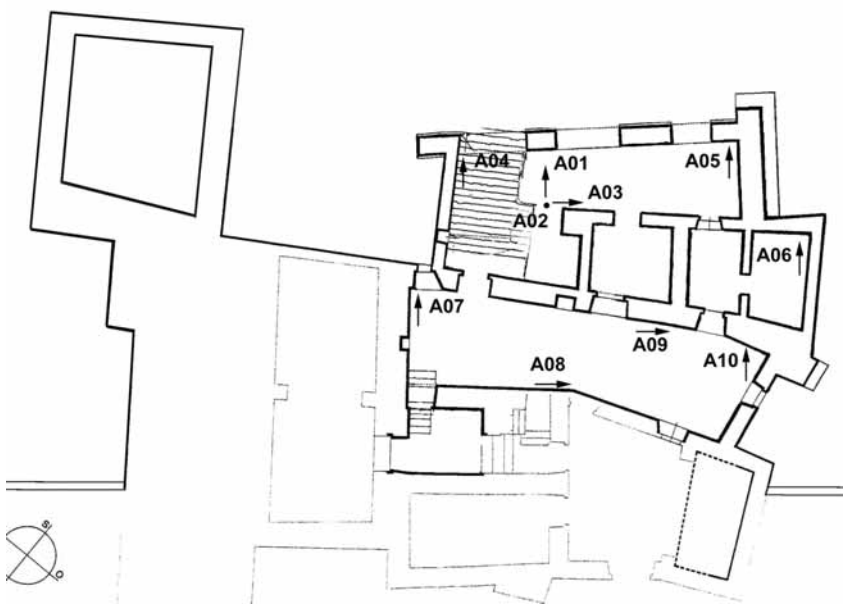

Fig. 14a. Schematic view of Level 1 with location of accelerometers in the permanent array.

Analyses of Data from Permanent Deployment

A complete set of an earthquake response analyses of data from one event for all channels of the permanent array is provided in [1]. A sample time-history of recorded response to a seismic event (of June 28th, 2000) is provided in Figure 15. Amplitude spectra of the same channels of permanent deployment are provided in Figure 16. From the amplitude spectra, translational and torsional frequencies of 9.7 and 10.4 Hz respectively. Using system identification, damping percentages that are very low (< 1%) are extracted. The identified frequencies and damping ratios are summarized in Table 2 in the Conclusions Section.

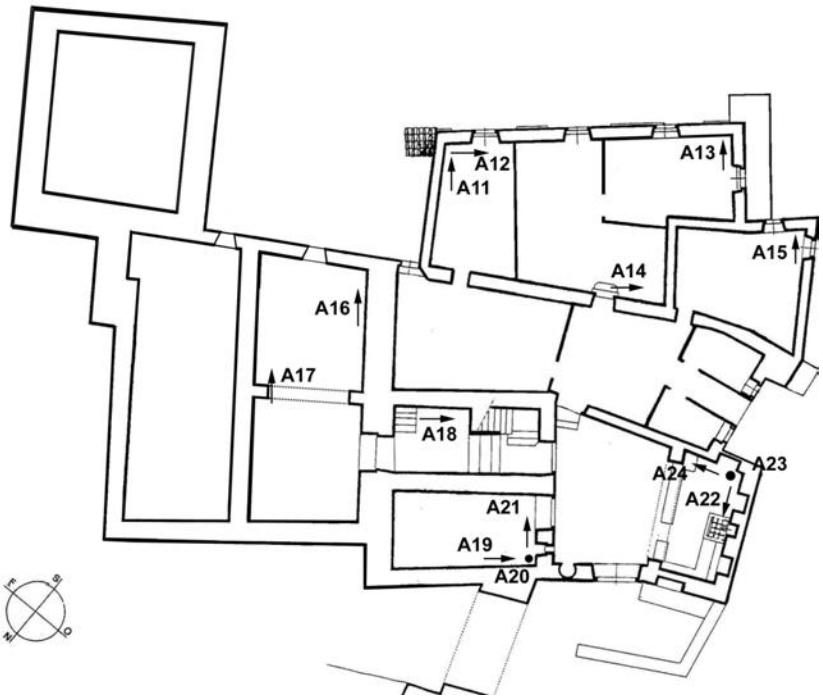

Fig. 14b. Schematic views of Level 2 with location of accelerometers in the permanent array

