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BEHAVIOUR OF SEISMIC ISOLATED BUILDING DURING CENTRAL ITALY 2016 – 2017 EARTHQUAKES

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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. In particular, some areas were involved also in the 2009 seismic events (L'Aquila earthquake).

After L'Aquila earthquake, during reconstruction period, many buildings with base isolation (both existing and new ones) have been realized in the city area.

Furthermore, collapsed buildings, or heavily damaged buildings, were demolished and reconstructed with base isolation (both in foundation and above first elevation columns). The isolation systems were generally composed by both rubber high damping isolators, and plane friction isolators (sliding).

Some buildings, which reported less structural damage during 2009 L'Aquila earthquake, were retrofitted with isolation systems, both with rubber high damping isolators, and plane friction isolators.

All these isolated buildings were completed before year 2016, that is before the new strong seismic events in Central Italy.

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, analysing 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.

1. Introduction

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 located 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.

The use of SI became particularly rapid especially after the Abruzzo earthquake of April 6, 2009, as a consequence 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.

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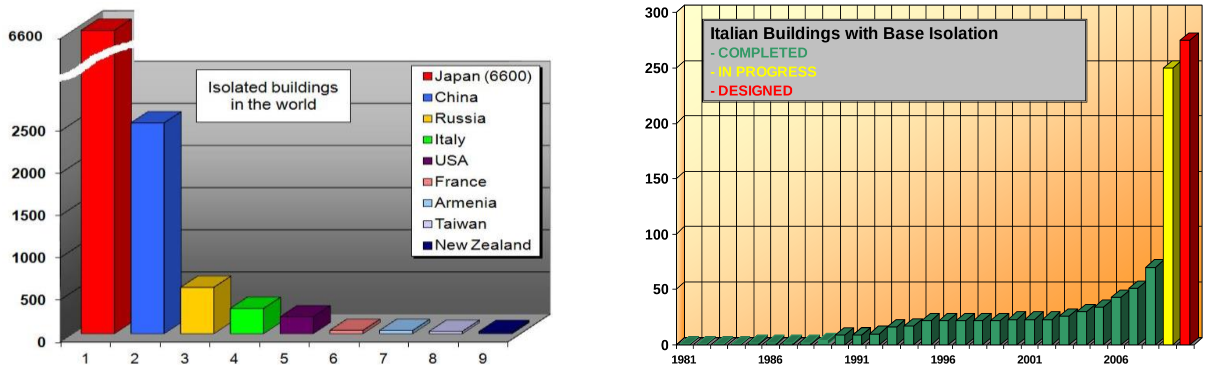

Figure 1. a) Isolated Buildings in the World; b) Buildings with Seismic Isolation in Italy.

2. Buildings retrofitted with seismic isolation after L'Aquila earthquake

L'Aquila city was struck down by a 6.3 M_w 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. 2.

In particular, 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 centre 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.

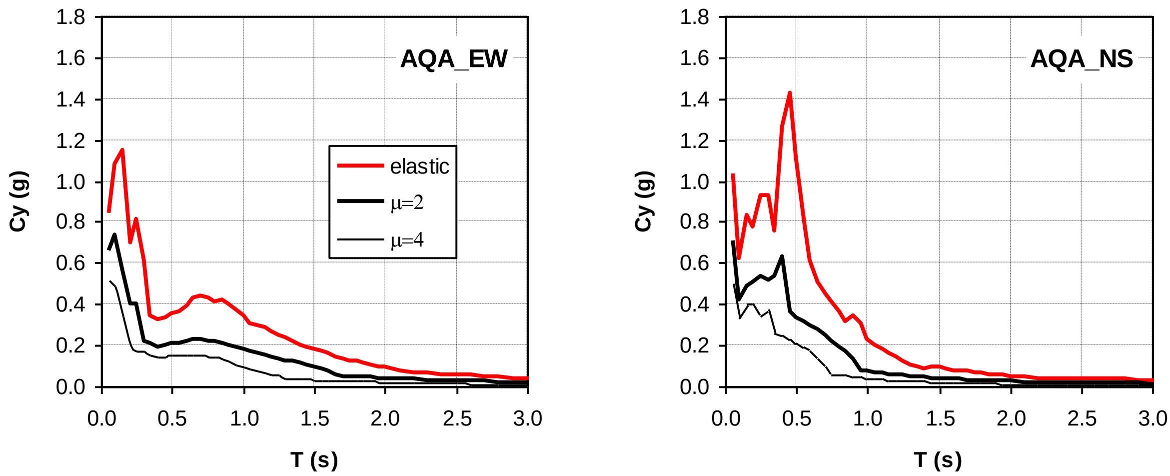

Figure 2. Response spectra in L'Aquila west area (near fault), amplification effect at 10.0 – 2.0 Hz.

