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EFFECTS OF FAR FAULT EARTHQUAKES IN RETROFITTED SEISMICALLY ISOLATED BUILDING

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Abstract

The seismic sequence during years 2016 and 2017 involved a great area In Central Italy, involving four regions and more than 100.000 buildings. Many main shock events occurred, namely Amatrice earthquake (Mw 6.0 on August 24th, 2016), Valnerina earthquakes (Mw 5.9 and 5.4 on October 26th, 2016), Norcia earthquake (Mw 6.5 on October 30th, 2016), and Montereale – Capitignano earthquakes (Mw 5.0, 5.5 on January 18th 2017) About 80.000 buildings were damaged in the seismic events. Some areas were involved also in the 2009 seismic events (L'Aquila earthquake).

After L'Aquila earthquake, during reconstruction period, many collapsed buildings, or heavily damaged buildings, were demolished and reconstructed with base isolation (both in foundation and above first elevation columns). Some buildings, which reported less structural damage during 2009 L'Aquila earthquake, were retrofitted with isolation systems. The isolation systems were generally composed by both rubber high damping isolators, and plane friction isolators (sliding devices).

Several different dynamic and seismic behaviour were observed in those buildings, depending upon isolation system (noticeable differences have been observed between curved sliding isolators and rubber high damping isolators) and upon soil – structure interaction. Significant displacement has been observed caused by soft soil, and inverse velocity seismic soil profile. Also, frequency response influenced isolated building behaviour.

In the work several buildings are examined, analyzing the seismic behaviour both in the 2009 earthquake (with no isolation system) and during 2016 – 2017 seismic events (with isolation system).

Keywords: Seismic isolation, earthquake, structure monitoring.

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1 INTRODUCTION

Seismic isolation is based on the terrific reduction of the energy that the soil transmits to a structure instead of relying on its resistance, so that the structure itself becomes less vulnerable to earthquakes. This result is obtained by increasing the fundamental period of vibration of a structure. As a result, the superstructure will be subject to very low accelerations under the design earthquake and can support its effects in the elastic range, without any damage to the structure and its content. The displacements, which increase with the period of vibration, are concentrated at the base of the building, i.e., at the isolation devices. These are subject to large relative displacements, while the superstructure vibrates slowly, almost like a rigid body. The historic analysis demonstrated that the concept of decoupling the motion of the structure from that of the soil is not new, even though the device technology developed recently.

According to the available data, more than 20,000 structures in the world have been protected by passive anti-seismic (AS) techniques such as seismic isolation (SI) or energy dissipation (ED) systems, shape memory alloy devices (SMADs), or shock transmitter units (STUs) [1-5]. They are in more than 30 countries (Fig. 1) and concern both new constructions and retrofits of existing structures of all kinds: bridges & viaducts, civil and industrial buildings, cultural heritage and industrial components and installations, including some high risk nuclear and chemical plants and components.

Base isolated structures are designed to satisfy:

- The no-collapse requirement, according to which the structure should withstand the design seismic action without local or global collapse. To address this requirement, the ultimate capacity of the isolating devices, in terms of strength and deformability, is not exceeded, at the ultimate limit state, at which the isolating devices may attain their ultimate capacity, while the superstructure and the substructure remain in the elastic range.
- The damage limitation requirement, according to which the structure should withstand a seismic action having a larger probability of occurrence than the design seismic action, without damage and limitations of use. To address this requirement, the interstorey drifts are limited in the substructure and the superstructure at the damage limitation state.

Following the probabilistic approach, the design earthquake is the event with a certain probability of exceedance in a fixed time length. In the optic of a deterministic approach, it is the maximum credible event at the site.

Values of the isolation system properties to be used in the analysis shall be the most unfavorable ones to be attained during the lifetime of the structure. The check of isolation devices is performed with reference to the maximum displacement, which are obtained by using their minimum stiffness at the time of their production. On the contrary, the check of the superstructure is done using the isolator stiffness after aging, which is higher than the initial one and corresponds to the maximum acceleration value

The use of SI became particularly rapid especially after the Abruzzo earthquake of April 6, 2009, because of the large damage caused by this event to the conventionally founded structures and cultural heritage [8-9]. The use of the traditional High Damping Rubber Isolators (HDRBs), in conjunction with some sliding devices (SDs), is also going on, in both L'Aquila and other Italian sites, for several new constructions and retrofits [6, 7, 10, 11]. The application of new retrofit techniques using SI, has also been applied for both reconstructing L'Aquila and for enhancing the seismic protection in a very earthquake-prone area.

It appears obvious that the seismic response of the isolation system under earthquakes with energy lower than the design one may be quite different than that under the design earthquake, and The stiffness of isolators that corresponds to very low shear strain determines an increase of the isolation vibration frequencies.

2 2009 L'AQUILA EARTHQUAKE

L'Aquila city was struck down by a 6.3 Mw and seismic moment M0 = 3.7 x 1018 N m (according to INGV) earthquake in 2009 April 6th. Its historical centre and all the surrounding suburbs were severely damaged, causing 309 casualties, and more than 1500 people injured. L'Aquila has been the first Italian important city directly destroyed by a near fault earthquake since Messina earthquake (1908). Many buildings collapsed completely, both in masonry structure and in reinforced concrete ones. Many buildings suffered heavy structural damages, like shear cracks in the pillars, shear cracks in the concrete walls, nodal ruptures, and even total or partial collapses. Some more recent buildings evidenced noticeable structural damage, mainly due to design errors and constructive inadequacy.

Registered data showed response spectra very different due to the local amplification effects.as shown in Fig. 1. Response spectra evidenced a local strong amplification in correspondence of the high frequencies (0 – 3 Hz) in the suburbs (Mount Pettino west area, in correspondence with an active local fault), where several reinforced concrete buildings were heavily damaged also in structural elements.

The damage can be associated to dynamic resonance in correspondence of the highest values in the response spectra, due to the reinforced concrete building characteristics (main frequency often in the range 2.0 – 10.0 Hz). Some differences, due to soil amplification effect, were found in the center of the city, as shown in fig. 3. The local site effect reveals itself noticeable in relationship with the dynamic behaviour of seismic isolated buildings.

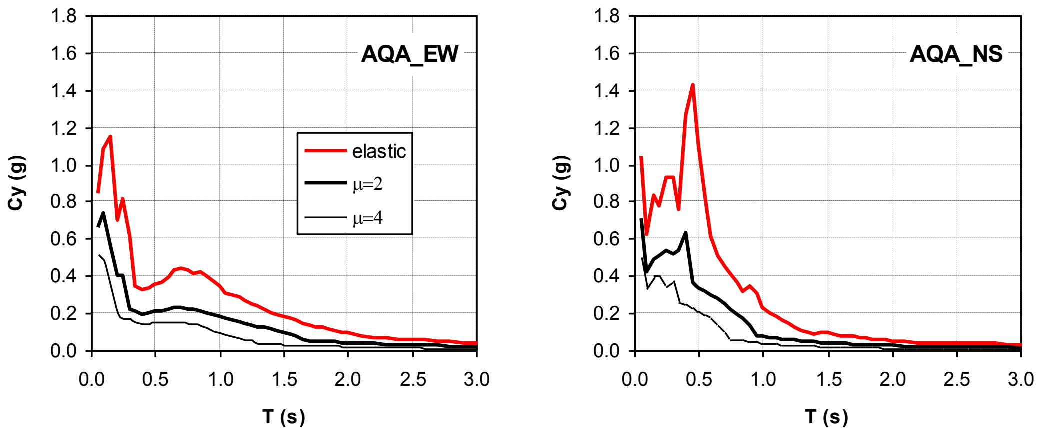


Figure 1. Response spectra in L'Aquila west area (near fault), amplification effect at 10.0 – 2.0 Hz

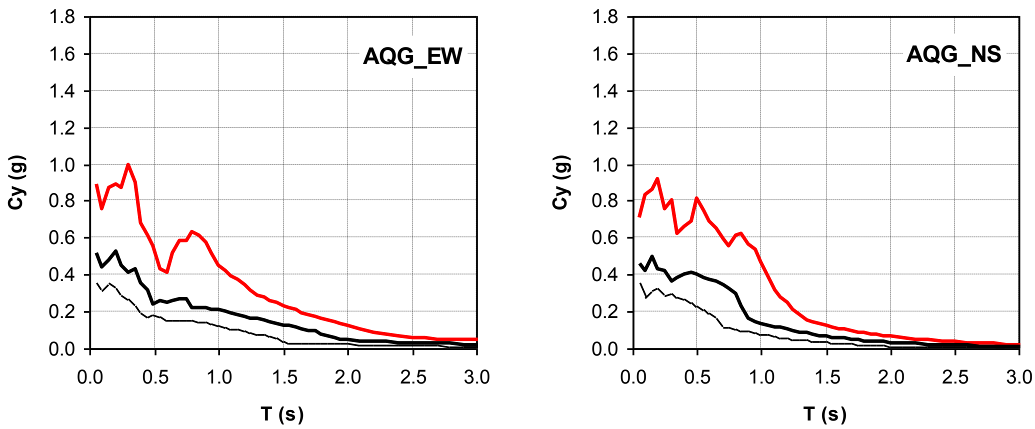


Figure 2. Response spectra in L'Aquila central area, with secondary amplification effect at 0.6 – 0.7 Hz

3 POST EARTHQUAKE RECONSTRUCTION AND ISOLATED RETROFITTED BUILDING

After the main seismic event, many buildings were retrofitted by the application of an isolation system.

