Base Isolation for the Seismic Protection of Historical Buildings

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ABSTRACT:
The work presented in this paper is developed within a research program aiming at improving the basic knowledge, the design procedures and the construction systems in order to promote the use of seismic isolation as a practical method to retrofit existing and historical masonry buildings. Base isolation represents an optimum solution indeed the high stiffness of masonry structures easily allows for the separation of the oscillating modes with a good efficiency of the isolation option, leading to the full protection against the maximum expected earthquake without works on walls in the elevation portion. The application of the base-isolation technique for the retrofitting of existing masonry buildings, used as study case, is presented and discussed. In particular the design of the retrofitting through a base isolation solution of the Gagliardi-Sardi Palace damaged in the last L'Aquila earthquake in 2009 is described.

Keywords: Base isolation, Historical buildings, Existing buildings, Architectural heritage

1. INTRODUCTION

The meaning of "historical" building is a problem open to debate. From a general point of view, the "historical" buildings are characterized by the inherent worth they possess due to their architectural, aesthetic and cultural role, representative of their era in history. In the present they must be preserved since they represent a social and cultural identity. Most historical buildings were built using stiff, heavy and low strength masonry structures, so they are particularly vulnerable to seismic attacks with consequent large damage and even failures, moreover these construction can result further jeopardized by the deterioration due to aging. The earthquake of April 6, 2006 that stroked the city of L'Aquila in Italy produced devastating consequences on the historical and architectural heritage (Figure 1) and highlighted once more the problem of the safety of the historical constructions related to the wide difference between the high expected demand, due to the seismic hazard of their location, and the low capacity, due to low quality of the ancient construction materials and to the vulnerability of their structural configuration. The preservation goal in retrofitting historic buildings, deriving from cultural requirements, requires to retain the aesthetic and artistic integrity of the structure by the use of the original materials. If modern methods and materials are used, they must be non-invasive and entirely reversible. On the other hand, the preservation goal requires to strength the structure so that it will not be seriously damaged or fail under a severe earthquake. Often, the resulting decision is a compromise that cannot entirely assure both the opposite requirements. To afford these problems two fundamental concepts of earthquake design must be considered: "demand" and "capacity". If a normal design procedure is used, the demand is taken as a given and the goal is to incorporate into the building the required capacity to resist this demand. Although this method can improve the seismic resistance, it makes not possible to reduce simultaneously deformations and accelerations. So, it is critical issue to fully observe both the principles of conservation and restoration without to devaluate the intrinsic architectural properties of the buildings. The alternative approach is to reduce the demand. The seismic response of a structure can be improved without devalue its architectural character if the retrofit strategy of base isolation is used allowing for a reduction of the seismic demand.

Figure 1. Damage to the architectural heritage in L'Aquila earthquake: (a) Church of Santa Maria del Suffragio; (b) Church of Santa Maria di Collemaggio; (c) Church of Santa Maria Paganica

Seismic isolation, including base isolation and passive energy dissipation, is a relatively recent technique which has already been proposed (Mezzi et al. 1989, Mezzi & Parducci 1998, Indirli et al. 2001) and applied (Allen & Bailey 1988, Poole & Clendon 1992, Davis & Robertson 2000, Seki et al. 2000) for the seismic protection of existing historical constructions. The work presented in this paper is developed within a research program aiming at improving the basic knowledge, the design procedures and the construction systems in order to promote the use of seismic isolation as a practical method to retrofit existing and historical buildings (Mezzi et al. 2011). The application of an effective seismic protection policy, based on the use of suitable techniques and avoiding the devaluation of the architectural worth, is really a hard problem and base isolation can represent the optimum system to solve the problem, indeed it allows for the reduction of both the structural deformations and floor accelerations, improving the protection of structure and contents. The high stiffness of masonry structures easily allows for the separation of the oscillating modes with a good efficiency of the isolation option, leading to the full protection against the maximum expected earthquake without works on walls in the elevation portion. The application of the base-isolation technique for the retrofitting of an existing historical building, Gagliardi-Sardi Palace in the historic center of L'Aquila, is presented and discussed in the following as a study case.

2. BUILDING DESCRIPTION AND HISTORICAL INFORMATION

Gagliardi-Sardi Palace (Figure 2) is a complex inscribed within a lengthened rectangle of about 58,0×18,0 m. It is articulate in plan, with an internal courtyard opened on one side to form a "belvedere" at the highest two levels. The height from the ground level is about 15,0 m. The palace consists of three story above the ground level and by a practicable attic (with a "belvedere" terrace). The building is surrounded by public streets along all the four sides. All the façades have an high quality, so confirming that there is not a privileged relation with the urban space associated with a street or place, but all the fronts are equally significant and also present important openings. Figure 3 shows some external views of the building.