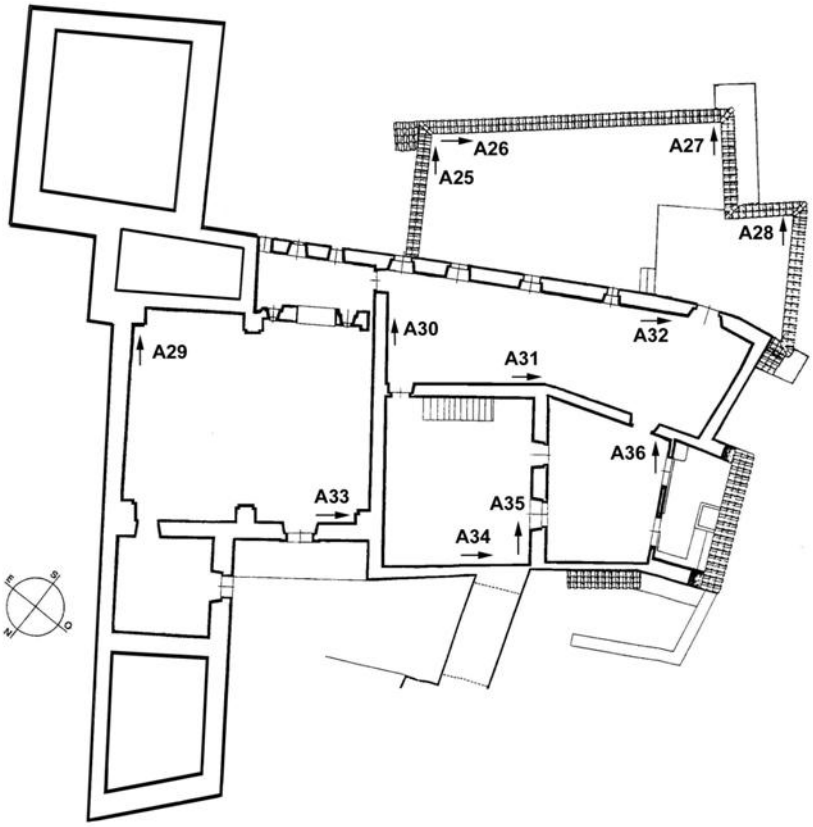

Fig. 14c. Schematic views of Level 3 with location of accelerometers in the permanent array.