The base isolation seismic protection is a technique increasingly widespread in Central Italy, which is strategic for repair and strengthening both damaged and retrofitted buildings and new ones. In particular, when in the presence of structures with considerable structural irregularities, both elevations that planimetric, with structural elements with poor energy dissipating capacity of the seismic input energy, and construction details not satisfying due to the seismicity of the area, the base seismic isolation is the only constructive solution to the problem of making these structures seismic-resistant under conditions compatible even with a complex architectural appearance of the buildings themselves.

The use of the anti-seismic systems and devices in the city context already includes not only the strategic structures (civil defence centres, hospitals) and the public ones (schools, churches, commercial centres, hotels), but also, and mainly, residential buildings and even many small and light private houses.

A noticeable number of existing (and also reconstructed) buildings were seismically improved by application of seismic isolators, in particular High Damping Rubber Isolators (HDRB) and Sliding Devices (SD). In the following some of them will be examined in their main features.

3.1 Building #1 (near west area)

The first building under examination is located in the west area of the city, were no secondary amplification effect are detected. The building was heavily damaged during L'Aquila earthquake and was retrofitted by an isolation system. The damage concerned mainly brittle fracture in some pillars at low levels, and significant damage to the external infill panels, internal brick masonry panels and secondary non-structural elements. The type of non-structural elements damage is strongly variable but it is mainly related to wrong construction techniques, and, in second order, to wrong design.

In most of these collapses, the presence of non-structural columns would prevent the rotation and failure.

The high deformability of reinforced concrete structures has carried out to high levels of the compression and shear forces. Storey drifts have reached high values, not compatible with the stiffness and relevant flexibility of masonry infills. After 2009 earthquake, which caused the noticeable damage in structural and non-structural elements, the only way to prevent further damage and increased collapse risk probability has been the seismic behaviour enhancement by applying anti seismic devices (isolators) with a retrofitting technique. Furthermore, the high planimetric non regularity of the building (T-shaped) can be regularized only by the application of an isolation system.

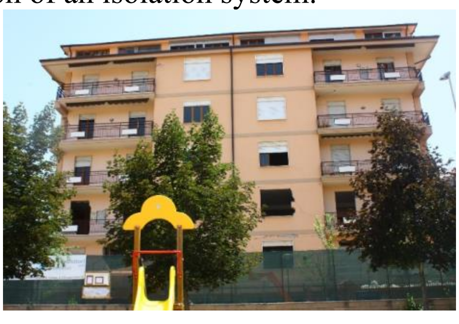


Figure 3. a) Building # 1 (seven storeys) b) Brittle fracture in a pillar

By cutting pillar top edge, after reinforcing foundation and pillar lower part, 32 elastomeric isolators and sliders have been positioned. The HDRBs are 9 FIP SI-S 700/200 and 10 SI-S 800/200, and the sliding devices area 13 FIP VM 250/700/100. In fig. 5 the insertion of an isolator in the top of the pillar is shown.

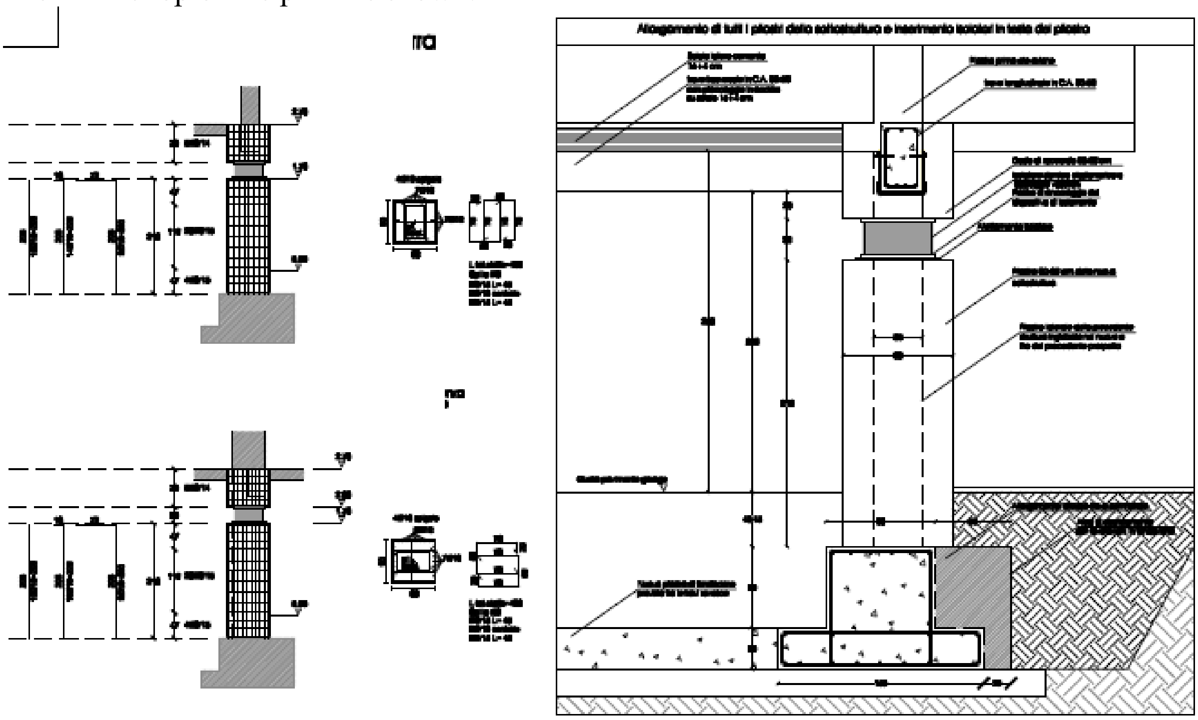


Figure 4. a) Enhancement of the lower part of pillars b) Insertion of a HDRB isolators at the top of the pillar

Figure 5. a) Strengthening of a pillar b) Cutting of a pillar for isolator insertion

Figure 6. a) Strengthening and cutting a pillar b) Control of a pillar cutting

Figure 7. a, b) Level 0 with all isolators at the top of strengthened pillars b)

The retrofitted structure has reached a level of vulnerability, by applying anti-seismic isolation, equal to the 80% of the corresponding new structure, according Italian seismic code. The same level of seismic vulnerability, before the application of the isolation system, was equal to only the 15%, value which is confirmed by the damage in the 2009 earthquake. This building was hit again by nine strong earthquakes almost in the same area (Central Italy, epicentral distance from 30 to 50 km), in 2016 and 2017, (Mw 6.0 on August 24th, 2016), Valnerina 3 earthquakes (Mw 5.9 and 5.4 on October 26th, 2016), Norcia earthquake (Mw 6.5 on October 30th 2016), and Montereale – Capitignano 4 earthquakes (Mw 5.0, 5.5 on January 18th 2017) with no damage at all.

3.2 Building #2 (west area)

The second building under examination is located in the west area of the city too, were no secondary amplification soil effect are detected. Also this building was heavily damaged during L'Aquila earthquake, and was retrofitted by an isolation system. The damage concerned mainly brittle fracture in almost all pillars at ground level, and heavy damage to the external infill panels, internal brick masonry panels and secondary non-structural elements. The type of non-structural elements damage has been caused by the low stiffness of the vertical structure, with expulsion of the infills at the first and second storey.

The high deformability of reinforced concrete structures has carried out to high levels of the compression and shear forces. Storey drifts have reached high values, not compatible with the stiffness and relevant flexibility of masonry infills. After 2009 earthquake, which caused the noticeable damage in structural and non-structural elements, the only possibility to prevent further damage and increased collapse risk, also for this building, has been evaluated by enhancing the seismic behaviour with the application of anti-seismic devices (isolators) with a retrofitting technique. Instead of realizing great plinth above the pillars, in this building the uplift of the structure was performed by inserting high strength steel bars, sustaining all the structure weight during isolators insertion in the top of the pillars.

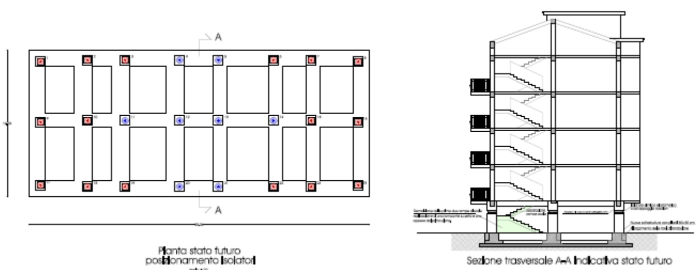


Figure 8. a) Position of isolators: red rubber isolator SI/N 450/126, blue sliders VM 250/250; b) section.

Figure 9. a) Building # 2 (six storeys) b) damage end demolition of the infills

The damage caused by the 2009 earthquake in the building infills determined the need to completely demolish all the infills at the first two levels, and partially at superior levels (Fig. 8).

The particular (and regular) shape in plan ed in elevation permitted to easily insert an isolation system, directly in the zero level, at the top of pillars, without any interference with secondary elements (infills, garage doors, lift) and with no compromission of the utilization of the rooms at that level.

