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INTERPRETATION OF RECORDS FROM TEMPORARY AND PERMANENT INSTRUMENTATION TO IDENTIFY THE DYNAMIC RESPONSE OF A HISTORICAL BUILDING TO SEISMIC ACTIONS

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Abstract. *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 Ms=5.4 and Ms=6, respectively, caused damages to it. Ambient vibration measurements were first performed by using fifteen SS-1 uniaxial velocity sensors (natural frequency 1.0 Hz) connected to five K-2 recorders and deployed in nine different configurations. Then the building was permanently instrumented by using 36 accelerometers. Results from analyses of representative seismic response data acquired from the building specific permanent deployment are also included and classified by means of cumulative normalized energy plots. 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 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. As stated the CEDRAV is an old buildings and has been altered repeatedly over time. This will cause dynamic interactions with other buildings or substructures during an earthquake.. On the base of recorded data a preliminary analysis in frequency domain, based on the determination of auto and cross power spectral density, has been carried out. Then the modal structure's identification has been performed by means of Ibrahim technique, working in the time domain, and Frequency Domain Decomposition technique, working in the frequency domain.*

1 INTRODUCTION

The dynamic response of the CEDRAV building in Cerreto di Spoleto (Italy), originally a monastery, built in the 14th century on the top of a rock ridge, has been deeply studied by means of experimental measurement campaigns and numerical modeling. Temporary arrays, excited by means of ambient vibration or weak motions, and a permanent array to obtain records of seismic events were deployed. Two events occurred on September 26th, 1997 (epicenter Colfiorito, distance $\approx$ 30 Km), with magnitude Ms=5.4 and Ms=6, respectively, and one on October 14th, 1997 (epicenter Sellano distance $\approx$ 10 Km), Ms=5.4. They caused damages to the building but only strong-motion records from the free-field accelerometric array were available to try to correlate the seismic input with the damage. Ambient vibration measurements were first performed by using fifteen SS-1 uniaxial velocity sensors (natural frequency 1.0 Hz) connected to five K-2 recorders and deployed in nine different configurations. Then the building was permanently instrumented by using 36 accelerometers. Transducers were installed in different locations of the structure. In particular, some of these were arranged on the perimeter walls to obtain torsional modes of the structure.

When recording seismic events, use integrated arrays is essential, i.e., to deploy free-field sensors in parallel to those in the building, to assess the ground shaking [1, 2]. It is worth noting that the structure may experience non-linear behavior during strong earthquakes. Thus, if the parameters of linear behavior are known beforehand, it may be easier to extrapolate the non-linear behavior but this process is very difficult for old damaged masonry buildings. For such cases, even for very small excitation, non-linear behavior may be experienced by the structure, which could be approximated with a pseudo-linear approach**.**

2 ENERGY PLOTS OF RECORDED EVENTS

Results from analyses of representative seismic response data acquired from the building specific permanent deployment are processed and classified by means of cumulative normalized energy plots. Recordings were obtained at 3 different level of the rock basement (CH01, CH02, CH03, CH19, CH20, CH21, CH22, CH23 and CH24 - Italic evidences sensors in the vertical direction). Data were compared with those obtained in the station "Cerreto Comune 1 Basement" of the permanent free field array for the event of January 21th, 2000. Figure 1 shows the cumulative Arias intensity for the records at the CEDRAV basement when figure 2 shows the values obtained at the free-field station: for this event the energy in the vertical component seems negligible compared to the horizontals ones. This trend is confirmed in two stations at the CEDRAV basement (CH02, CH20). Figure 3 shows instead the values of cumulative Arias intensity at the array station of "Cerreto Comune 2 Roof" for records obtained during the damaging events (September 26th and October 14th, 1997). First of all we have to outline that accelerograms were recorded by an accelerograph installed in the roof of the building. Of course a larger energy level is observed but the vertical components are still less demanding than the horizontal ones. What it is important to outline is the fact that the aftershock of October 14th was much more damaging for the historical center of Cerreto di Spoleto then the main shock of September 26th. The reason is evident looking at figure 3 where the cumulative Arias intensity evaluated from the acceleration components recorded on October 14th are 4 to 5 times larger than the ones recorded during the main shock (second shock of September 26th). This is shown as well in figure 4 where the cumulative Arias intensity of accelerometric components obtained at Borgo Cerreto Torre station are compared. Values are, of course, smaller because site effect as the hill morphology and the structural amplification are not included, but the global trend is similar.

