Monitoring of seismic isolated buildings: state of the art and results under high and low energy inputs

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ABSTRACT: The experimental response of base isolated structures under seismic loading is shown and discussed in this paper. Actually, the good performance of isolation systems has been demonstrated during strong earthquakes occurred in Japan, United States and China where the reduction of the seismic accelerations from the basement to the top has been recorded. The behaviour under low intensity earthquake could be different as in the case of some base isolated buildings subject to the recent Central Italy earthquakes in Italy. These experiences pointed out the importance of the non-linear analysis, able to point out the different behaviour under different input energy.

1 INTRUDUCTION

The seismic monitoring of seismic isolated buildings is important and necessary to assess the possible dynamic behaviour of such structures during earthquakes and to gain experience on the general seismic behaviour of such structures to be used in future design and analyses.

The results of past seismic monitoring of structures has facilitated development of data bases, which in turn have been used in establishing new formulas or reference values for estimation of fundamental periods of structures and critical damping percentages to be used during dynamic analyses. Data bases are sufficiently populated for traditional buildings, but not yet for base isolated buildings (Martelli & Clemente, 2015).

With reference to buildings, a suitable accelerometric network should include at least:

- a triaxial accelerometer sensor on the foundations, under the seismic isolation system;
- three (better four) accelerometers on the first floor above the isolation layer;
- three (better four) accelerometers on the upper floor.

Other sensors should be considered at intermediate levels especially for tall buildings. In order to check the behaviour of the devices, relative displacement trasducers should be used, in order to allow a real time evaluation of the effective seismic response and to define any intervention. Finally, at least two triaxial sensors should be deployed in the soil, one on surface quite close to the building and another in the subsoil at a suitable distance below the previous one.

As well know, ambient vibrations, which are becoming the most used source of vibrations for the dynamic characterization of structures due to the low cost, are not suitable in case of base isolated buildings. These are characterised by low resonance frequencies when subject to strong earthquakes but should exhibit different behaviour under low intensity dynamic actions. This occurrence poses some problem in the dynamic characterization of base isolated buildings. This can be carried out by means of the classic release test, which consists in giving an initial displacement to the structure along the assigned direction and in releasing it suddenly in order to verify its fundamental period during free vibrations. A release test could have a significant cost, so it is used in practice only in few cases.

It is worth noting that the isolation devices must have a low horizontal stiffness, which allows the relative displacements between the upper and lower faces in case of seismic events, but also an adequate stiffness in order to avoid vibrations under low horizontal actions, such as wind, traffic or ambient vibrations. So, also in case of low magnitude earthquake, isolation devices could not be put in action; as a result their filtering function is missing and the superstructure can be subjected to seismic actions higher than those assumed in the design (Clemente et al, 2016).

In this paper some interesting cases of the seismic response of base isolated buildings under strong earthquake are reminded. Then the preliminary analysis of the seismic response under low magnitude earthquakes are shown.

2 SEISMIC BEHAVIOUR UNDER STRONG EARTHQUAKES

In several countries the extensive adoption of the new anti-seismic systems started after strong earthquakes, in which the already existing base isolated buildings exhibited an excellent behaviour. An overview about the applications all over the world is given in Benzoni (2015) and in Clemente & Martelli (2017).

This happened in Japan, which is without doubt the leader in the application of base isolation. As a matter of fact, the number of seismic isolated buildings in Japan increased very much after the 1995 *Hyogo-ken Nanbu* earthquake (M = 7.3), when two isolated buildings in the epicentre area, near Kobe, reported no damage during the quake. One of these was the communication minister in Sanda City (Fig. 1a), which was about 30 km far from the epicentre. It had been isolated by means of low damping rubber bearings and elasto-plastic energy dissipators. The monitoring systems allowed to state that the ratio between the acceleration peak at the top and that on the basement was about 1/9, so with a significant reduction of the seismic action. Also during the severe earthquakes occurred after 1995 all seismic isolated buildings behaved very well and the increase of number of applications in Japan is continuing. The reinforced concrete building in Ojiya City (Fig. 1b), Japan, completed in 1994 and isolated by means of rubber bearings and sliders, supported very well the 2004 Mid Niigata earthquake (M = 6.8); the peak acceleration was 0.725 g at the base and 0.194 g at the top, with a reduction ratio of about 1/4.

(a) (b)

Fig. 1 – (a) The communication minister in Sanda City and (b) the reinforced concrete building in Ojiya City, Japan.