In order to strengthen the structure, an enlarged concrete section with new reinforcement bars were set up in all the pillars (Fig. 10 b).

Figure 10. a) Brittle fracture in the top of a pillar b) Increase of section and reinforcement bar in a pillar

Depending on the structural characteristics (stiffness, residual capacity, deformability and interaction with infills), the isolation system has been designed in order to full satisfy the seismic demand in terms of displacement at the isolation level. It's worth noticing that this building is located near an important fault (which caused destructive earthquake in the pas centuries), were near faults effects have to be taken into account in order to avoid inappropriate dynamical behaviour (vertical and horizontal resonances, soil – isolation system – structure interaction)

Figure 11. a) HDRB and sliding devices at top of pillar b) Sliding device at top of a pillar

Figure 12. a) HDRB rubber isolator SI/N 450/126 b) Sliding device in correspondence of the staircase

The building has been retrofitted with sixteen SI-N 450/126 high damping rubber isolators and eight sliding devices VM 250/250. It's worth noticing the position of sliding devices in correspondence of the staircase, (Fig. 12b) where they have been placed at a different height with respect the isolation level. The area of this retrofitted building is quite different from the preceding one, and is located near an active fault which caused several strong earthquakes in the past. The area has some resonances caused by the fault proximity. Also, this structure has been completely designed according to Italian code for new structures.

3.3 Building #3 (central area)

The third building under examination is located in the central area of the city, were an important secondary amplification soil effect is detected. Also this building was heavily damaged during L'Aquila earthquake, and after demolition has been rebuilt with isolation system.

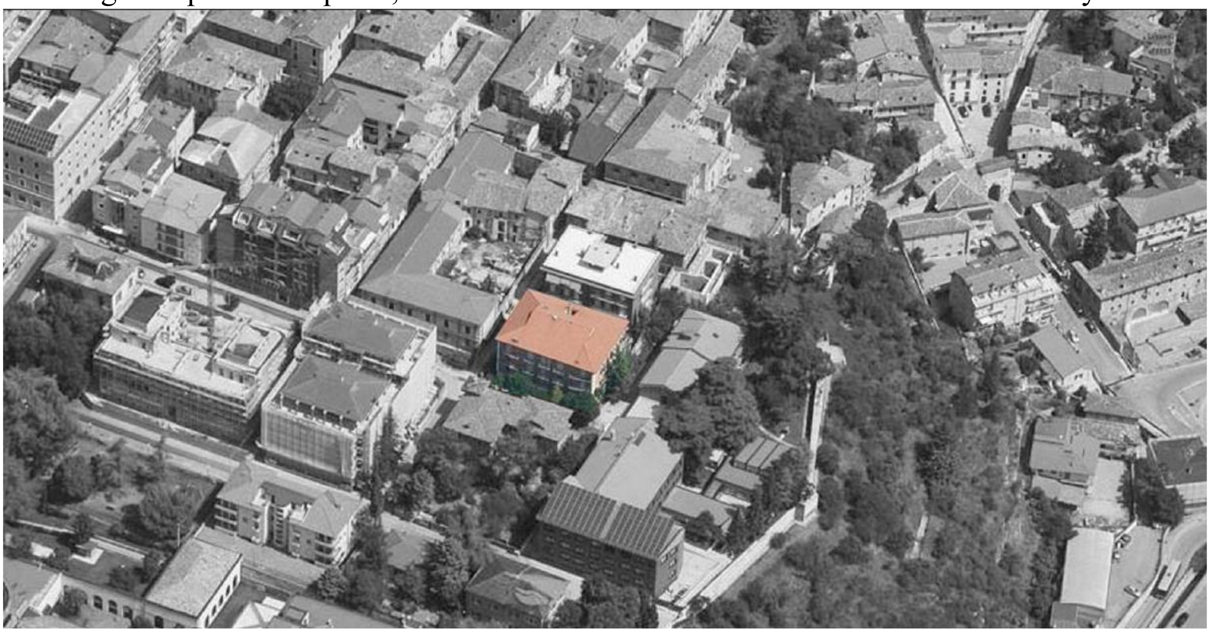


Figure 13. Isolated building in the centre of L'Aquila, with secondary amplification effect at low frequencies.

The maximum seismic performance for this building has been gained by seismic isolation, but, according to the shown amplification effect (fig. 2), an accurately seismic design has been performed to take into account the probable high displacement during earthquakes in this area. Isolators were positioned underground, in correspondence of the new pillars, following the scheme in fig. 13a, with HDRB isolators FIP SI-S 800/160, and sliding devices FIP VM 300/600/600.

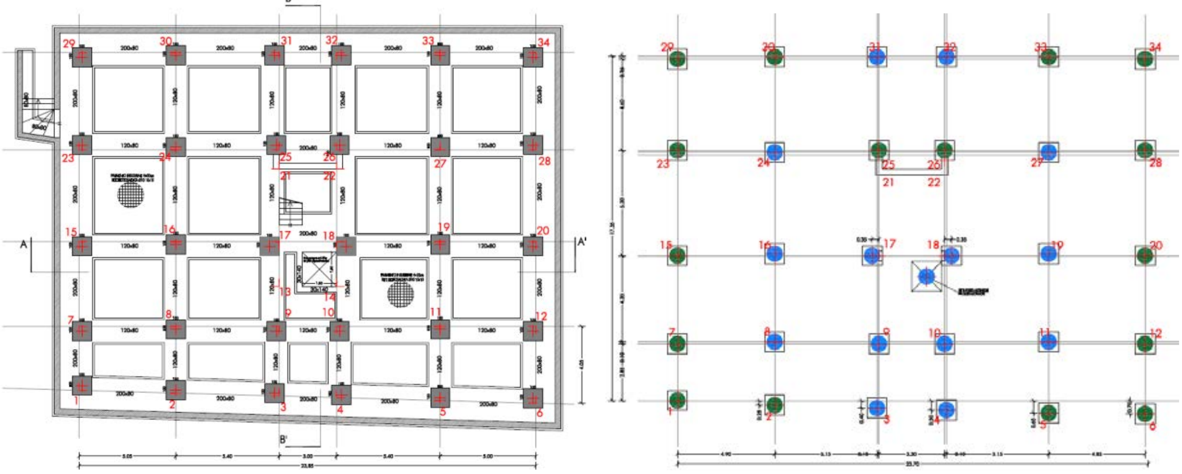


Figure 14. a) Understructure of isolation system b) HDRB isolator SI-S 800/160, sliders VM 300/600/600

The isolation system has been designed in order to take into account not only the structure typology, but also the soil – structure interaction, in particular the secondary resonance at low frequencies which area typical of the centre of the city (Fig. 2). In particular (Figs. 14, 15), seismic movement joints have been designed to permit large displacement of the superstructure.

Figure 15. a) HDRB isolator SI-S 800/160 b) sliding device VM 300/600/600

Figure 15. a) HDRB isolator and external seismic gap b) Horizontal gap understructure - superstructure

3.4 Building #4 (Umbria Civil Protection Center In Foligno)

The Operative Centre Building of the Umbria Civil Protection Centre at Foligno is composed by several isolated buildings, among which a hemispherical shape, with four storeys above the ground level, the first of which contain the isolators, and an underground storey, and more regular buildings.

The superstructure of the dome building is seismically isolated by means of ten high damping rubber bearings, located along the perimeter, which transfer the loads to the foundations. These are composed of reinforced concrete plinths, supported by four piles each and connected to each other by means of reinforced concrete beams. The height of the building from the extrados of the isolators is 17.6 m, the diameter of the first floor is 31.4 m. The characteristics of the isolation devices assumed in the structural design are reported in Tab. 1. As usual, the nominal values of G and ξ are referred to a unitary shear strain.

Fig. 16 – The structure of the Operative Centre of the Civil Protection Department at Foligno during the construction

The superstructure is formed of ten radial arch elements, equally spaced along the perimeter and corresponding to the isolation device locations. They run from the first floor, where they are connected by a perimeter ring beam, to the top of the building, where they are connected to another smaller ring beam. The arches support two other intermediate floors by means of ring beams along their perimeters. All the three floors can be considered rigid in their plane. They have a central hole delimited by an outer concrete cylinder, 16 cm thick, which starts from the first floor and rises up to the top, linking all the floor. Another 16 cm thick cylinder is inside the previous one and contains the elevator and all the facilities. It has a concrete slab at its lower end, is suspended from the top ring beam and ends 3.74 m below the ground level. A helicoidal staircase, with a concrete slab of 12 cm, and the landings at the floors connect the two cylinders. Inside the lift cylinder there is a metal structure that support the infill masonry wall, which has a negligible interaction with the concrete structure.

Both the cylinders were supported at their base during the construction of the building. Then the provisional support structures were removed and the loads acting on the cylinders (self-weight and additional permanent loads) were transferred to the arch elements at their top.

The building was designed according the Italian code for building in seismic area in force at the time of construction (OPCM 3274, 2003). A detailed analysis of the seismic hazard was carried out on purpose and allowed assuming a design value for the peak ground acceleration on rigid soil equal to 0.28g.