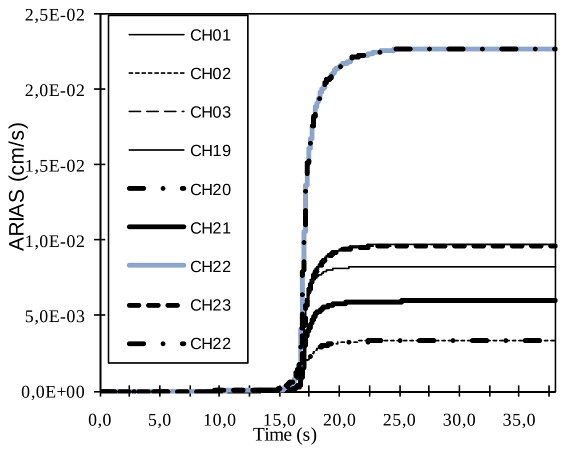


Figure 1: Cumulative Arias Intensity plots for the acceleration time histories obtained at the basement of the CEDRAV during the seismic event of the January 21st, 2001, Ml=4.

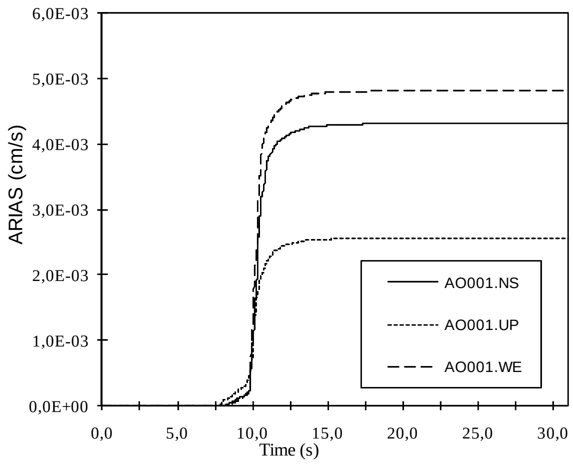


Figure 2: Cumulative Arias Intensity plots for the acceleration time histories obtained at “Cerreto Comune 1 Basement” during the seismic event of January 21st, 2001.

3 PERMANENT ARRAY VERSUS TEMPORARY DEPLOYMENT

Information on CEDRAV building may be obtained from two sources: dynamic testing of the structure (ambient and forced vibration) and analyses of data from permanent array. The second is based on strong-motion response data, which depends on a long duration project that is costly to implement and maintain. Therefore, whenever possible, low-amplitude tests are used to verify the results of analytical studies. On the other hand the seismic behavior of structural systems 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. In more details, temporary arrays are generally used for dynamic characterization of structures, which can be excited by means of ambient or forced vibrations [3].

The CEDRAV building was both instrumented with a temporary deployment of velocimetric sensors in 9 configurations and then with a permanent strong-motion array of accelerometric sensors [3]. Recordings of both arrays were analyzed and compared to recover the dynamic characteristics of the building (resonance frequencies, damping, etc.) [3, 6]. Of course, the interest of results is limited by the fact that the building was not instrumented during the shocks of September 26th and October 14th, 1997. Nevertheless the following results were obtained:

a) The building is very complex and rigid; translational and torsional frequencies are close to one another;

b) 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.

c) The results obtained from the velocimetric recordings are very similar to those obtained by means of the accelerometric recordings. The differences in the resonance frequency values are to be related to the fact that higher energy events were recorded by the temporary arrays.