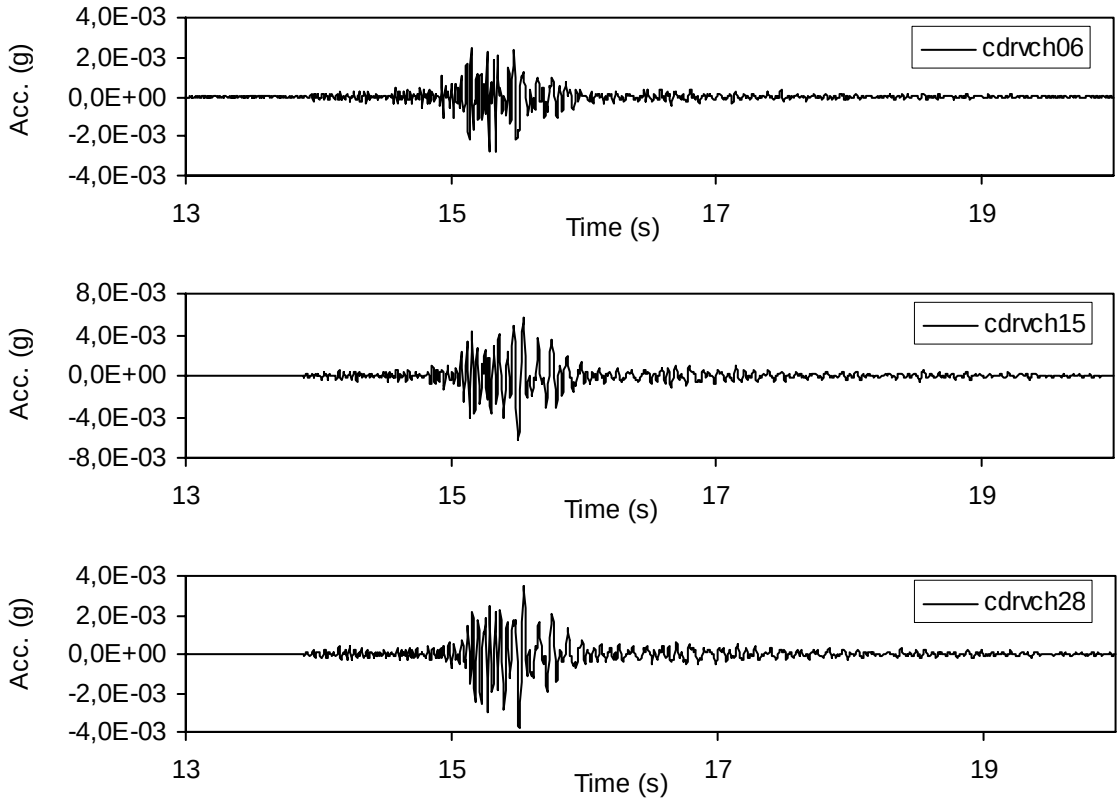

Fig. 15. Recorded acceleration time-histories of Ch6 (Level 1), Ch15 (Level 2) and Ch28 (Level 3) exhibit the beating effect of the structural response at higher levels [event of June 28th, 2000].

DISCUSSION AND CONCLUSIONS

Extensive interpretations of dynamic response of the CEDRAV building as recorded by temporary and permanent arrays are presented. Assessing dynamic characteristics of such buildings is essential (a) to understand the structural behaviour of such a complex historical building and (b) derive from the results insight as to how such a building can be strengthened to reduce its seismic risk during future events. Table 2 summarizes the dynamic characteristics extracted from the data corresponding to different excitations. The building is very complex and rigid. Translational and torsional frequencies are close to one another. Coupling occurs. Damping percentage is low. Coupling of the frequencies and the low damping are two factors that cause beating effect when shaking is strong enough. In this study, the shaking levels are not large but the building is affected by beating effect yet.

Tab. 2. Dynamic Characteristics of CEDRAV Building

Excitation	Freq. (Hz)		Damping (%)
	Translation	Torsional	
Ambient	8.88	10.05	
Man-Induced	9.08	10.15	
Temp. Array (Earthquake)	8.60	9.75	.5
Perm. Array (Earthquake)	9.70	10.40	<1.0

For example, the approximate beating period is computed for the June 28th, 2000 earthquake as (taking $T_1 = 1/9.7 = 0.104$ s, and $T_2 = 1/10.4 = 0.096$ s):

$T_b = 2T_1T_2/(T_1-T_2) = 2(.104)(.096)/(.104-.096) = 2.5$ s.

This short length of beating effects are observable in the time history plots provided in Figure 15 for the mentioned event. However, similar beating effects are also seen in Figures 4 and 5 for other excitation sources.

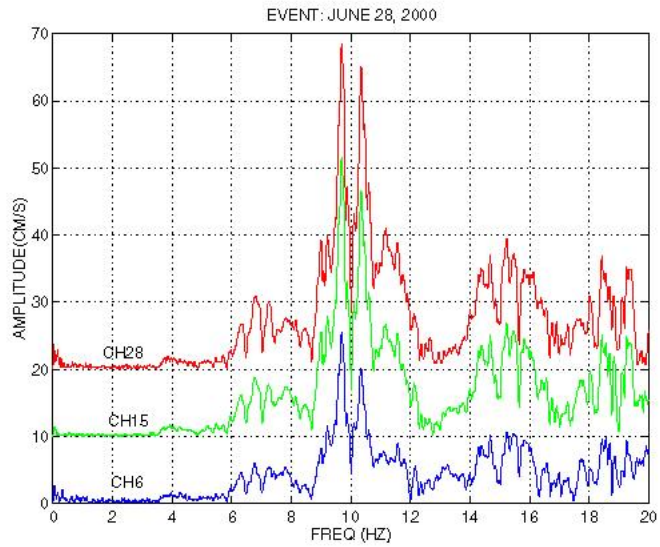

Fig. 16. Amplitude spectra of Ch6 (Level 1), Ch15 (Level 2) and Ch28 (Level 3), event of June 28th, 2000.