Diameter Φ (mm)	1000
Thickness of the rubber layers t_i (mm)	10
Total rubber thickness t_e (mm)	240
Shear modulus of the rubber G (N/mm^2)	0.4
Thickness of the steel laminates t_s (mm)	4.0
Thickness of the end steel plates t_{ss} (mm)	30
Equivalent horizontal stiffness K_e (kN/m)	1310
Equivalent damping ratio ξ (%)	≥ 10

Table 1 – Geometrical and mechanical characteristics of the HDRBs

The seismic monitoring system is composed of twelve accelerometers, deployed in the building as follows (Fig. 17):

- three accelerometers were at the basement (A01 along x direction, A02 in the vertical direction and and A03 in y direction);
- seven accelerometers were at the first floor, just above the isolation system: three of them in the vertical direction (A04, A05 and A06), two in y direction (A07 and A09) and two in x direction (A08 and A10; A10 is oriented in the opposite direction of A08, therefore the sign of the recorded time histories was changed and indicated as -A10);
- two accelerometers were at the top of the building in the horizontal directions (A11 in y direction, A12 in x direction).

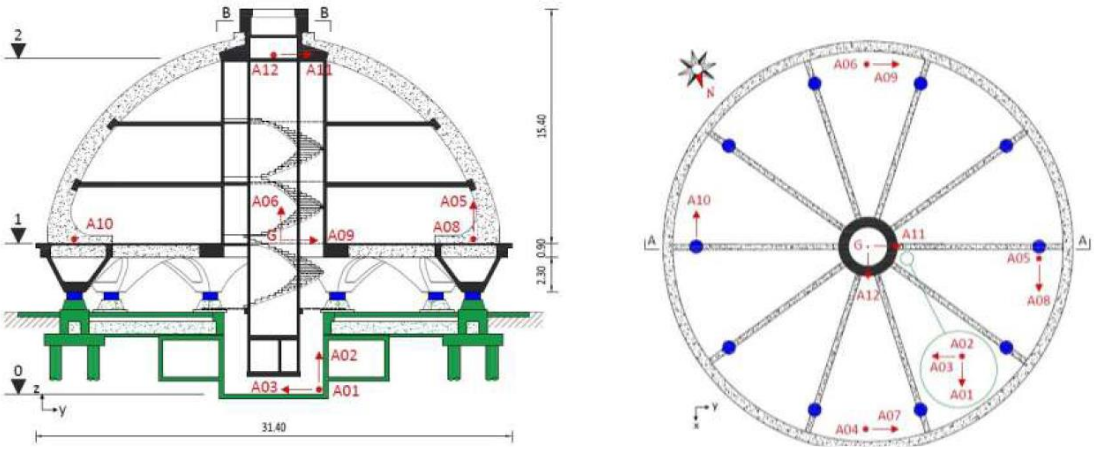


Fig. 17 – Accelerometers network: A01, A02 and A03 are at the basement inside the building; A04 to A10 are at the first floor above the isolation system; A11 and A12 are at the top of the building.

The accelerometer network recorded all the events that struck Central Italy since August 24th, 2016. The epicentres of earthquakes occurred in far field, as the epicentral distance of

2016 – 2017 earthquakes was at about 50 km. A detailed analysis of the behaviour of the seismic isolation system under different energy earthquakes was carried out.

The design fundamental frequency of the isolated building was equal to 0.38 Hz. Actually, different values were found during the earthquakes recorded. A fundamental frequency of about 1.9 Hz was estimated during ambient vibration tests and low energy earthquakes, whiled a first resonance frequency of about 1.0 Hz was found under the strongest event recorded. Anyway, the effectiveness of the seismic isolation system under all the events of the sequence was verified and discussed in a previous paper.

A secondo building in the Civil Protection Center in Foligno is the Forest Ranger Building and the Monitoring System, with an Isolation System

The Forest Ranger building of the Umbria Civil Protection Centre in Foligno is a seismically isolated reinforced concrete building (Figure 18). It has an underground level and two floors above the ground. The maximum dimensions in plan are about 16 x 31 m, in x and y direction, respectively. The inter-floor heights are 3.14, 4.14, and 3.34 m, for the underground, first and second level, respectively.

Figure 18. View of the Forest Ranger building (photo P. Clemente)

The isolation system is composed by (Figure 19):

1. 12 HDRBs of Type 1, located along the perimeter of the main rectangular portion;

2. 4 flat slider devices (SD) with a lubricated steel-PTFE (polytetrafluoroethylene) interface, having a nominal friction factor of 1.0%, located at the internal column of the main rectangular portion;

3. 4 HDRBs of Type 2, located at the columns external to the main portion.

The isolation devices are located at the top of the columns of the underground level. The characteristics of the HDRBs are shown in Table 2. Schematic outlines of the isolators are in Figure 19.

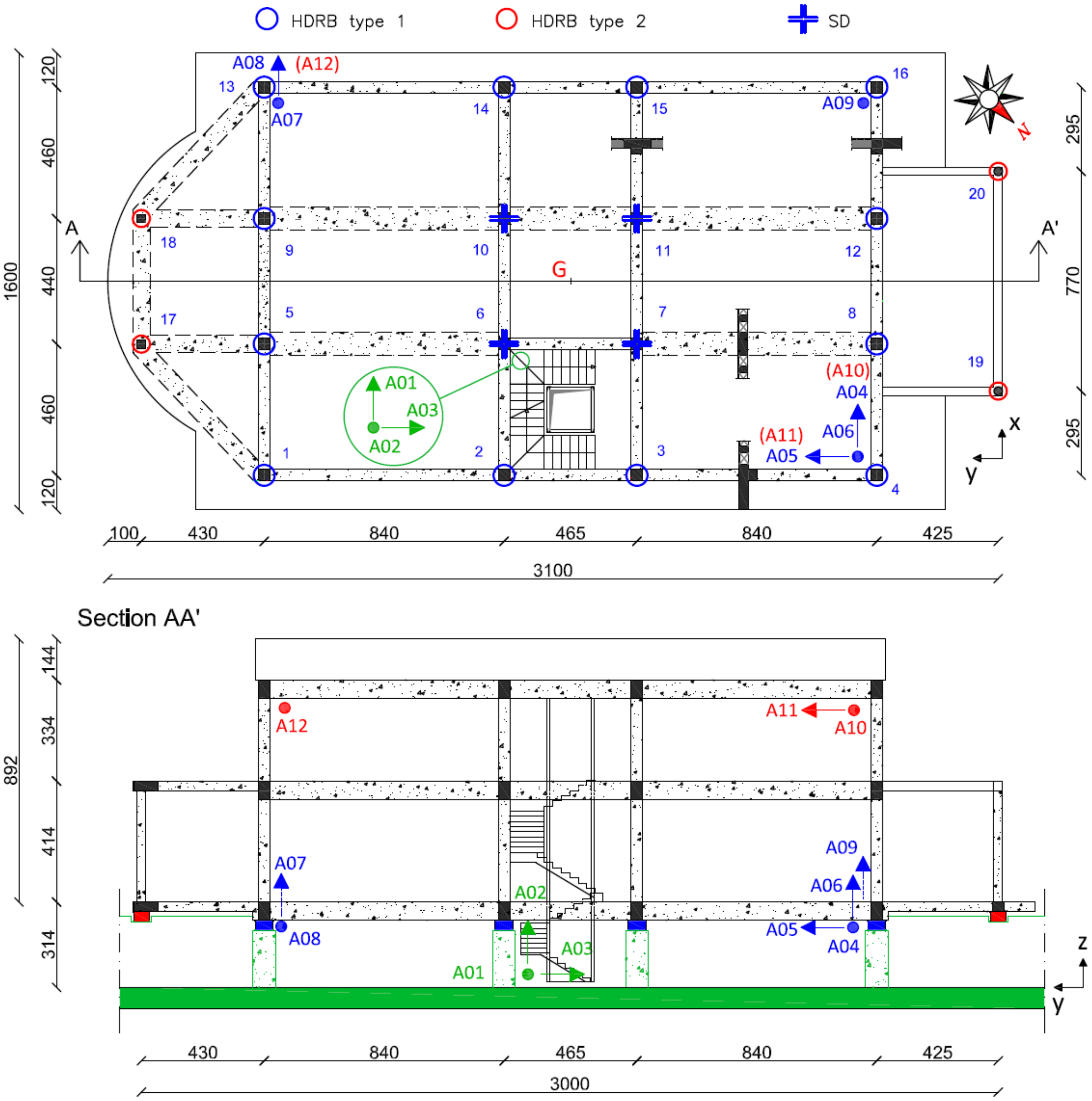


Figure 19. First floor with isolation system and vertical section.

Characteristic	Type 1	Type 2
Number of devices	12	4
Diameter (mm)	700	550
Total rubber thickness (mm)	284	300
Thickness of a single rubber layer (mm)	7	5
Shear modulus of rubber at $\gamma = 1$ (N/mm2)	0.4	0.4
Equivalent horizontal stiffness at $\gamma = 1$ (N/mm)	541	317
Equivalent damping factor at $\gamma = 1$ (%)	10	10
Maximum displacement (mm)	379	395

Table 2. Nominal characteristics of the two types of HDRBs.