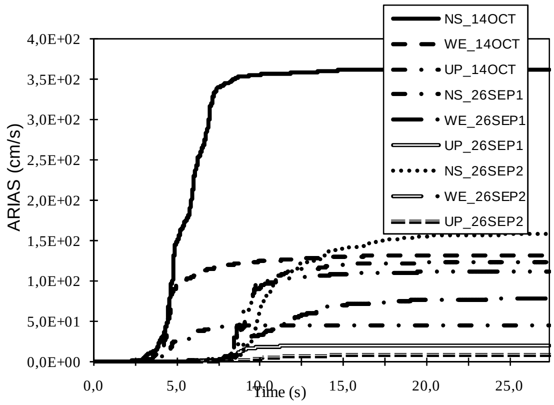


Figure 3: Cumulative Arias Intensity plots for the acceleration time histories obtained at "Cerreto Comune 2 roof" during the seismic event of September 26st, 1997 (2 shocks magnitude Ml=6 and Ml=5.4, epicenter in Colfiorito), and of October 14th, 1997 (Ml=5.4, epicenter in Sellano).

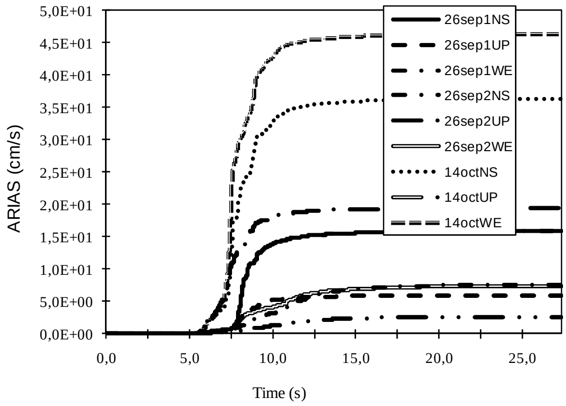


Figure 4: Cumulative Arias Intensity plots for the acceleration time histories obtained at "Borgo Cerreto Torre" during the seismic event of September 26st, 1997 (2 shocks magnitude Ml=6 and Ml=5.4, epicenter in Colfiorito), and of October 14th, 1997 (Ml=5.4, epicenter in Sellano).

Figure 5 shows velocity time-histories from the temporary array recorded at the three different levels of the building, where an approximate period of 2.5 *s* for the beatings was computed. In figure 6 the comparison between PSDs of recordings obtained from ambient noise, weak motion and impulse, produced by lifting a caterpillar tractor arm and dropping)., in Configuration1 is shown. It is clear that the most severe excitation was the impulse.

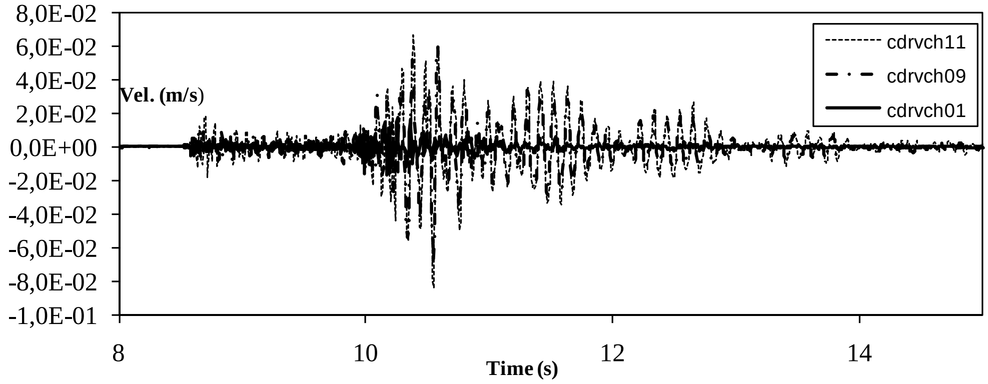


Figure 5: Velocity time-histories from the temporary array, Configuration1. Records were obtained at 3 different level (cdrvch01=basement, cdrvch09=2nd floor, cdrvch11=3rd floor).

