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Experimental analysis and seismic rehabilitation of an earthquake damaged building

G. Buffarini[1], P. Clemente[1], and G. Mancinelli[2]

[1] ENEA, Rome, Italy
[2] Struct. Eng., Fabriano, Italy

ABSTRACT: The knowledge of the health status of a structure is needed to design its seismic retrofit. The problem could be complicated in case of building that suffered the effects of a strong earthquake. In these cases the experimental analysis, which allows the characterization of the dynamic behavior, could be very useful for the selection of the most suitable solution for the retrofit. The study of a reinforced concrete building, damaged by the L'Aquila earthquake, was the occasion to analyze in detail several aspects, such as the influence of the non structural elements and the geometrical irregularities. The analysis also showed that, in order to restore the structure, recently built, without renouncing to the safety requirements, the seismic retrofit should be base on new anti-seismic technologies. In particular, the proposed solution is based on the insertion of a base isolation system under the first existing decks.

1 INTRODUCTION

Buildings subjected to strong earthquake often have damages that cannot be detected by means of a simple visual inspection. So in order to design a suitable seismic retrofit, a detailed analysis of the structural health status is needed. This can be done by means of the dynamic testing of the structure, which allows pointing out the characteristics of the structure and any irregular behavior. Besides, also building that seem to have suffered no or very low damages could not be able to support future earthquake. For example, sometimes the non structural elements, such as the masonry infill walls, have suffered very serious cracks, dissipating lots of energy and so preserving the structure from the collapse. In this case, in which the retrofit of the building is very hard and certainly not sustainable from the economic point of view, use of new anti-seismic technologies is advisable. These allow reducing the seismic action on the building instead of basing on its resistance.

The structure subject of this study is a residential building of five levels, composed by three blocks having V shape in plan, deployed as in figure 1, which was damaged by the L'Aquila earthquake of April 6th, 2009. The three blocks have suffered different kind and level of damage. In block 1 the collapse of one masonry infill wall of first level and heavy damages of masonry infill walls at upper levels occurred. In block 3, originally equal to block 1, apparent cracks are in the masonry infill walls, at the same location of block 1, but without collapse. Block 2, which is more regular than the other two, suffered very light damages. An experimental campaign, based on ambient vibration measurements, pointed out the dynamic behavior of each block of the building. Then an anti-seismic retrofit has been proposed, consisting in the insertion of a base isolation system just under the first floors, which should be joined to avoid relative displacements between themselves.

2 EXPERIMENTAL ANALYSIS

Fifteen seismometers (velocimeter sensors) have been used, deployed in four different configurations, a global configuration and three local configurations.

2.1 Global and local configurations

In the first one the sensors have been deployed in all the blocks in order to detect the differences between the three blocks; in the others the three blocks have been tested separately, in order to analyze in details the dynamic characteristics of each of them.

In the global configuration three sensors have been deployed on the basement of block 2, in the longitudinal, transversal and vertical direction, respectively. Two horizontal sensors in the longitudinal and transversal horizontal direction, respectively, have been deployed in the middle of each block, on the third and fifth level (Figure 1).

In each of the local configurations, three sensors have been deployed on the basement in the longitudinal, transversal and vertical direction, respectively. Six horizontal sensors, two in the longitudinal and four in the transversal horizontal direction, have been deployed, on the third and fifth level (Figure 2). It is worth pointing out that the deployment is a bit different for block 2, which is differently oriented and in which the hatched floor in figure 2 guarantees a good connection between the left and right side of the building.

2.2 Experimental tests

For each configuration three tests of about 300 *s* have been carried out, with a sample rate of 200 *point/s* using ambient noise only as source of vibration. The level of excitation being very low, a quasi-linear behavior has been shown and therefore the spectral analysis is meaningful. The data has been analyzed in the frequency domain by plotting the power spectral density (PSD) of each record and the cross spectral density (CSD), in terms of amplitude and phase factor, of selected couples of records with the corresponding coherence functions. As well known, peaks on PSD could be associated to structural frequencies while the same peaks on CSD, with value of phase factor equal to 0° or 180° and value of coherence function close to unity, confirm this statement and give some indications on the modal shape associated to each structural frequency (Bongiovanni et al. 1990, Clemente 2002).