Most of the 118 isolated buildings affected by the 2011 Tohoku earthquake, located in the Tohoku area or in other Japanese sites, behaved quite well, even though they had been designed to withstand less severe earthquakes. Among these, the 4-storey National Western Art Le Corbusier Museum in Tokyo, retrofitted in 1999 by inserting high damping natural rubber bearings in a sub-foundation; these isolation system reduced the PGAs in the two horizontal directions from 0.19 and 0.27 g at the base to 0.08 and 0.10 g at the top during the 2011 Tohoku quake. It is worth reminding that also seismic isolated bridges and viaducts, most of those protected by rubber bearings (LRBs and HDRBs), showed an excellent behaviour during the quake, but a certain number of them was then destroyed by the subsequent tsunami, due to deck rotation toward the upstream side, resulted from the uplifting force (Saito, 2015).

In China the application of modern seismic isolation systems started in 1991 and increased rapidly. A very significant increase occurred when two concrete seismic isolated buildings and even a 6-storey masonry building showed an excellent behaviour during the 2008 Wenchuan earthquake (M_W = 7.9). They had been designed for horizontal peak ground acceleration value about 1/10 of the actual one but showed no damage during the quake. During the Lushan earthquake (M_W = 7.0) of April 20th, 2013, two primary school buildings, one close to the other, showed a quite different behaviour, as demonstrated by the recordings obtained by means of the seismic monitoring systems installed in them. In the first one, which was conventionally founded, the peak ground acceleration value of 0.2 g was amplified to 0.72 g at the top; in the second building, which was protected by means of a base isolation system, the acceleration peak was equal to 0.12 g (Zhou 2015, Zhou et al 2013).

In California the USC hospital in Los Angeles showed a very good behaviour during the 1994 Northridge Earthquake. It was about 30 km far from the epicentre and the ratio between the acceleration peak at the top and that on the basement was about 1/9. In spite of that and other excellent behaviour of base isolated buildings in USA and the long experience of application of this technique to such structures (since 1985), the number of new base isolated buildings keeps still limited. This is a consequence of the very penalizing design code for the isolated buildings.

3 SEISMIC BEHAVIOUR UNDER LOW ENERGY INPUTS

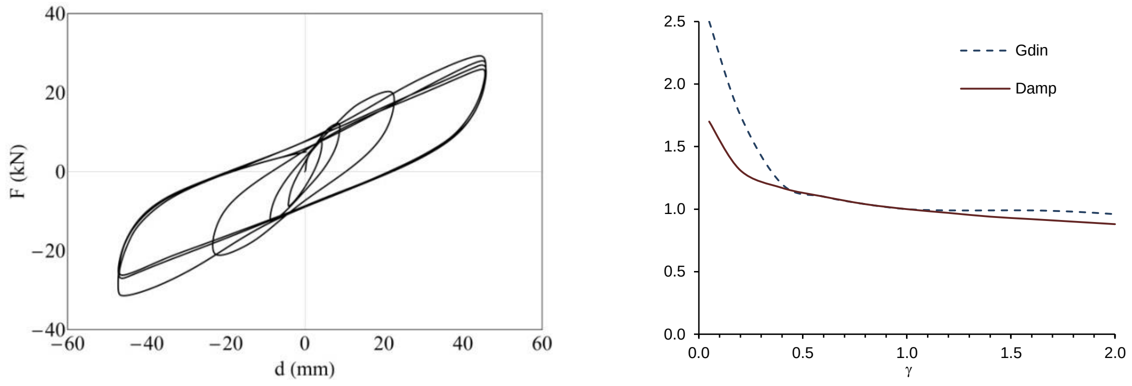
At the present quite few seismic isolated buildings have already been provided with monitoring systems in Italy. Among these:

- the new Jovine school building in San Giuliano di Puglia, instrumented by means of 30 acelerometers in the framework of a research project organized by ENEA in collaboration with the Italin Civil Protection Department and the Municipality of San Giuliano di Puglia (Bongiovanni et al, 2015);
- the Operative Centre and the Forestry Building in the Civil Protection Centre of Umbria Region in Foligno, each of them instrumented by means of 12 accelerometers in the framework of a reserach project organized by ENEA in collaboration with the Umbria Region (Bongiovanni et al, 2016);
- some buildings of the C.A.S.E. project in L'Aquila, built for temporarily hosting the homeless residents; these consisted in 184 wood, reinforced concrete or steel pre-fabricated houses, each of them placed on a large isolated reinforced concrete slab supported by means of curve surface sliders; each of them has been instrumented by means of 10 accelerometers (Turino, 2010).