The substructure is composed by the foundation beams (120 x 75 cm) and 16 columns (80 x 80 cm), on which the isolators are placed. The superstructure is a frame structure (columns 40 x 40 cm, beams 40 x 64 or 80 x 34 cm). The floors are reinforced concrete and hollow tiles mixed floors, while the external cornices are in reinforced concrete as well as the stairs between the first floor and the second floor. The elevator shaft is a light steel structure linked to the first, second and covering floors and suspended to them. Additionally, the stairs between the underground and the first floor are in steel and hanged to the elevator steel structure.

4 THE 2016 – 2017 SEISMIC EVENTS AND THE BEHAVIOUR OF THE ISOLATED BUILDINGS

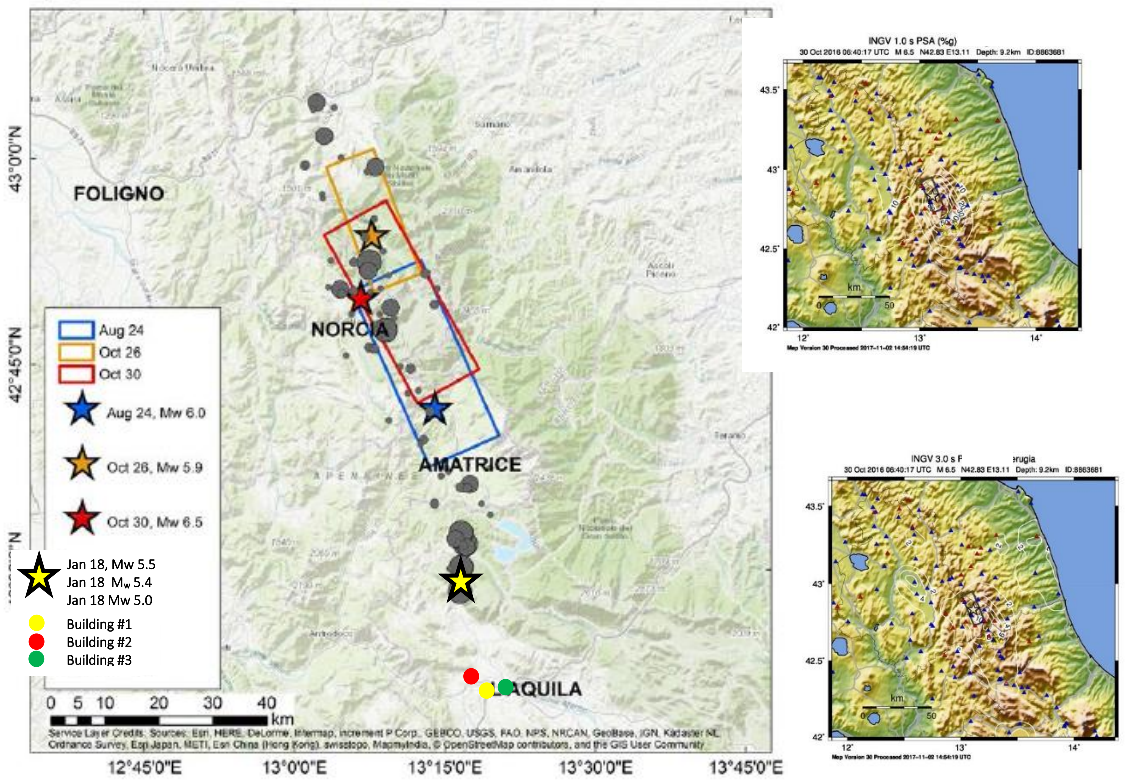


Figure 20 a)– 2016 – 2017 seismic events and position of the isolated buildings b) spectral data (INGV)

The above mentioned earthquakes, with a continued sequence of nine mainshocks, occurred in the same area of L'Aquila and 2009 earthquake. In particular, the buildings under examination have a short distance from the epicentres (about 35 km from Amatrice, 55 km from Norcia, and 20 km from the 2017 sequence). The overall main events are reported in the following table.

SOURCE Time [Utc]	Latit.	Longit.	Depth [km]	Magnitude	Name Record
24/08/2016 01:36:32	**42,698**	**13,234**	**8.1**	**6.0-Mw**	**TN015**
24/08/2016 01:56:01	42,601	13,276	7.7	4.3-Mw	**TN018**
24/08/2016 02:33:29	42,792	13,151	8.0	5.4-Mw	**TN032**
24/08/2016 03:40:11	42,614	13,244	10.7	4.1-Mw	**TN045**
24/08/2016 04:06:51	42,771	13,124	6.2	4.4-Mw	**TN047**
24/08/2016 11:50:31	42.82	13.16	9.8	4.5-Mw	**TN066**
24/08/2016 17:46:09	42,659	13,215	10.3	4.2-Mw	**TN074**
24/08/2016 23:22:06	42,654	13.21	11.8	4.0-Mw	**TN078**
25/08/2016 03:17:17	42,745	13,193	9.0	4.3-Mw	**TN080**

25/08/2016 12:36:05	42.6	13,282	7.5	4.4-Mw	**TN083**
26/08/2016 04:28:26	42,605	13,292	8.7	4.8-Mw	**TN086**
27/08/2016 02:50:59	42,843	13,238	7.8	4.0-Mw	**TN093**
28/08/2016 15:55:35	42,823	13,232	8.7	4.2-Mw	**TN102**
03/09/2016 01:34:12	42.77	13,132	8.9	4.2-Mw	**TO015**
03/09/2016 10:18:51	42,861	13,217	8.3	4.3-Mw	**TO017**
16/10/2016 09:32:35	42,748	13,176	9.2	4.0-Mw	**TP016**
26/10/2016 17:10:36	**42.88**	**13,128**	**8.7**	**5.4-Mw**	**TP021**
26/10/2016 19:18:06	**42,909**	**13,129**	**7.5**	**5.9-Mw**	**TP026**
26/10/2016 21:42:02	42,863	13,121	9.9	4.5-Mw	**TP053**
27/10/2016 03:19:27	42,843	13,143	9.2	4.0-Mw	**TP071**
27/10/2016 03:50:24	42,984	13.12	8.7	4.1-Mw	**TP073**
27/10/2016 08:21:46	42,873	13,097	9.4	4.3-Mw	**TP086**
27/10/2016 17:22:23	42,839	13,099	9.0	4.2-Mw	**TP103**
29/10/2016 16:24:33	42,811	13,095	10.9	4.1-Mw	**TP144**
30/10/2016 06:40:17	**42,832**	**13,111**	**9.2**	**6.5-Mw**	**TP151**
30/10/2016 07:34:48	42,922	13,129	9.9	4.0--ML	**TP170**
30/10/2016 11:58:17	42.84	13,056	10.2	4.0-Mw	**TP235**
30/10/2016 12:07:00	42,845	13,078	9.7	4.5-Mw	**TP237**
30/10/2016 13:34:54	42,803	13,165	9.2	4.1-Mw	**TP251**
30/10/2016 18:21:09	42.79	13,152	9.6	4.0-Mw	**TP275**
31/10/2016 03:27:40	42,766	13,085	10.6	4.0-Mw	**TP310**
31/10/2016 07:05:45	42,841	13,129	10.0	4.0-Mw	**TP322**
01/11/2016 07:56:40	43	13,158	9.9	4.8-Mw	**TP354**
03/11/2016 00:35:01	43,029	13,049	8.4	4.7-Mw	**N.R.**
12/11/2016 14:43:34	42,723	13,209	10.1	4.1-Mw	**TQ077**
14/11/2016 01:33:44	42.86	13,158	11.0	4.0--ML	**TQ092**
29/11/2016 16:14:03	42,529	13.28	11.1	4.4-Mw	**TQ171**

Table 3 – main seismic 2016 events in the area

Many buildings in the area are under monitoring. The examined buildings reported an ideal behaviour in heavy seismic conditions.

Spectral data, recorded at the site of L'Aquila, evidenced some differences between central area and the western area of the city, due to well-known soil resonances in the central area.

The 2016 Norcia earthquake, in particular, caused a damaged building collapse in the central area.

The isolated building had an optimal behaviour during the earthquake. They reported absolute absence of any kind of damage, structural and non-structural. Also, isolators (both HDRB and SD) had no damage and no residual displacement.

The control of the displacement of the isolated structures, in the examined buildings, put into evidence some differences.

In particular, maximum displacement was measured for each superstructure and insolation system in each building, as follows:

Building #1 – maximum displacement 25 mm
Building #2 – maximum displacement 30 mm
Building #3 – maximum displacement 100 mm
Building #4 – maximum displacement 10 mm
Building #5 – maximum displacement 10 mm

The difference of displacement depends on the soil – structure interaction and the relevant differences between the considered areas, and also on the directivity of the earthquake waves.

It's worth noticing that each system has been designed according to the parameters reported in table 2.

Building #	HDRB	SD	K_{esi} [KN/mm]	x	Isolation Period	Design displacement	Maximum displacement
1	9 FIP SI-S	13 FIP VM					

	700/200 10 FIP SI-S 800/200	250/700/100	17.03	15%	2.64 s	300 mm	25 mm
2	16 FIP SI-N 450/126	8 FIP VM 250/250	16.16	10%	2.28 s	250 mm	30 mm
3	16 FIP SI-S 800/160	15 FIP VM 300/600/600	20.16	10%	2.43 s	300 mm	100 mm
4	10 SI-S 1000/240	-	13.10	10%	2.56 s	400 mm	10 mm
5	12 SI-N 700/284 4 SI-N 550/300	4 FIP VM 550/600/600 -	7.76	10%	2.56 s	400 mm	9.28 mm

Table 4 – design parameter and maximum displacement for the buildings

As for the isolated building in Foligno, the effects of the Norcia earthquake of October 30th, 2016, were quite attenuated at Foligno site, due to the distance and the different directivity. It is interesting to evaluate the effects under a strong earthquake. Therefore, the acceleration due to the same event of October 30th, 2016, but recorded at Norcia La Castellina (NOR station), was assumed as input for the dynamic nonlinear analysis of the building. Nor station is very close to the epicentre, at a site with flat surface and subsoil classified as type B.