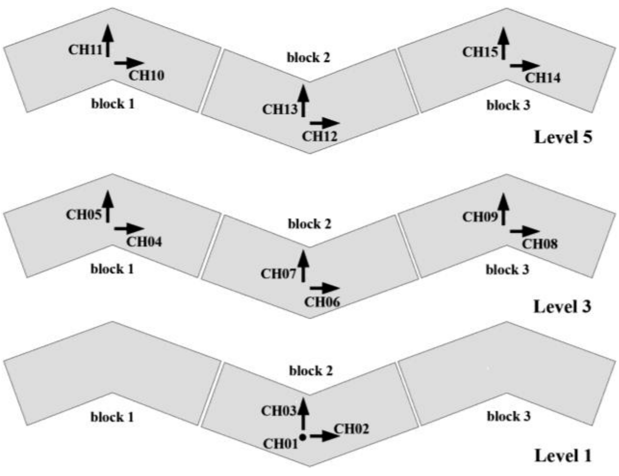

Figure 1. General plan of the building composed by three blocks and global configuration.

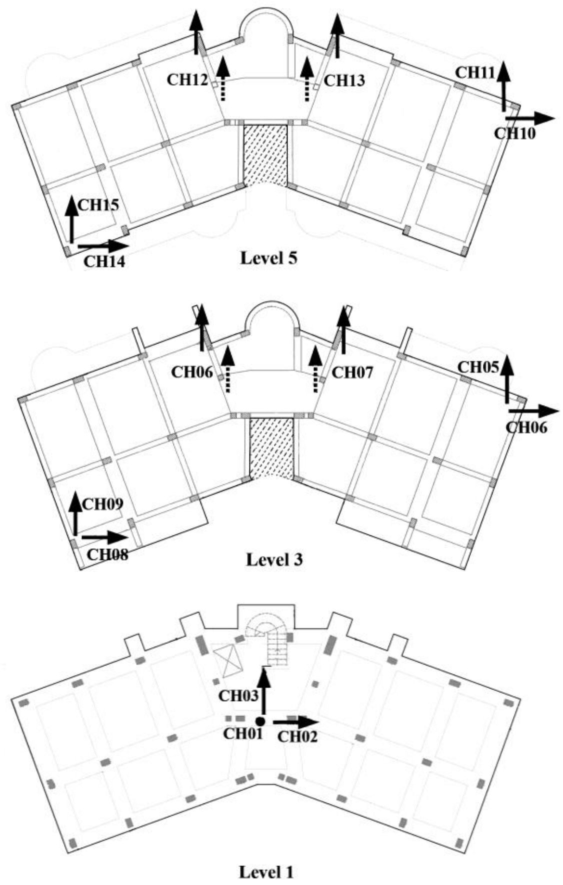

Figure 2. Local configurations (dotted arrows for CH6, CH7, CH12 and CH13 are relative to block 2, in which the hatched floor is present)

3 DATA ANALYSIS

3.1 Global configuration

In figure 3, PSDs of the three sensors in longitudinal direction and of the three sensors in transversal direction, on level 5, are plotted. The different response both in terms of resonance frequencies and corresponding spectral amplitudes, demonstrated that the three blocks vibrate separately and joints are effective.

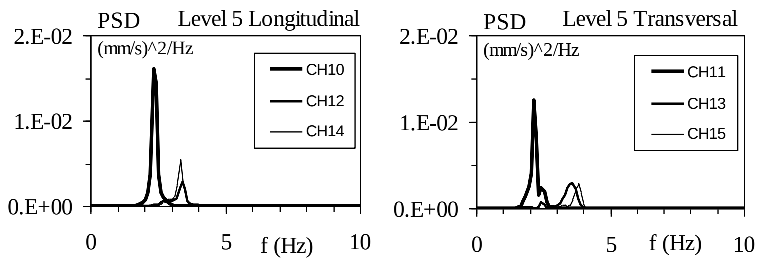

Figure 3. PSD sensors Level 5 Global Configuration

It is apparent the higher flexibility of block 1 with reference to block 2 and block 3. As a matter of fact, peak at the first frequency is much higher and also the frequency is shifted to lower value. That is consistent with the loss of stiffness subsequent to the loss of masonry infill; this also determines a reduction of the mass, but the first effect is evidently more significant. In table 1 the resonance frequencies for each block are reported. The slight differences between the two less damaged blocks (block 2 and block 3) could be associated to a different distribution of mass and/or to slight structural differences.

Table 1. First resonance frequencies of each block in the global configuration.