Up to now no strong earthquakes have been recorded by these network but several low energy quakes, which allow some considerations.

It is worth noting that base isolated systems are usually designed to face the design earthquake at the site and the equivalent characteristics, in terms of stiffness and damping, are used for the seismic check in the linear analysis (Clemente & Buffarini, 2010). Obviously, this procedure gives results on the safe side if the isolation system is not put in action; if the check is satisfied, the structure is certainly safe also for events of lower intensity for which the displacements exhibited by the devices are lower. Under very low intensity earthquakes, and also under ambient vibrations, the isolation system is not put in action, so the higher modes of the superstructure are activated and some amplification of the response in terms of acceleration could occur. In order to analyse in detail this aspect the case of high damping rubber bearings (HDRB) and that of curved surface sliders (CSS) must be distinguished.

The force-displacement curves relative to a cycle test of HDRBs show that their behaviour varies strongly for one cycle to the other, depending on the maximum displacement reached (Fig. 2a). So also in the linear analysis, assuming for each cycle the equivalent values relative to the maximum displacement, both shear modulus and damping ratio vary very much as a function of the shear strain γ. So the equivalent values, usually relative to γ=1, could be quite lower than those relative to very low shear strain γ. This is clear from figure 2b, where the shear modulus G_{din} and the damping ratio ξ are plotted versus the shear strain γ.



(a) (b)

Fig. 2 – (a) Typical force-displacement diagram for a HDRB and (b) typical variation of the elastic dynamic shear modulus G_{din} and of the equivalent damping factor ξ_e as ratios of their values at γ=1, obtained during dynamic test of a high damping rubber bearing (HDRB).

The behaviour of CSSs is influenced strongly by the static frictions at the onset of motion (μ_0) and at the maximum displacement for each cycle (μ_1) when the velocity sign changes (Fig. 3). Furthermore, the friction μ during the dynamic phase is usually assumed to be constant, but the experimental analysis showed significant variations (Lomiento & Benzoni 2016, Lomiento et al 2013). In any case, the dynamic friction is the lowest and the initial static friction the highest: $\mu < \mu_1 < \mu_0$ (Clemente et al., 2015).

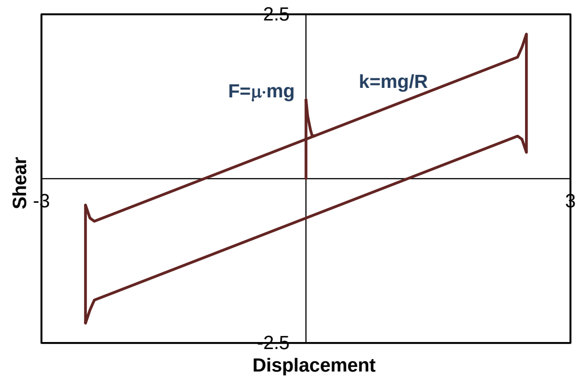
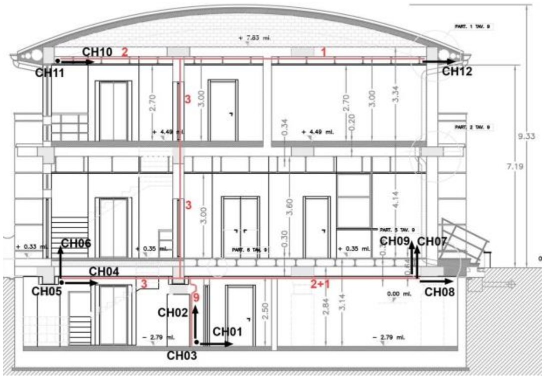


Fig. 3 – Typical force-displacement diagram for a CSS. The three types of friction are apparent as well as their influence on the dynamic behavior of the devices.