4.1 Behavior under Ambient Vibrations

The structure was first dynamically characterized using ambient vibrations. For this purpose, a temporary network of 12 velocimeter sensors deployed in the same location of the accelerometers of the permanent network, was used. Data were analyzed in the frequency domain evaluating the power spectral densities (PSD) of all the recording and the cross spectral densities (CDS) of all the significant couples of sensors. The following first three resonance frequencies were extracted by means of the peak picking technique:

3.13 Hz, 3.71 Hz and 3.88 Hz. These resonance frequencies are related to the superstructure modes because the isolation system was not excited by ambient vibrations. The analysis of the phase factors of CSDs allowed to state that the first frequency is associated with a torsional mode, while the second and the third ones are associated with translational modes. They will be compared with the frequencies recorded during the seismic events, in order to check the decoupling of the motion between the superstructure and the ground.

The permanent monitoring system is composed by a data acquisition system Kinemetrics K2 and 12 accelerometric sensors Kinemetrics FBA11. The sensors are deployed as follows (Figure 2):

1. Three accelerometers, A01, A02 and A03, are at the basement (level 0, L0) in x, vertical and y direction, respectively;
2. Five accelerometers are on the slab above the isolation interface (level 1, L1), as follows: A04 and A08 in x direction, A05 in y direction, and A06, A07 and A09 in the vertical direction;
3. Three accelerometers are at the top of the building (level 2, L2), as follows: A10 and A12 in x direction and A11 in y direction.

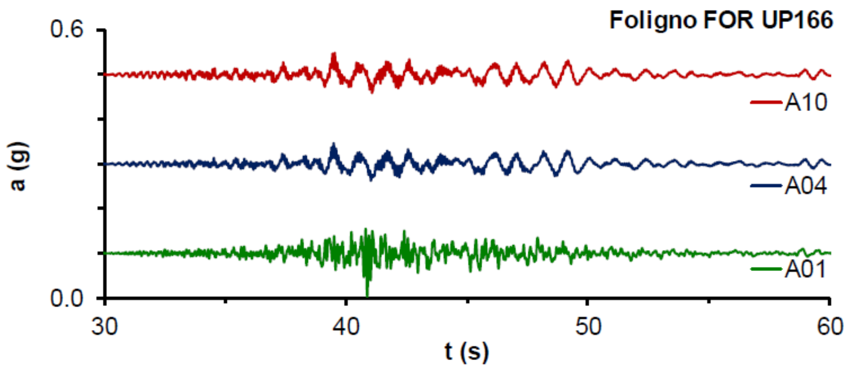
A short term average/long term average (STA/LTA) logic is used to recognize seismic events. The mean value of a signal in a short-time interval of 6 s is compared with the mean value of the same signal in a long-time interval of 60 s.

The permanent monitoring system recorded all the seismic events that struck Central Italy between August 2016 and January 2017. Among these only the most representative earthquakes were chosen to analyze the behavior of the building.

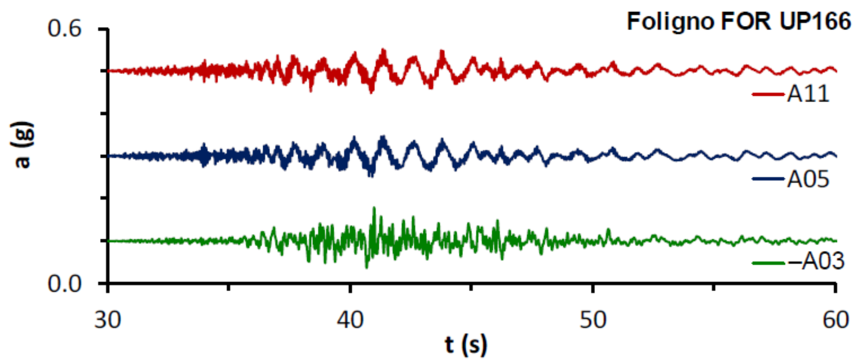
The 30 October 2016 Norcia earthquake was the event with the maximum magnitude in the sequence, but also the event that induced the maximum effects at the site of the building.

In Figure 21 the acceleration time histories recorded in x and y direction, respectively, at the basement L0 (A01 and A03), at the first floor above the isolation interface L1 (A04 and A05) and at the top of the building L2 (A10 and A11) are plotted. The peaks of the acceleration, for the same levels, are PBA = 0.098 g, PIA = 0.054 g and PTA = 0.059 g, respectively.

The absence of amplification from the basement to the top, which characterizes isolated structures, is clearly recognizable. On the contrary, there is a reduction in acceleration between the basement (L0) and the first floor above the isolation system (L1).



(a)



(b)

Figure 21. Time histories at the basement (green), at the first floor above the isolation system (blue) and at the top of the building (red) during the 30 October 2016, Norcia earthquake in (a) x direction and (b) y direction (the sign of record at A03 has been changed; therefore, it is named –A03

The Fourier spectra for the horizontal sensors are plotted in Figure 22.

The sensors in the same direction, deployed in the superstructure, show a peak of amplitude for the same frequency, equal to 0.95 Hz in x direction and 0.81 Hz in y direction. These resonance frequencies are much lower than the resonance frequencies recorded under ambient vibrations and related to the superstructure. The spectrum rotates of the recordings obtained at the couples A04–A05 and A10–A11 confirmed the presence of two different frequencies along the two main directions.

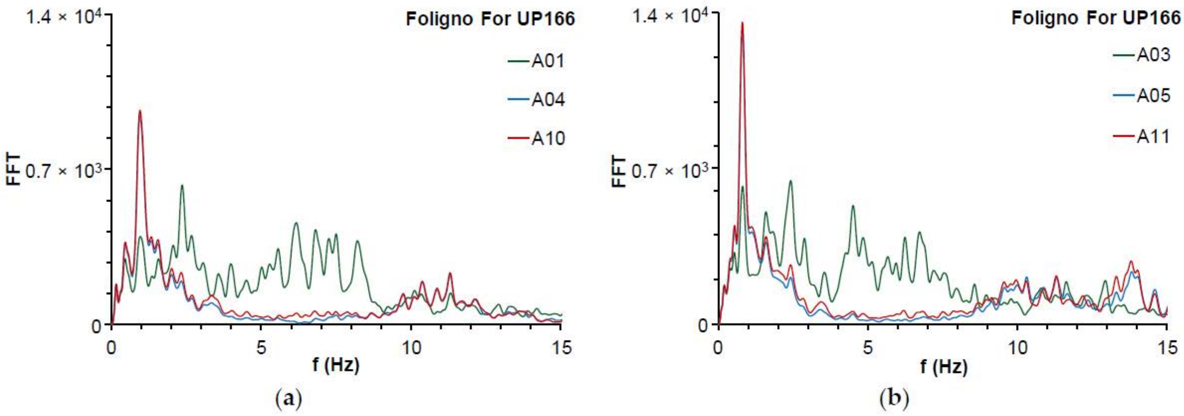


Figure 22 - Fourier spectrum amplitude at different levels obtained during the 30 October 2016 Norcia Earthquake in (a) x direction and (b) y direction

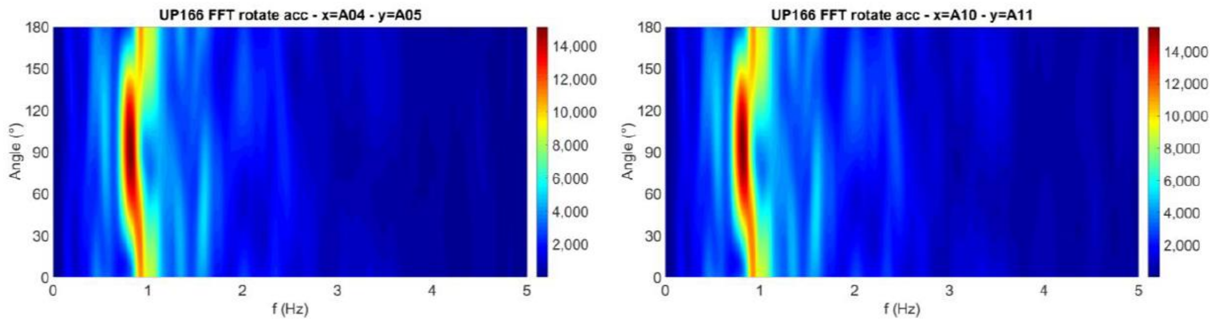


Figure 23. Spectrum rotates of the couples of recordings A04-A05 and A10-A11, obtained during the 30 October 2016 Norcia earthquake