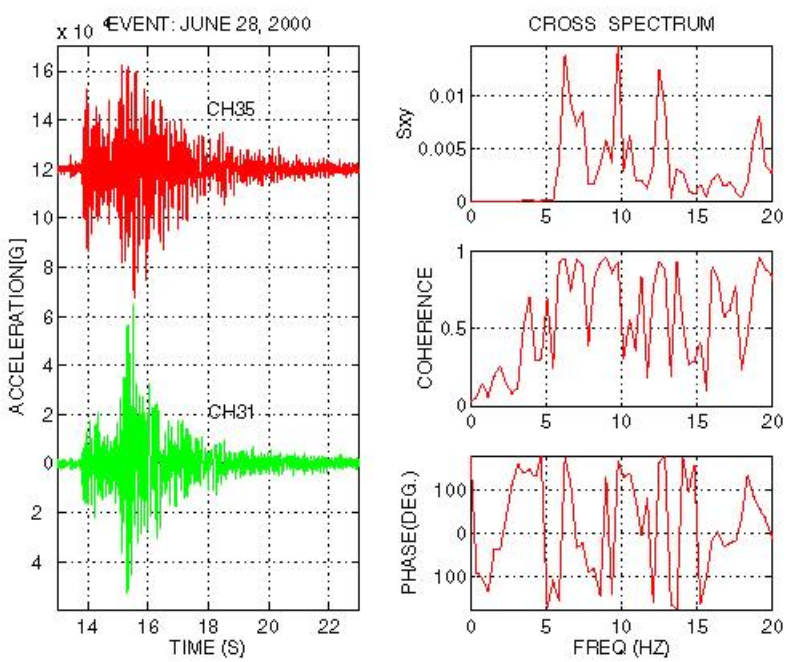

Fig. 17. Time-histories of orthogonal Ch35 and Ch31 (left) and their cross-spectrum (right-top), coherence (right-centre) and phase (right-bottom) for event of June 28, 2000. There is very high coherence (at ~ 10 Hz) between the motions at the locations of Ch35 and Ch31. The phase angle ~180 degrees indicates torsional effect.

Although analysed data clearly exhibits the dynamic behaviour of the complex and non-symmetric structural system of the CEDRAV building, additional analyses of the extensive data set would be very useful and is recommended.

Material mechanical properties of historical buildings must be systematically assessed to be used in studies such as this one. Since CEDRAV Building is damaged and since further future damage during earthquakes needs to be averted in order to preserve this important cultural heritage, several options are available to strengthen the structural system of the building [2, 3]:

- An external steel frame system can be designed such that the relative displacements of the CEDRAV building at key locations can be minimized to prevent damage to the building and its walls some of which contain invaluable frescos. If this option is used, at key locations (joints and corners) viscous dampers can be used to further assist in minimizing displacements. The locations of the displacement preventive elements can be identified by making several analysis with the already developed finite element model of the building;
- Alternatively, a combination of steel grid-work and pre-tensioned cables can be used to minimize the displacements of the walls and prevent beating and excessive shear stresses and deformations;
- There are significant number of internal walls within the building that are covered with ordinary stucco and no frescos. After careful analyses, some of these walls may be strengthened with fibre-reinforced material. However, this must be done with care and analysing as strengthening one element may redistribute the stresses to others;
- There are a number of open spaces between the intervened walls of the building. If architecturally it can be worked out, it may be possible to "insert" into each one of these opening a steel frame system and viscous dampers such that the displacements are again minimized.

REFERENCES

1. ENEA "*Analisi dinamica dell'edificio CEDRAV, per mezzo di reti velocimetriche e accelerometriche*." Programma ENEA – MURST (legge 95/95 annualità 1996) "Catastrofi naturali e loro conseguenze sul patrimonio culturale ed ambientale italiano. Mitigazione e previsione di alcune tipologie di eventi", Report to MIUR, 2003.
2. Clemente P., Bongiovanni G., Buffarini G., Rinaldis D. "Strategies for the seismic preservation of historical centres". *Proc., 7th International Symposium of the OWHC* (Rhodes, 23-26 September), 2003.
3. Clemente P., Margottini C. "Seismic Preservation of the Collective Memory". *Proc., International Conference "Choices and Strategies for Preservation of the Collective Memory"* (Dobbiaco, 25-29 June 2002), Ministero per i Beni Culturali, Amministrazione Archivistica (Invited lecture), 2002.