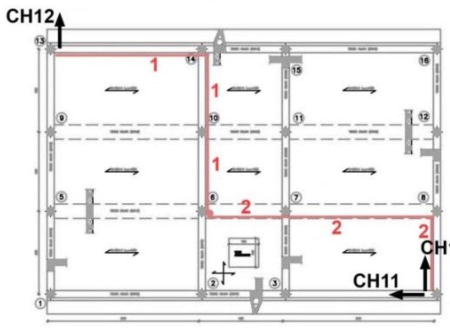
In the following two cases are shown in which the previously described behaviours were exhibited during the recent Central Italy earthquake of October 30th, 2016. The Forestry Building in the Civil Protection Centre of Umbria Region in Foligno (Fig. 4) has been instrumented by means of twelve accelerometers, deployed in the building as follows (Fig. 5):

- three accelerometers (CH01, CH02 and CH03) were on the basement, under the isolation system;
- six accelerometers were on the first floor, just above the isolation system: three of them in the vertical direction (CH06, CH07 and CH09), one in *x* (longitudinal) direction (CH05) and two in *y* (transversal) direction (CH04 and CH08);
- threeo accelerometers were at the top of the building: one in *x* (longitudinal) direction (CH11) and two in *y* (transversal) direction (CH10 and CH12).

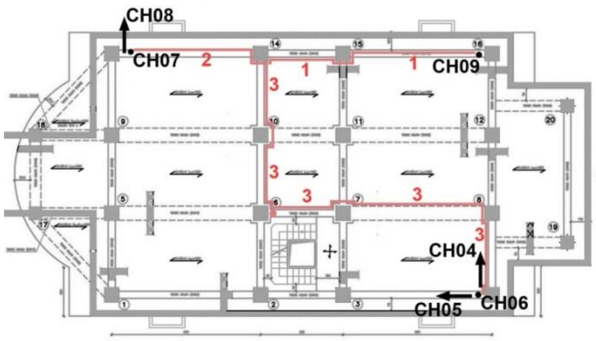
Fig. 4 – The Forestry Building in the Civil Protection Centre of Umbria Region at Foligno, Italy



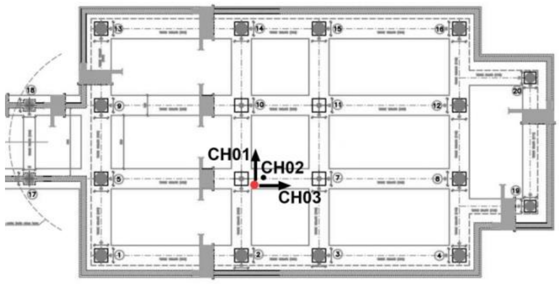
(a)



(b)

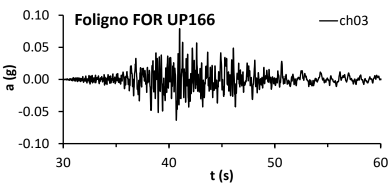


(c)

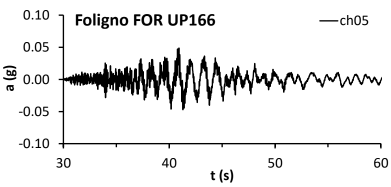


(d)

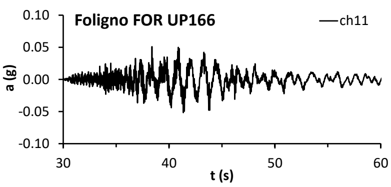
Fig. 5 – Sensor deployment in the Forestry Building at Foligno: (a) vertical section, (b) top floor, (c) first floor above the isolation interface, (d) basement.



(a)



(b)



(c)

Fig. 6 – Forestry Building at Foligno: accelerometric recordings obtained during the October 30th earthquake (M=6.5) at (a) the basement, (b) on the first floor just above the isolation system and (c) at the top of the building.

The structure is at about 36 km far from the epicentre of the events (M=6.5) that struck Central Italy on October 30th, 2016. In figure 6 the recordings obtained in the transversal direction are shown. It is apparent the absence of amplification to the top and also a change in the frequency content. This is confirmed by the Fourier spectra (Fig. 7), in which the amplification at a frequency around 1 Hz is apparent. This value is consistent with the stiffness of the rubber bearings for low displacements (Clemente et al., 2016). In figure 8 the drift between the first floor and the basement is plotted.

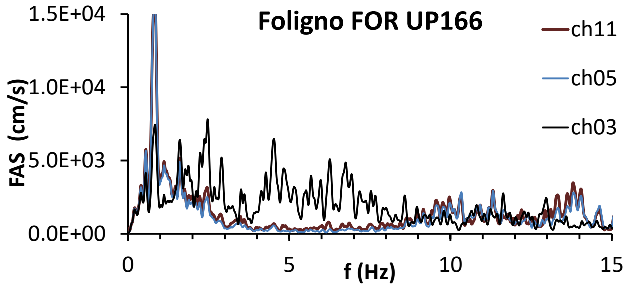


Fig. 7 – Forestry Building at Foligno: Fourier spectra of recordings in the longitudinal direction.