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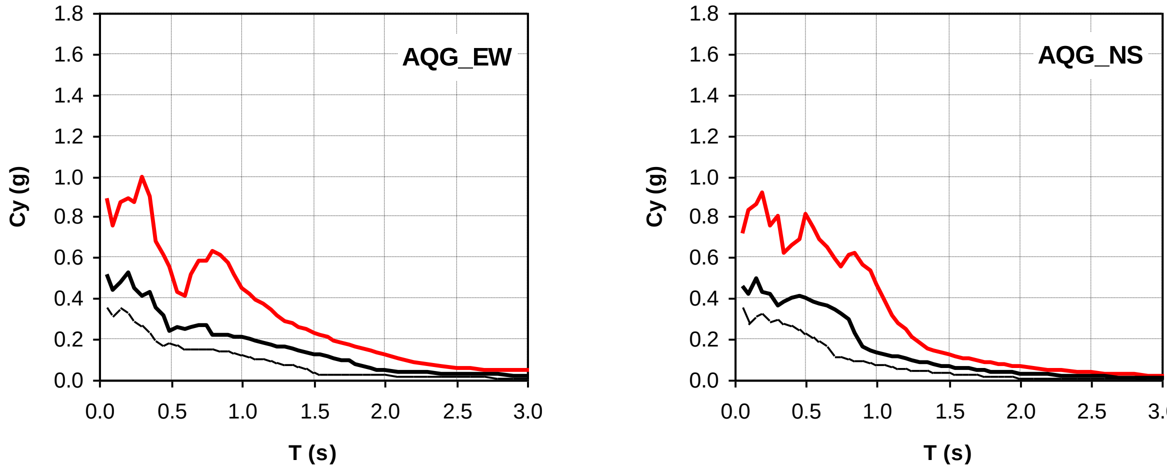


Figure 3. Response spectra in L'Aquila central area, with secondary amplification effect at 0.6 – 0.7 Hz

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.

2.1 Building #1 (near west area)

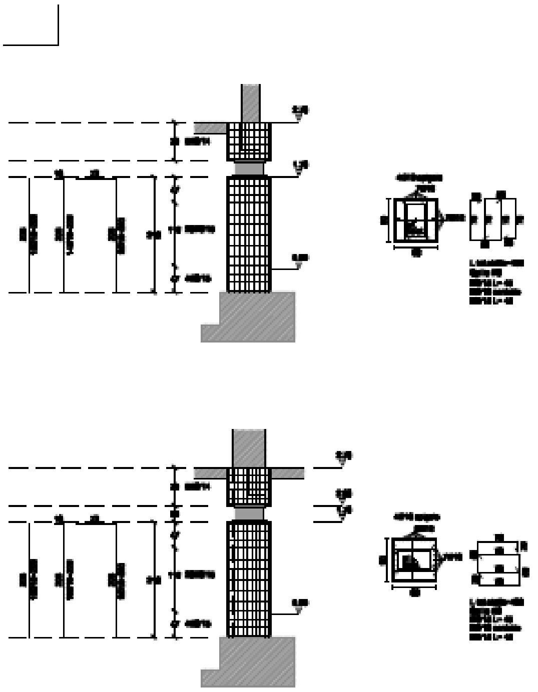
The first building under examination is located in the west area of the city, were no secondary amplification effect are detected. The building was heavily damaged during L'Aquila earthquake and was retrofitted by an isolation system. The damage concerned mainly brittle fracture in some pillars at low 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 4. 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.