Block	*First transversal frequency (Hz)*	*First longitudinal frequency (Hz)*
1	2.15	2.34
2	3.51	3.41
3	3.80	3.32

3.2 Block 1 – local configuration

Two frequencies are apparent in the PSDs of the records obtained on the fifth level, in transversal direction, except for CH12 (Figure 4). CSDs CH05-CH09 and CH11-CH15 (Figure 6) show that the lower frequency is associated to a translational mode, while the other is relative to a torsional one with center of rotation close to CH12. A higher frequency, apparent in the mentioned CSDs, is associated to a complex modal shape in which the left and the right parts of the block rotate around a center close to the stair area. Their movement in the horizontal plane is like the flutter of the wings of a bird.

In PSD of CH10 only the first longitudinal resonant frequency is apparent, while in CH14 also the already found complex one is present; the torsional frequency, very similar to the longitudinal one, is less visible being the sensors very close to the center of rotation (Figure 5). The values of the frequencies are reported in table 2.

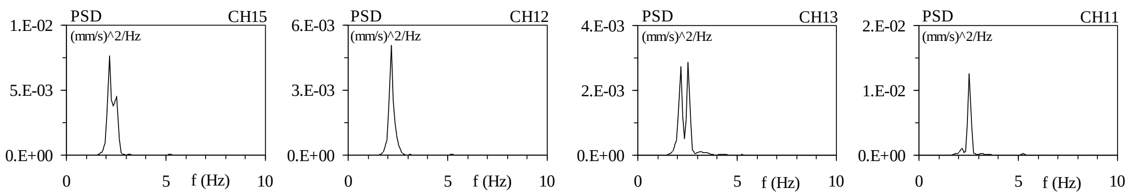

Figure 4. Block 1 – local configuration. PSD of transversal sensors on level 5.

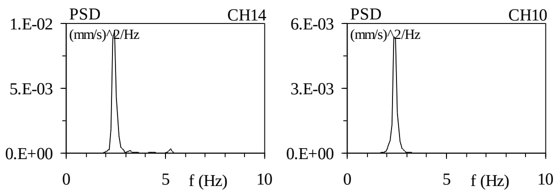

Figure 5. Block 1 – local configuration. PSD of longitudinal sensors on level 5.

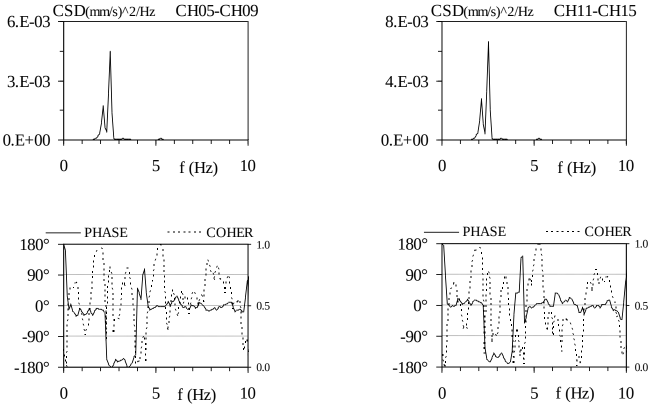

Figure 6. Block 1 – local configuration. CSD of transversal sensors on level 3 and level 5.

Table 2. Resonance frequencies (*Hz*) of all the blocks.

Block 1	*Block 2*	*Block 3*	*Description*
2.15	3.51	3.80	Transversal
2.34	3.41	3.32	Longitudinal
2.54	4.39	4.80	Torsional
5.37	-	7.80	Complex

3.3 Block 2 – local configuration

As for block 1, two frequencies are apparent in the PSD of records obtained in transversal direction on level 5 (Figure 7). The CSD CH05-CH09 shows that the lower one is associated to a translational mode and the other is relative to a torsional mode (Figure 9). It is worth noting the absence of the complex modal shape, pointed out in block 1. This occurrence is due to the presence in block 2 of a portion of floor, which is absent in block 1, as already pointed out in figure 1. Only one frequency is evident in the PSD of records obtained at CH10, which is in the longitudinal direction (Figure 8). Instead, the torsional one is also apparent in CH14. As a result the center of rotation is close to CH10. The frequencies obtained for block 2 are summarized in table 2.