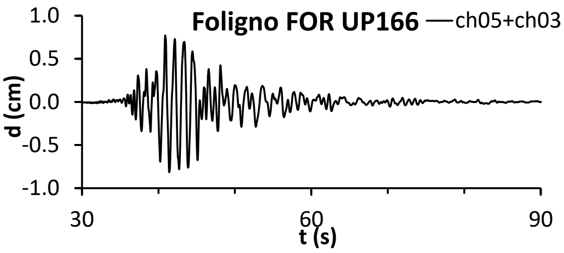
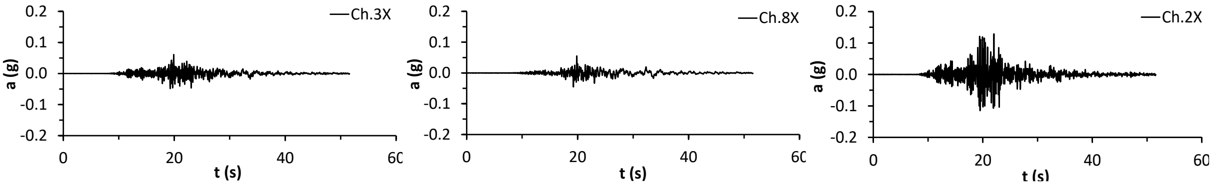


Fig. 8 – Forestry Building at Foligno: relative displacement between the first floor and the basement.

The use of seismic isolation increased rapidly after L'Aquila earthquake of April 6th, 2009, as a consequence of the large damage caused by this event to conventionally founded structures and to cultural heritage structures, but also thanks to the use of such protection system to buildings for temporarily hosting about 17,000 homeless residents (C.A.S.E. project). These consisted in 184 wooden, reinforced concrete or steel pre-fabricated houses, each of them placed on a large isolated reinforced concrete slab supported by means of curve surface sliders (CSS), manufactured in Italy, installed at the top of circular columns (Fig. 9).

Fig. 9 – Typical isolated platform of the C.A.S.E. project in L'Aquila

The recordings obtained during the event of 30th October, 2016, on the C4 building at Bazzano, L'Aquila, are plotted in figure 10. The amplification from the basement (Ch.3X) to the top (Ch.2X) is apparent, demonstrating a behaviour of the isolation devices different from that assumed in the design. The absence of the filtering function is confirmed by the Fourier spectra (Fig. 11). In figure 12 the drift between the top and the first floor is plotted.



(a) (b) (c)

Fig. 10 – C4 building at Bazzano, L'Aquila: accelerometric recordings obtained during the October 30th earthquake (M=6.5) at (a) the basement, (b) on the first floor just above the isolation system and (c) at the top of the building (elaboration of data of the Department of Civil Protection, PCM, Italy).

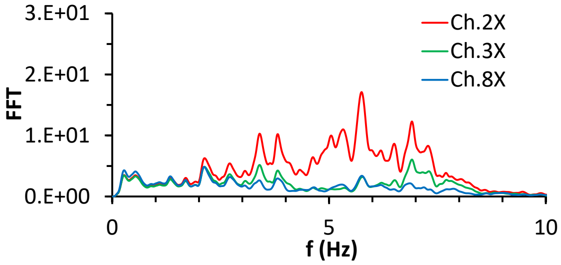


Fig. 11 – C4 building at Bazzano, L'Aquila: Fourier spectra of recordings obtained during the October 30th earthquake (M=6.5) at (Ch.8X) the basement, (Ch.3X) on the first floor just above the isolation system and (Ch.2X) at the top of the building (elaboration of data of the Department of Civil Protection, PCM, Italy).

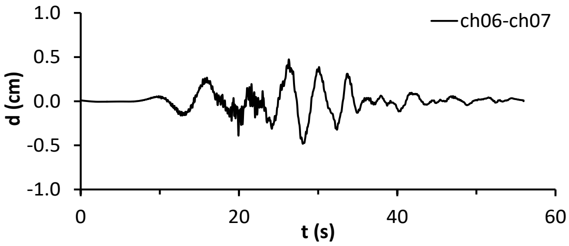


Fig. 12 – C4 building at Bazzano, L'Aquila: relative displacement between the first floor and the basement.

The experimental results pointed out the importance of the nonlinear analysis of base isolated structures. The effects of the events that interested Central Italy between August and October, 2016, were recorded. The preliminary analysis of the recorded data pointed out the problem related to the activation of the seismic isolation, which in some cases behaved as rigid. More detailed analysis is necessary.