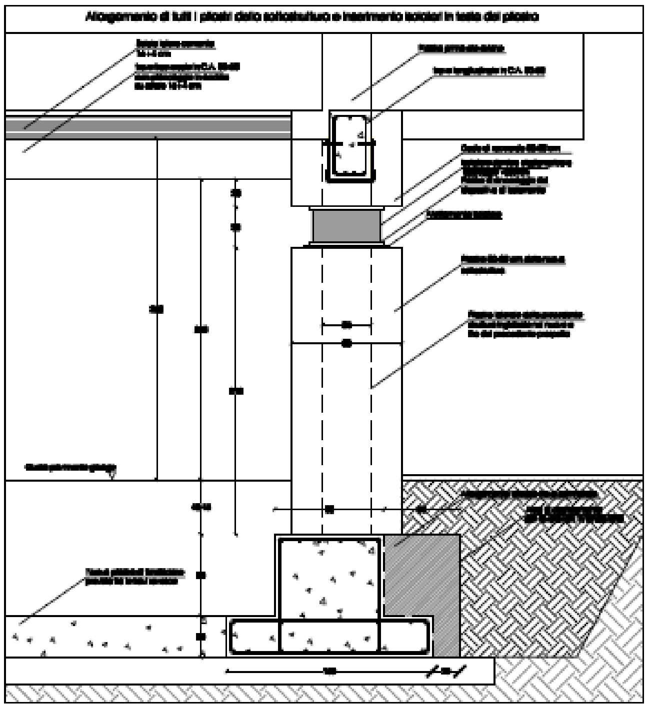


Figure 5. a) Enhancement of the lower part of pillars b) Insertion of a HDRB isolators at the top of the pillar

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

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Figure 5. a) Strengthening and cutting the top of a pillar b) Control of the cutting of a pillar

Figure 6. a) Insertion of an elastomeric HDRB SI-S 800 b) Insertion of a slider Vm 250/700/700

Figure 6. 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.

2.2 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

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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.

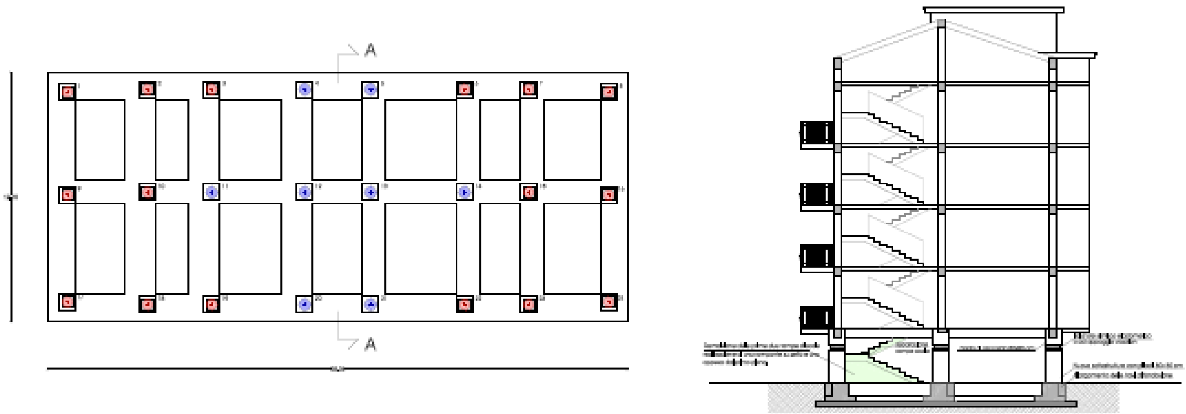

Figure 7. a) Position of isolators: red rubber isolator SI/N 450/126, blue sliders VM 250/250; b) section.

Figure 8. 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. 9 b).

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Figure 9. 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 10. a) HDRB and sliding devices at top of pillar b) Sliding device at top of a pillar


Figure 11. 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. 11b) 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.

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2.2 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.