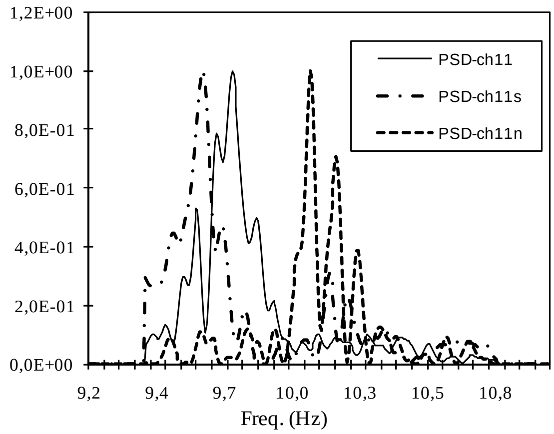


Figure 6: PSD (normalized to the peak) of time-histories from the temporary array (CH11), Configuration1. Records are obtained from weak motion, ambient noise (n) and impulse (s)

As previously stated, the 9 configurations of the temporary array were used for the dynamic characterization of the building, which have been excited by means of ambient or forced vibrations (shock) and sometimes by means of weak seismic events [1, 2, 3, 6]. The knowledge of the influence of the dynamic interactions with adjacent buildings on the modal shapes and frequencies is of fundamental importance to characterize the mechanisms that underlies the damage time history, as will results in the description of behavior of the building. It is worth pointing out that temporary arrays are useful to analyze private buildings, where sensors fixed on the structure are usually not allowed. The reason to select a certain number of configurations depends on the cost/benefit analysis: more configurations you select more accurate your analysis is, but this requires more resources to use for the analysis. So we decided to use eight configurations: four configurations to study the building behavior, and four configurations to investigate the structure-environmental built interaction [6].

The dynamic characterization of the structure, using ambient and forced vibration tests, allowed to have very important information about the health status of the structure and to point out its main dynamic characteristics. Results from Configuration 6 outline a peak at 6.2 *Hz* associated to a modal shape involving the rectangular building and the church motion, in which the structure rotate with respect to a vertical axis. Results from Configuration 8, in which CEDRAV and a smaller building connected to it by means of a masonry arch were instrumented, pointed out that the behavior of the CEDRAV wall with reference to the masonry arch depends on the analyzed event. These observations may be important to evaluate the damage induced mechanism by the October 14th 1997 event (Ml = 5.4) on the NW wall of the CEDRAV building.

4 NUMERICAL MODEL AND EXPERIMENTAL DATA

A 3D finite element model has been developed by using the computer code COSMOS with the purpose to compare the numerical results with those obtained by the experimental measures [4]. Based on standard (obtained from literature) material mechanical characteristics, the values of the frequencies for the first twenty modes were evaluated. In particular the elastic modulus was obtained equating the first resonance frequency with the experimental one. Figure 7a shows the selected finite elements representing the CEDRAV building and the environmental built and figure 7b, 7c and 7d show the first three modal shapes. In order to validate this elastic model the acceleration time-histories recorded at the basement during the June 28th 2000 event was used as seismic input for the model, and acceleration time-histories at the measurement points evaluated and compared with the experimental ones.

Subsequently it has been proceeded to the modal structure identification by means of the Ibrahim technique, working in the time domain, and the Frequency Domain Decomposition technique, working in the frequency domain.

The Ibrahim technique was much more performing then the Frequency Domain Decomposition technique due to very close peaks in the PSD of recorded accelerograms [4].