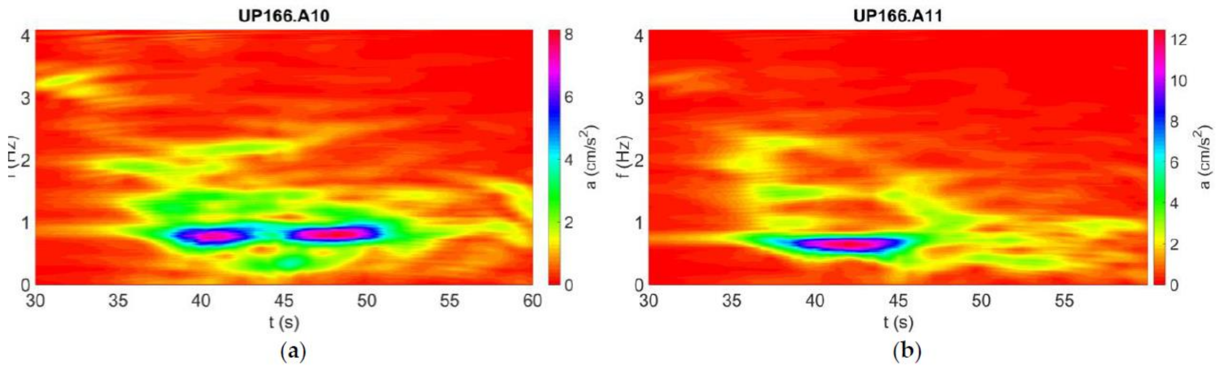


Figure 24. Time-frequency analysis for (a) A10 and (b) A11

The presence of two different resonance frequencies in the two directions could be related to a non-perfect symmetry of the isolation system. The wavelet transform, plotted in Figure 24 for sensors A10 and A11, show that the dominant frequencies vary during the seismic event and the frequencies related to the isolation system are particularly evident only during a small portion of the time histories.

One can deduce that the resonance frequencies changed during the earthquake and that the isolation system did not work for the entire recording.

These occurrences justify the presence of more peaks in the spectra around the resonance frequency. Furthermore, between 46 s and 50 s, vibrations prevail in x direction.

By means of a double integration in the frequency domain, the time histories of the displacements (Figure 25) were obtained from the acceleration time histories. The maximum values of the horizontal displacements of the gravity centers at L0, L1 and L2 were 27.3, 31.8 and 32.0 mm, respectively.

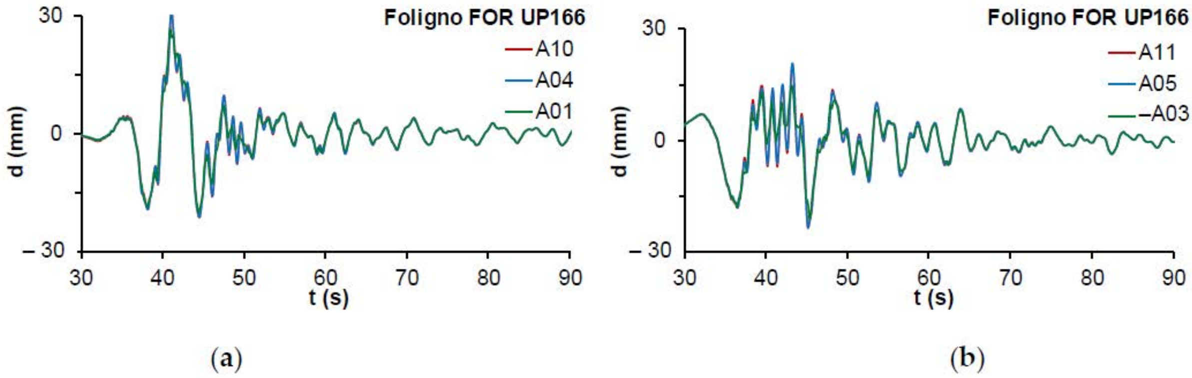


Figure 25. Time histories of the absolute displacements at different level in (a) x direction (b) y direction (the sign of record at A03 has been changed; therefore, it is named –A03 in the legend).

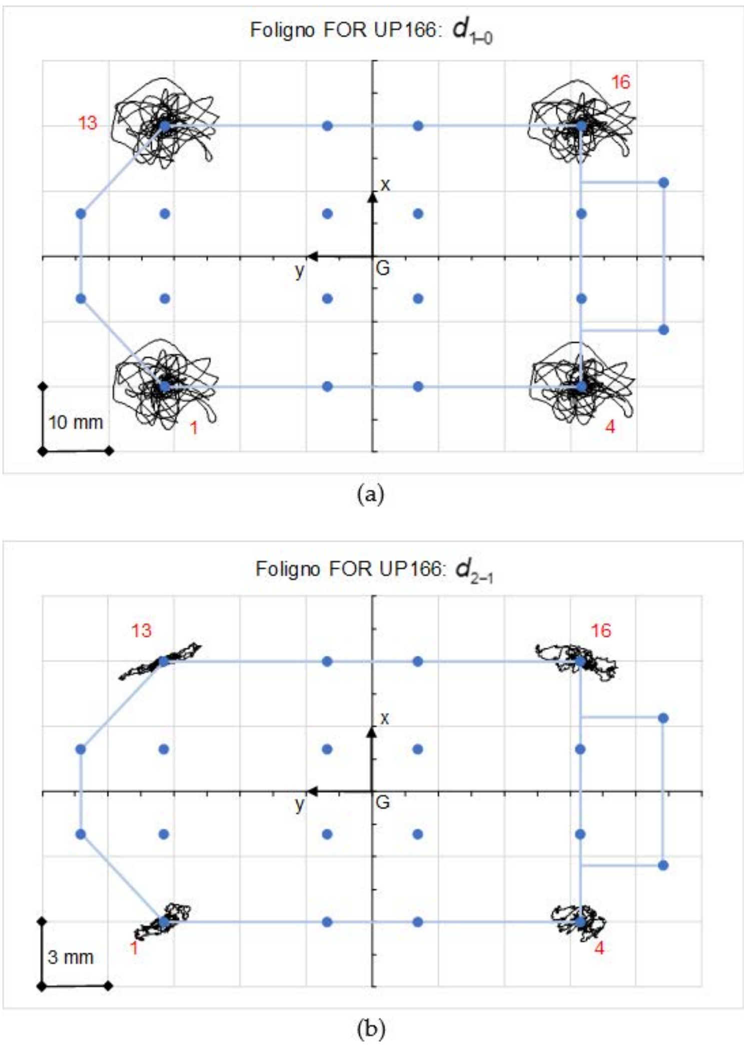


Figure 26. Relative particle motions at the points corresponding to the position of the corner isolation devices between (a) L1 and L0, and (b) L2 and L1

The relative horizontal displacements between L1 and L0, and between L2 and L1 were obtained for the 4 corner points, which correspond to the position of the isolation devices Is01, Is04, Is13 and Is16. The relative particle motions of these points are plotted in Figure 26, while the maximum values are summarized in Table 3. As one can see, the maximum displacement of the building does not exceed 32 mm.

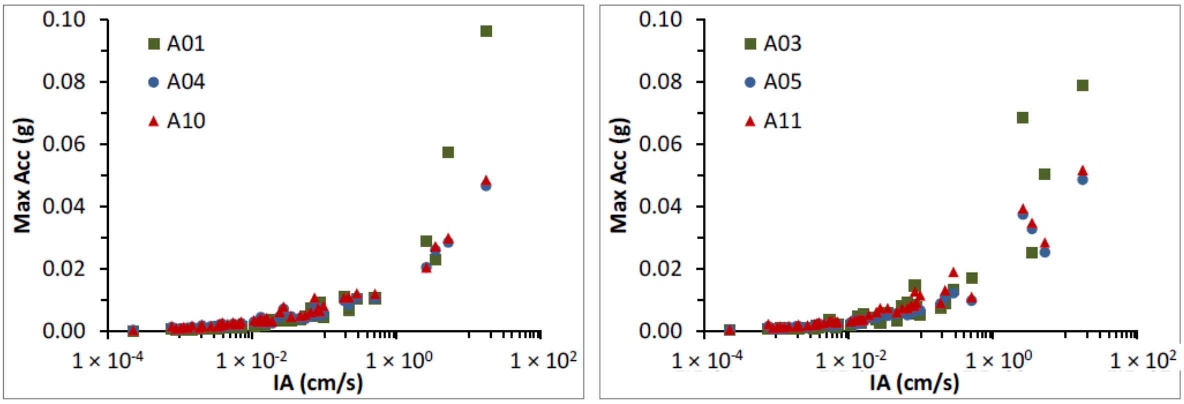


Figure 27. Maximum absolute acceleration at the basement PBA (A01 and A03 in x and y direction, respectively), above the isolation system PIA (A04 and A05), and at the top of the building PTA (A10 and A11), for all the recorded seismic events

The superstructure has a maximum relative displacement of about 2.2 mm between L2 and L1. This value is much lower than the limit value allowed by the Italian technical code at the serviceable limit state for strategic seismic isolated buildings, which is equal to h/450, h being the inter-story height. The displacement is concentrated at the level of the isolation system, where the maximum relative displacement in the isolation devices is about 9.3 mm, corresponding to a shear strain of 0.033.