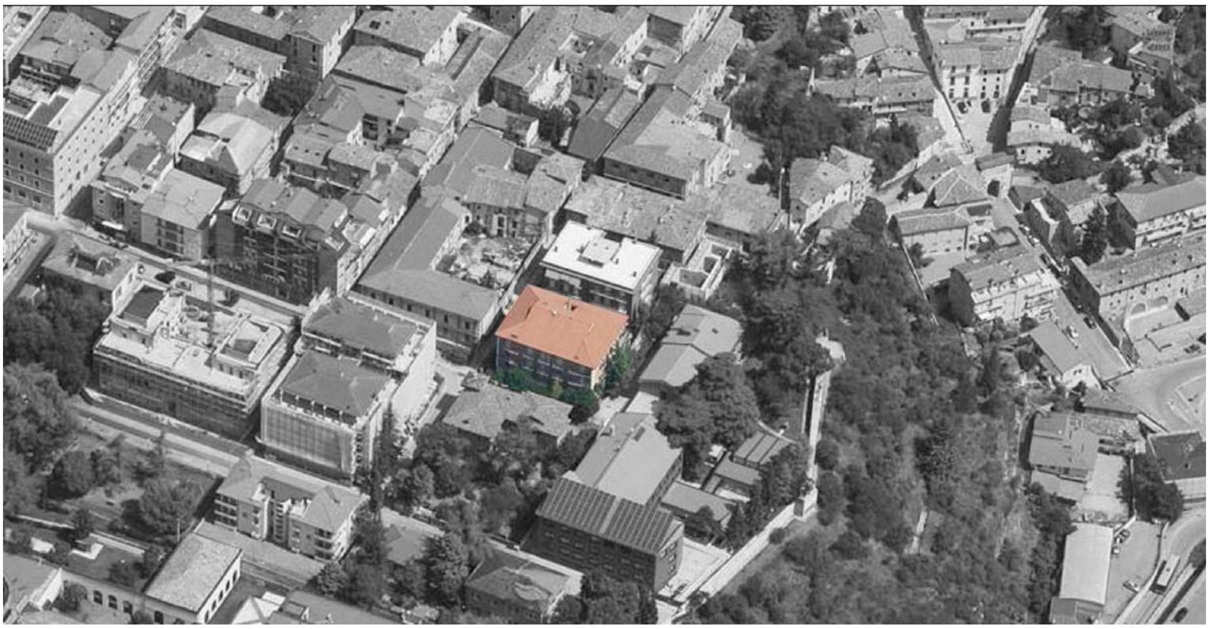

Figure 12. Isolated building in the centre of the city of L'Aquila,

where secondary amplification effects occur at low frequencies.

The maximum seismic performance for this building has been gained by seismic isolation, but, according to the shown amplification effect (fig. 3), 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.

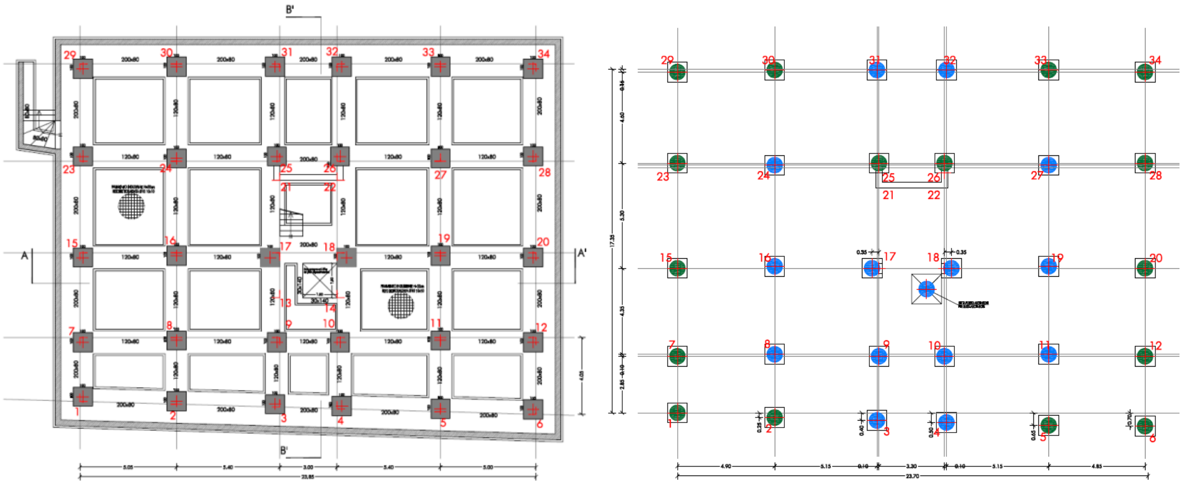

Figure 13. a) Undestructure of the isolation system b) HDRB isolator SI-S 800/160, sliders VM 300/600/600

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. 3). In particular (Figs. 14, 15), seismic movement joints have been designed to permit large displacement of the superstructure.