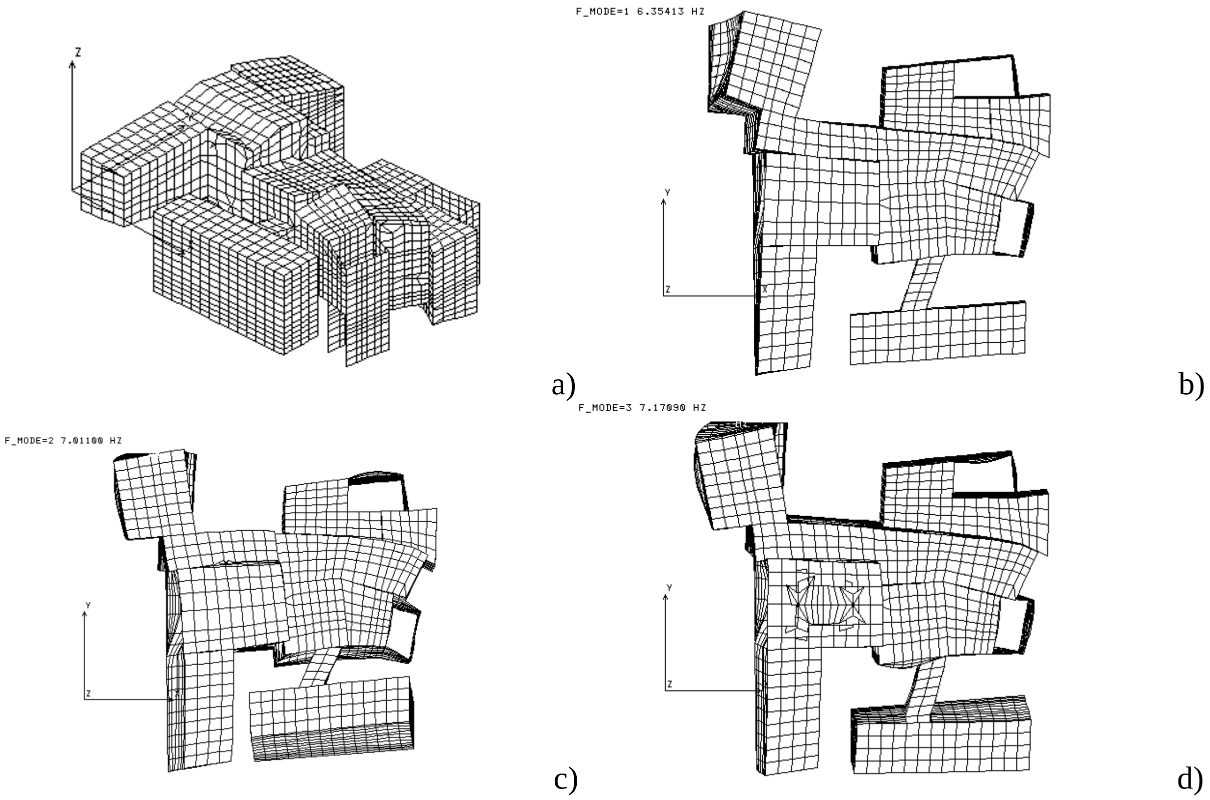
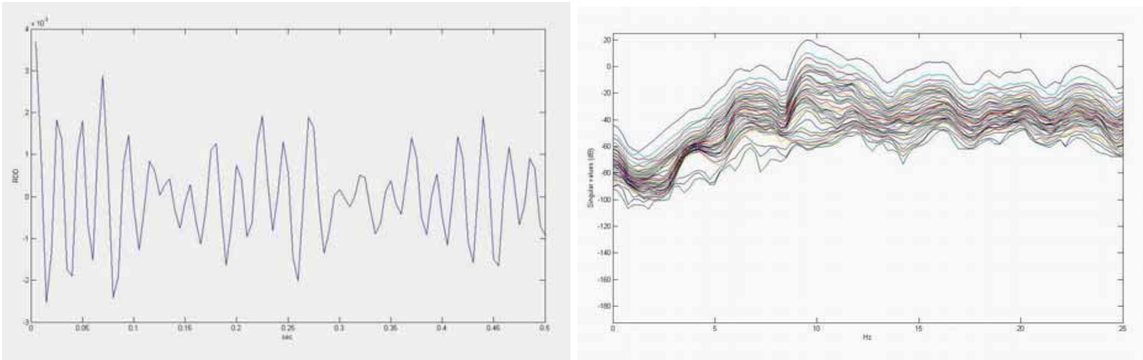


Figure 7: a) Finite elements model; b) first, c) second and d) third modal shapes.



a) b)

Figure 8: a) Correlation function (Ibrahim technique) and b) singular values of power spectral density matrix function (FDD technique).