	Event SH008	TX064	TX066	UR115	TX053	UP036	UP041	TX040	UP166
PBA (g)	0.0005	0.0012	0.0054	0.0094	0.0175	0.0706	0.0291	0.0575	0.0975
PIA (g)	0.0008	0.0014	0.0043	0.0111	0.0134	0.0379	0.0397	0.0300	0.0539
PTA (g)	0.0011	0.0017	0.0053	0.0136	0.0136	0.0411	0.0373	0.0327	0.0589
PBD (mm)	0.0066	0.0271	0.2439	2.2917	1.1813	3.3642	9.7588	15.415	27.302
PID (mm)	0.0138	0.0378	0.2467	2.3663	1.3072	5.5737	14.443	16.213	31.809
PTD (mm)	0.0171	0.0417	0.2524	2.3821	1.3349	5.8568	14.367	15.765	31.956
$d_{1\text{-}0}$ (mm)	0.0116	0.0230	0.0728	0.2907	0.6282	5.0766	6.7810	4.9572	8.7882
$d_{2\text{-}1}$ (mm)	0.0046	0.0107	0.0261	0.1503	0.1453	0.3685	0.6432	1.1301	1.6426
$d_{1\text{-}0}$ Is01	0.0116	0.0224	0.0744	0.2869	0.6686	5.0513	6.6656	5.2281	9.2833
$d_{1\text{-}0}$ Is04	0.0142	0.0236	0.0727	0.2847	0.6206	5.0211	6.7040	4.7085	8.7999
$d_{1\text{-}0}$ Is13	0.0114	0.0234	0.0730	0.2968	0.6384	5.1327	6.8636	5.2482	8.8119
$d_{1\text{-}0}$ Is16	0.0149	0.0251	0.0738	0.2947	0.5880	5.1030	6.9015	4.7466	8.3750
$d_{2\text{-}1}$ Is01	0.0045	0.0107	0.0279	0.1439	0.1424	0.4136	0.5993	0.9671	1.4852
$d_{2\text{-}1}$ Is04	0.0046	0.0111	0.0292	0.1385	0.1310	0.4408	0.5747	0.9542	1.3457
$d_{2\text{-}1}$ Is13	0.0047	0.0113	0.0272	0.1735	0.1680	0.3127	0.7596	1.5602	2.1928
$d_{2\text{-}1}$ Is16	0.0049	0.0109	0.0264	0.1631	0.1531	0.3454	0.7973	1.5626	2.1249

Table 5. Maximum accelerations, displacements, relative displacements of the gravity centers and maximum relative displacements at the corner isolators for the selected seismic events

For all the recorded events a frequency domain analysis was performed. In a lower energy range, the resonance frequency is independent of the seismic energy and varies in a small range around the value related to the superstructure. In these cases, the isolation system was not activated probably because of the friction forces of the SDs. For higher values of IA, instead, the seismic isolation system was put in action and the first resonance frequencies, related to the isolation system, decrease almost linearly with Log(IA). For low energy earthquakes the resonance frequencies approach those of the superstructure and there was no decoupling of motion.

The displacement is concentrated at the level of the isolation system, where the maximum relative displacement in the isolation devices is about 9.3 mm, corresponding to a shear strain of 0.033.

The results of the dynamic numerical analysis were compared to the seismic behavior observed during the Norcia earthquake. The good agreement between the acceleration time histories is apparent (Figure 28). Little discrepancies in terms of amplitudes can be attributed to a little lower stiffness of the numerical model with respect to the real structure. For the same reason the numerical displacement peaks are a little higher than those recorded during the earthquake (Figure 29). However, the frequency content of the recordings obtained during the event is well reproduced by the numerical model, as both the acceleration and displacement time histories show.

As already said, some crack patterns were observed on the partition walls of the first floor after the main event of 30 October 2016. In order to investigate this aspect, the relative displacements between the lower and upper beams were analyzed. It can be seen that an excursion greater than 2.0 mm around the value under vertical loads with a high frequency content, which occurred during the quake, can justify the cracks.

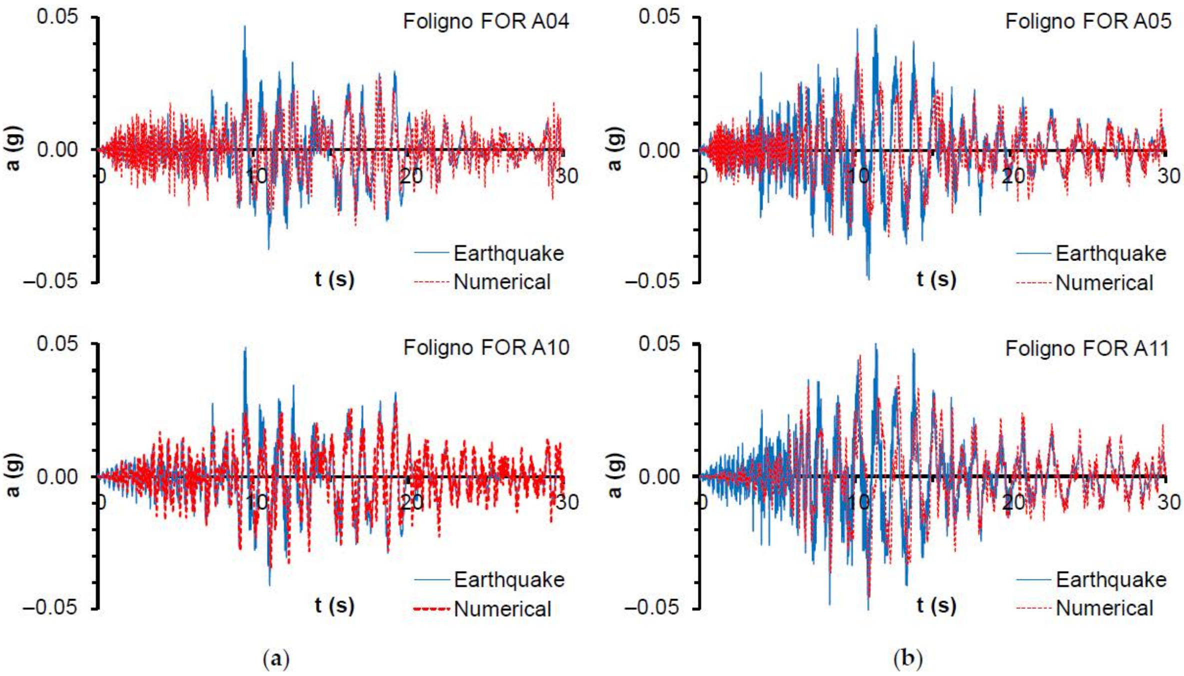


Figure 27. Comparison between the earthquake and numerical accelerations (a) in x direction and (b) in y direction

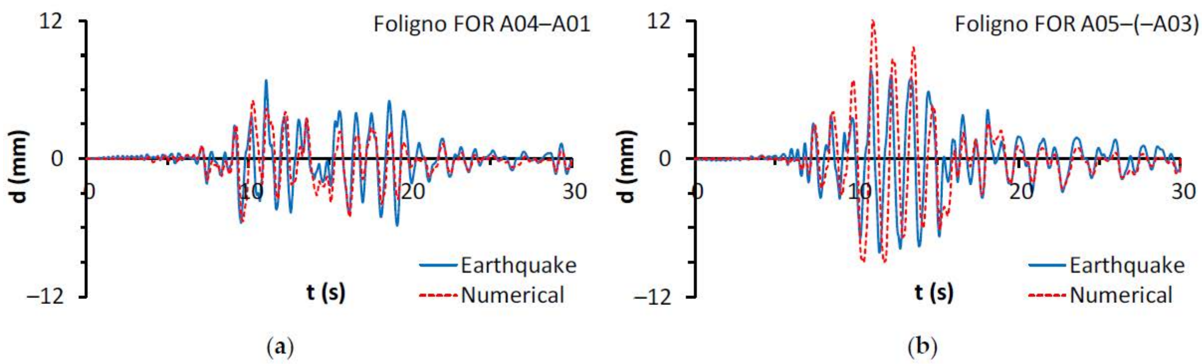


Figure 28. Comparison between the earthquake and numerical relative displacements between L1 and L0, (a) in x direction and (b) in y direction

5 CONCLUSION

The behaviour of the isolated buildings retrofitted or rebuilt after L'Aquila earthquake, subjected to new strong earthquakes in the same area, has been clear evidence of the excellent performance obtained by seismic isolation. After the 2009 earthquake, in the city of L'Aquila some hundred buildings have been seismically isolated. None of them reported any damage in consequence of the seismic events of 2016 – 2017, in the neighbourhoods of L'Aquila and in FOligno. In particular, five isolated buildings have been monitored and controlled, and the results show that each building, without damage, had an optimal performance, permitting the use of the buildings itself with no interruption. Also the isolation system didn't reported any damage and any residual displacement and deformation.

Seismically isolating the structure represents the best tool in order to maintains seismic security, resilience, total absence of damage (both structural and non-structural) and immediate usage of buildings and infrastructures even during very strong earthquakes.

A detailed analysis of the recorded behavior during the main event of 30 October 2016 was first shown. Then, the effects of a number of selected events were analyzed and compared. Finally, a suitable finite element model was set up, in which a non-linear model for the elastomeric isolators, based on previous experimental data, and a friction model for the sliders were assumed.

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