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Figure 14. a) HDRB isolator SI-S 800/160 b) sliding device VM 300/600/600

Figure 15. a) HDRB isolator with external seismic joint b) Horizontal joint with superstructure

The 2016 – 2017 seismic events and the behaviour of the isolated buildings

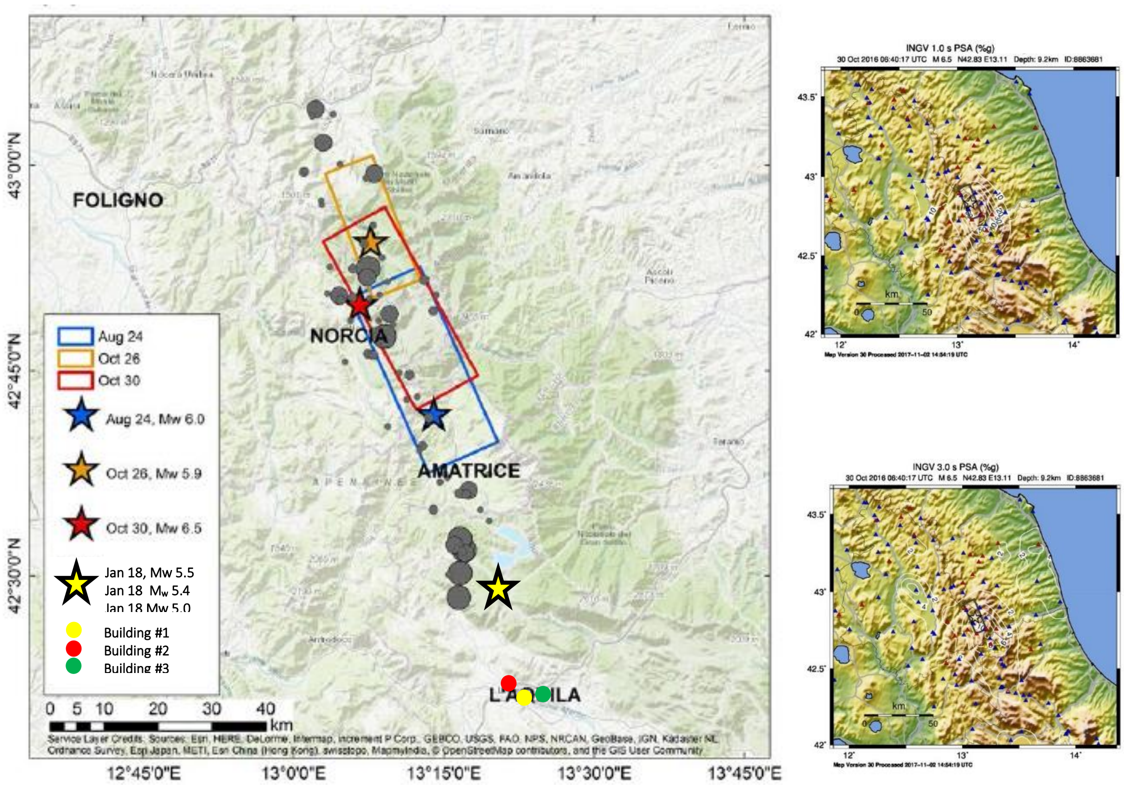

Figure 16 a)– 2016 – 2017 seismic events and position of the isolated buildings b) spectral data (INGV)

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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.