4 CONCLUSIONS

The seismic monitoring of seismic isolated buildings allowed testing the good performance under strong earthquakes in different countries, such as Japan, United States and China. In all cases the strong reduction of the seismic acceleration to the top of the buildings is apparent the frequency content.

In Italy, very few buildings are provided with seismic monitoring systems and only earthquakes with reduced effects at the sites of interests have been recorded up to now. Anyway, the recordings allowed pointing out some considerations about the correct design of a base isolation system. These should include an accurate non-linear analysis of their behaviour under earthquakes of different magnitudes and to verify that the seismic action in the superstructures do not exceed those assumed in the design.

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6 REFERENCES

Benzoni G. (Ed) 2015. Proc. 14th World Conf. on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures (14WCSI, San Diego, Sep 9-11), Univ. of California San Diego, CA USA.

Bongiovanni G., Buffarini G., Clemente P., Saitta F., De Sortis A., Nicoletti M., Rossi G. 2015. Behaviour of the base isolated Jovine School in San Giuliano di Puglia, Italy, under the December 20th 2013 earthquake. Proc. 14th World Conf. on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures (San Diego, Sep 9-11 2015), Univ. of California San Diego, CA USA.

Bongiovanni G., Buffarini G., Clemente P., Saitta F., Serafini S., Felici P. 2016. Ambient vibration analysis of a strategic base isolated building. Proc. 6th Int. Civil Struct. Health Monitoring (CSHM-6, Belfast, 26-27 May, 2016), Queen's University Belfast.

Clemente P., Bongiovanni G., Buffarini G. and Saitta F. 2016. Experimental analysis of base isolated buildings under low magnitude vibrations. Int. J. of Earthquake and Impact Engineering, Vol. 1, No. 1-2, 199-223, Inderscience Publishers, DOI: 10.1504/IJEIE.2016.10000961.

Clemente P., Buffarini G. 2010. Base isolation: design and optimization criteria. J. of Seismic Isolation and Protection Systems, 1 (1), 17-40, Mathematical Science Publisher, DOI 10.2140.siaps.2010.1.17.

Clemente P., Martelli A. 2017. Anti-seismic systems: Worldwide application and conditions for their correct use. Proc. 16th World Conf. on Earth. Eng., (16WCEE, Santiago del Chile, Jan 9-13), Keynote lecture, IAEE & ACHISINA.

Clemente P., Saitta F., Grossi C., Salvatori A. 2015. On the behaviour of buildings with curved surface sliders: consideration and preliminary analyses. Proc. 14th World Conf. on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures (San Diego, Sep 9-11), Univ. of California San Diego, CA USA.

Lomiento G., Benzoni G. 2016. Testing protocols and acceptance criteria for performance characterization of pendulum isolators. Proc. 16th World Conf. on Earth. Eng., (16WCEE, Santiago del Chile, Jan 9-13), IAEE & ACHISINA.

Lomiento, G., Bonessio. N., and Benzoni, G. (2013): Friction model for sliding bearings under seismic excitation, *Journal of Earthquake Engineering*, **17** (8), 1162-91.

Martelli A., Clemente P. 2015. Need for an Adequate Seismic Monitoring of Seismically Isolated Buildings to Ensure Safety During Their Life. In De Stefano A. (ed), Proc. 7th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure (SHMII-7, 1-3 July 2015, Turin), RS2, ISHMII & Politecnico di Torino.

Saito T. 2015. Behaviour of response controlled and seismic isolated buildings during severe earthquake in Japan. Energia, Ambiente e Innovazione, 5, 31-37, ENEA, Roma, DOI: 10.12910/EAI2015-078.

Turino R. (ed) 2010. L'Aquila: il Progetto C.A.S.E. IUSS Press & Costruttori for C.A.S.E.

Zhou F.L. 2015. Earthquake tragedy and application of seismic isolation, energy dissipation and other seismic control systems to protect structures in China. Energia, Ambiente e Innovazione, 5, 23-30, ENEA, Roma, DOI: 10.12910/EAI2015-077.

Zhou F.L., Tan P., Heisa W.L.H., Xian X.L. 2013. Lu Shan earthquake M7.0 on 2013.4.20 and recent development on seismic isolation, energy dissipation & structural control in China. Proc. 13th World Conf. on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures (13WCSI, Sendai, Sept 24-26), JSSI, Tokyo.