5 CONCLUSIONS

The analysis of energy plots from the main shocks of the Umbria-Marche seismic sequence outline the severity of the seismic event. The damage induced to the CEDRAV building was essentially due to the horizontal components of motion. In particular the seismic event of October 24th, 1997, was much more damaging then the main shock of September 26th, 1997, (e.g. the energy in the NS component of the acceleration of the October 14th event was double then the same component in the September 26th event). The dynamic characterization of the structure, using ambient and forced vibration tests, allowed to have very important information about the health status of the structure and to point out its main dynamic characteristics. The knowledge of the influence of building dynamic interaction in modifying the dynamic characteristics is of fundamental importance to characterize the mechanisms that underlie the damage time history. The analysis of temporary array configurations outline how important is the interaction between the building and the environmental built, to the damage mechanism of the NW wall of the building. A deeper investigation of the material mechanical characteristics and the analysis of a model as a sub-assemblies ensemble linked to identification techniques may better correlate the experimental results to the dynamic characteristics.

The health status of the building seems to be quite good. The connections between the walls are effective except for those between the main block and the two adjacent smaller blocks. The structure vulnerability is essentially related to the absence of rigid diaphragms between the walls, necessary to guarantee a suitable distribution of the seismic actions. The floors, in fact, are very flexible to satisfy this requirement. The strengthening of the building will regard essentially this aspect: the existing floors, especially the third and the fourth ones, should be substituted by new rigid floors. The connection between the floors, old and new, and the walls must be realized. The input energy was very low: more evident non-linear effects could be observed in the case of seismic actions.

REFERENCES

[1] Clemente P., Rinaldis D. (2004). "Design of temporary and permanent arrays to assess dynamic parameters in historical and monumental buildings". Proc., North American Euro-Pacific Workshop "Sensing Issues in Civil Structural Health Monitoring", Cshm, (Honolulu, 10-13 November), invited paper.

[2] Rinaldis, D., De Stefano and Clemente, P. (2005). ''Design of Seismic Arrays for Structural Systems,'' In: Ou, J.P., Li, H. and Duan, Z.D. (eds), Proc., 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure, (SHMII-2'2005), Nov. 16–18, 2005, Shenzhen, P.R. of China, Taylor & Francis/ Baltemia, Leiden, The Netherlands, Vol. 2, 1447–1453.

[3] Rinaldis, D., Celebi, M., Buffarini, G. and Clemente, P. (2004). ''Dynamic Response and Seismic Vulnerability of a Historical Building in Italy,'' Proc., 13th World Conference on Earthquake Engineering, Vancouver, 1–6 August, IAEE & CAEE, Mira Digital Publishing, Saint Louis, Paper No. 3211.

[4] Rinaldis D., Clemente P. and Teresi G., (2006). "Experimental Modal Analysis of the CEDRAV Historical Building", First European Conference on Earthquake Engineering and Seismology Geneva, Switzerland, 3-8 September, Paper Number: 646.

[5] Clemente P., Rinaldis D. and Buffarini G. (2007). "Experimental Seismic Analysis of a Historical Building", Int. J. of Intelligent Material Systems and Structures, Vol. 18, 777-784, August.

[6] Rinaldis D, Clemente P. and Buffarini G., (2010). "Dynamic Behavior of a Historical Building" , Proc. Of 7th International Conference on Structural Analysis of Historic Constructions, Shanghai, China Part 2, pp. 659-664. TTP Switzerland.