Table 1 – main seismic 2016 events in the area

SOURCE Time [Utc]	Latit.	Longit.	Depth [km]	Magnitude	Source	Name Record
24/08/2016 01:36:32	**42,698**	**13,234**	**8.1**	**6.0-Mw**	**BULLETIN**	**TN015**
24/08/2016 01:56:01	42,601	13,276	7.7	4.3-Mw	BULLETIN	**TN018**
24/08/2016 02:33:29	42,792	13,151	8.0	5.4-Mw	BULLETIN	**TN032**
24/08/2016 03:40:11	42,614	13,244	10.7	4.1-Mw	BULLETIN	**TN045**
24/08/2016 04:06:51	42,771	13,124	6.2	4.4-Mw	BULLETIN	**TN047**
24/08/2016 11:50:31	42.82	13.16	9.8	4.5-Mw	BULLETIN	**TN066**
24/08/2016 17:46:09	42,659	13,215	10.3	4.2-Mw	BULLETIN	**TN074**
24/08/2016 23:22:06	42,654	13.21	11.8	4.0-Mw	BULLETIN	**TN078**
25/08/2016 03:17:17	42,745	13,193	9.0	4.3-Mw	BULLETIN	**TN080**
25/08/2016 12:36:05	42.6	13,282	7.5	4.4-Mw	BULLETIN	**TN083**
26/08/2016 04:28:26	42,605	13,292	8.7	4.8-Mw	BULLETIN	**TN086**
27/08/2016 02:50:59	42,843	13,238	7.8	4.0-Mw	BULLETIN	**TN093**
28/08/2016 15:55:35	42,823	13,232	8.7	4.2-Mw	BULLETIN	**TN102**
03/09/2016 01:34:12	42.77	13,132	8.9	4.2-Mw	BULLETIN	**TO015**
03/09/2016 10:18:51	42,861	13,217	8.3	4.3-Mw	BULLETIN	**TO017**
16/10/2016 09:32:35	42,748	13,176	9.2	4.0-Mw	BULLETIN	**TP016**
26/10/2016 17:10:36	**42.88**	**13,128**	**8.7**	**5.4-Mw**	**BULLETIN**	**TP021**
26/10/2016 19:18:06	**42,909**	**13,129**	**7.5**	**5.9-Mw**	**BULLETIN**	**TP026**
26/10/2016 21:42:02	42,863	13,121	9.9	4.5-Mw	BULLETIN	**TP053**
27/10/2016 03:19:27	42,843	13,143	9.2	4.0-Mw	BULLETIN	**TP071**
27/10/2016 03:50:24	42,984	13.12	8.7	4.1-Mw	BULLETIN	**TP073**
27/10/2016 08:21:46	42,873	13,097	9.4	4.3-Mw	BULLETIN	**TP086**
27/10/2016 17:22:23	42,839	13,099	9.0	4.2-Mw	BULLETIN	**TP103**
29/10/2016 16:24:33	42,811	13,095	10.9	4.1-Mw	BULLETIN	**TP144**
30/10/2016 06:40:17	**42,832**	**13,111**	**9.2**	**6.5-Mw**	**BULLETIN**	**TP151**
30/10/2016 07:34:48	42,922	13,129	9.9	4.0--ML	Survey	**TP170**
30/10/2016 11:58:17	42.84	13,056	10.2	4.0-Mw	Survey	**TP235**
30/10/2016 12:07:00	42,845	13,078	9.7	4.5-Mw	Survey	**TP237**
30/10/2016 13:34:54	42,803	13,165	9.2	4.1-Mw	Survey	**TP251**
30/10/2016 18:21:09	42.79	13,152	9.6	4.0-Mw	Survey	**TP275**
31/10/2016 03:27:40	42,766	13,085	10.6	4.0-Mw	Survey	**TP310**
31/10/2016 07:05:45	42,841	13,129	10.0	4.0-Mw	Survey	**TP322**
01/11/2016 07:56:40	43	13,158	9.9	4.8-Mw	Survey	**TP354**
03/11/2016 00:35:01	43,029	13,049	8.4	4.7-Mw	Survey	**N.R.**
12/11/2016 14:43:34	42,723	13,209	10.1	4.1-Mw	Survey	**TQ077**
14/11/2016 01:33:44	42.86	13,158	11.0	4.0--ML	Survey	**TQ092**
29/11/2016 16:14:03	42,529	13.28	11.1	4.4-Mw	BULLETIN	**TQ171**

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Many buildings in the area are under monitoring. The three 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 #1 – maximum displacement 100 mm

The difference of displacement depends on the soil – structure interaction and the relevant differences between the considered areas.

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

Table 2 – design parameter and maximum displacement for the buildings

Building #	HDRB	SD	K_{esi} [KN/mm]	ξ	Isolation Period	Design displacement	Maximum displacement
1	9 FIP SI-S 700/200 10 FIP SI-S 800/200	13 FIP VM 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

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. In particular, three 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.

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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.

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