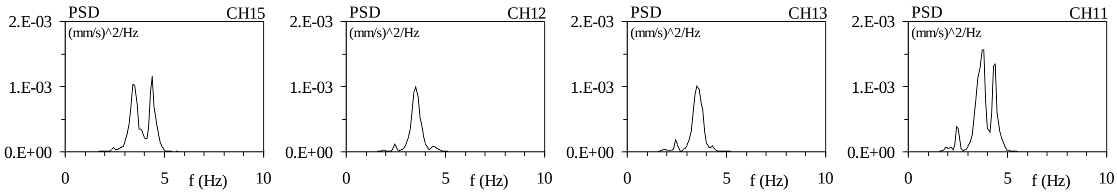

Figure 7. Block 2 – local configuration. PSD of transversal sensors on level 5.

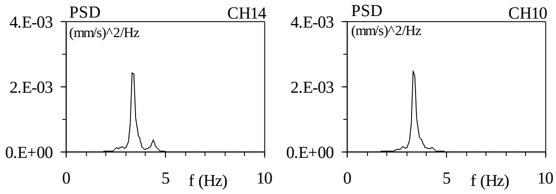

Figure 8. Block 2 – local configuration. PSD of longitudinal sensors on level 5.

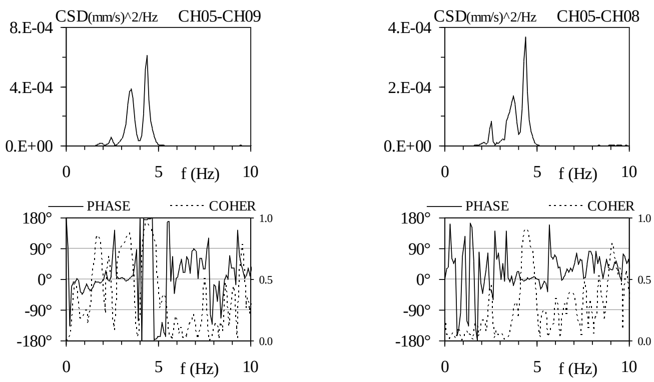

Figure 9. Block 2 – local configuration. CSD sensors on level 3.

3.4 *Block 3 – local configuration*

The PSDs of the records obtained in transversal direction on level 5 show three frequencies associated to a translational mode, to a torsional mode and to a complex mode similar to the one of block 1, respectively (Figure 10). The CSD CH05-CH09 (Figure 12) confirms this statement. From PSD CH14, are apparent the frequency in the longitudinal direction and the mentioned torsional and complex frequencies (Figure 11). Only peack at the translational frequency is evident in CH10, which is very close to the center of rotation. In table 2 also the frequencies obtained for block 3 are reported.

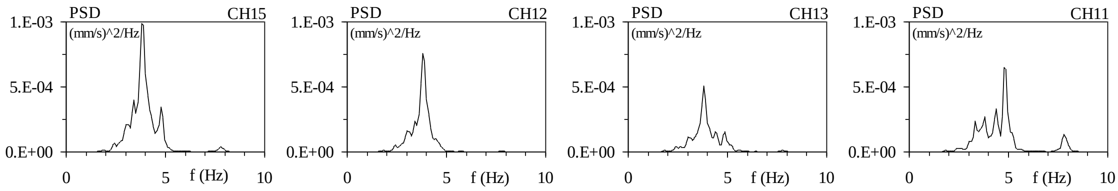

Figure 10. Block 3 – local configuration. PSD of transversal sensors on level 5.

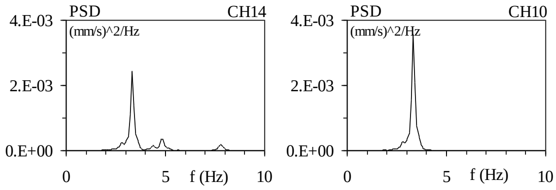

Figure 11. Block 3 – local configuration. PSD of longitudinal sensors on level 5.

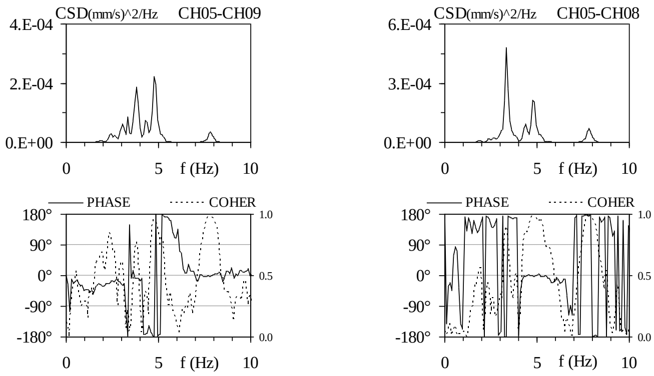

Figure 12. Block 3 – local configuration. CSD sensors on level 3.

3.5 Considerations

As already pointed out, the collapse of the masonry infill wall has produces the significant reduction of the first resonance frequency of block 1. The higher damage level in block 1 was probably related to the complex mode, related to the absence of the portion of floor. In table 3 the modal amplitudes of the translational and torsional modes, at the sensor location on level 5, are reported for the three blocks. For the translational mode, only block 2 shows a homogeneous field of displacements, while a torsional component is present for block 3 and bock 1. The amplitudes of the torsional mode show that the center of rotation is almost on the symmetry axis for block 2, which is almost regular and no damaged, while it is shifted in block 3 and even more in block 1, in the opposite direction of the collapse wall.

Table 3. Normalized transversal and torsional modal amplitude.

	Transversal mode					*Torsional mode*				
Block	*Freq. (Hz)*	*CH15*	*CH12*	*CH13*	*CH11*	*Freq. (Hz)*	*CH15*	*CH12*	*CH13*	*CH11*
1	*2.15*	1.00	0.81	0.60	0.37	*2.54*	-0.60	-0.19	0.48	1.00
2	*3.51*	0.96	0.94	0.95	1.00	*4.39*	-0.93	-0.25	0.20	1.00
3	*3.80*	1.00	0.88	0.71	0.52	*4.78*	-0.73	-0.23	-0.49	1.00

4 HYPOTHESIS OF INTERVENTION

A suitable retrofit of the building should concern the consolidation of all the structural elements, which showed high deformability during the seismic event. Besides, also the effectiveness of the structural joints should be checked to verify their consistency with the present safety requirements. The solution proposed is to introduce an isolation system, in order to limit the seismic action that affect the structure in case of earthquake.

First of all, the seismic vulnerability of the building in its present condition (i.e., after the simple restoration of the damaged parts) has been evaluated, in order to find out the maximum seismic action that the superstructure can support in the elastic range. Then, the isolation system has been designed, which reduces the seismic input to the superstructure to that maximum one.

The problem of the relative displacements between the blocks has been solved by joining them at the first floor above the isolation system. Due to the slenderness of the building in the transversal direction, some devices could be subjected to traction under seismic actions. In order to avoid that, a very high period of vibration has been chosen ($T \approx 3.0$ *s*), so the spectral amplitude is very low. The final solution is in figure 13: 26 HDRB (K_e= 744 *N/mm*) and 55 sliding device compose the system.

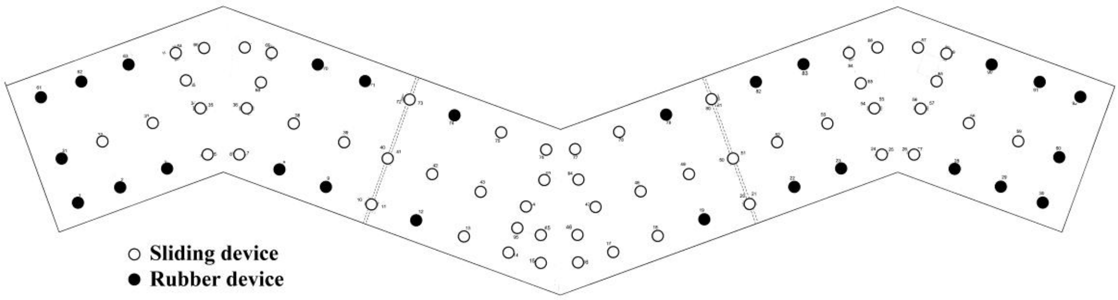

Figure 13. Isolation devices deployment.

5 CONCLUSIONS

The studied building suffered important damages during L'Aquila earthquake. Before designing the seismic retrofit, the experimental dynamic analysis has been performed, which pointed out the following characteristics:

- non structural elements, such as masonry infill walls, played an important role in the dynamic behavior of the building; they probably saved the structure from collapse;
- block 2 presented a more regular dynamic behavior with reference to blocks 1 and 3, due to the presence of a part of floor and therefore suffered lower damages;
- block 1 and block 3 show a complex modal shape, which caused the higher damage level.

The restoration of the building, using traditional technologies, could be very expensive and not suitable in reducing the seismic vulnerability of the structure. Therefore a seismic retrofit, based on the insertion of a base isolation system, has been proposed, which seems to satisfy all the safety requirements.

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