Figure 2. Aerial view of the façade on S. Flaviano St. and general plan of the building location

The study of the palace and the collection of the literature on the argument (Spagnesi & Properzi 1972, Moretti & Dander 1974, Stockel 1981, Centofanti & Colapietra 1992, Clementi & Piroddi 2009) allows for the formulation of hypothesis on its historical evolution, indeed the building plan is very different from the traditional scheme of a palace built in 17th century. A first core datable between the 14th and the 15th century can be identified. It is built with a simple construction technology consisting of a masonry texture (defined "apparecchio aquilano") consisting of facing small stone blocks organized in horizontal layers with staggered joints. The floors consists of wooden floors or stone vaults substituted since the 15th century with plastered masonry vaults. The actual first building phase date back to the 16th century with the enlargement of the building and an important architectural reconfiguration. It is not known the damage undergone by the building in occasion of the earthquake stroking L'Aquila in 1703, but probably the earthquake was the occasion for relevant works of rearrangement and construction during all the century that represent the second building phase. Finally the last building phase dates since the end of the 19th century to the beginning of the 20th and consists of the construction of a large one story forepart overlooking Grazie St on the area of an ancient garden.

(a) (b) (c)

Figure 3. (a) Façade on San Flaviano Sq.; (b) façade on San Flaviano St.; (c) forepart on Grazie St.

3. DAMAGE SURVEY AND PROVISIONAL WORKS

The damage state after the 2006 earthquake can be hardly described with a brief synthesis. In any case, for the sake of brevity, the main collapse mechanisms that result to be activated are shortly listed:

- overturning of the walls along the streets San Flaviano and Dei Sardi;
- overturning of the wall overlooking San Flaviano square, the cracks on the vault covering the hall are also due to the rotation of the wall;
- serious damage of the vaults of the main staircase;
- fall down of the balustrade of the back terrace and of some stone portions of the façades;
- sliding of the roof cover (tiles);
- serious and large cracks in the vault covering the hall to the internal court;
- cracks having width of the order of centimeters are present on the floors and ceilings of the rooms at the first and second floor (the cracks are congruent with the rotation of the perimeter wall toward the exterior);
- collapse of false ceilings and partition walls at the interior;
- wide cracks are present at the connection between the transverse walls and the façade walls;
- collapse of the arch and vault covering the main staircase adjacent the wall overlooking Sardi St. (this damage is one of the most dangerous because the structures are seriously cracked and because the ultimate collapse would involve the street beneath, that is Grazie St.);
- widespread shear cracks of the masonry panels.

The following Figure 4, Figure 5, Figure 6 and Figure 7 show some of the most important damage state of the building. The security measures consisting of shoring up works performed after the earthquake allowed to make safe the building avoiding the risk of successive collapse.

Figure 4. Cracks of the vault on the entry to the courtyard and damage of the vault of the staircase on Sardi St.

Figure 5. Collapse mechanisms of the lateral façadesand of the façade overlooking San Flaviano Sq.

Figure 6. Failure of nonstructural elements: false ceilings and partitions

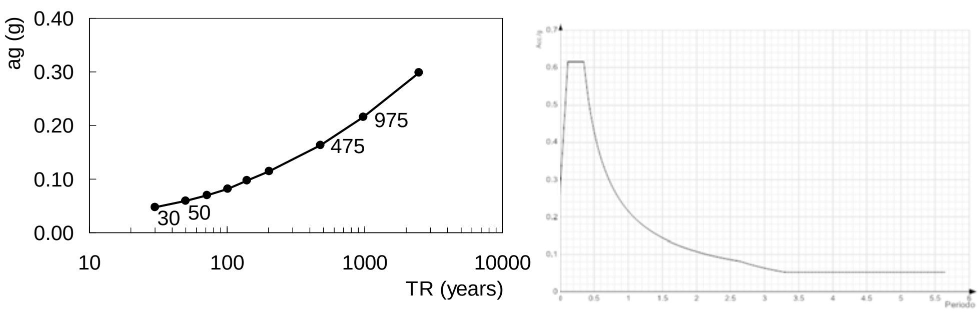
Figure 7. Cracks on the flooring of the first floor and collapse of the "belvedere" of staircase

Provisional works aimed at making the building safe with respect to further failures and collapses and at making safe the streets surrounding the building were performed in the first days and weeks after the earthquake. The provisional works were defined as a consequence of the damage analysis, of the generating causes, of the identification of the probable collapse mechanism. This allowed to define aimed remedies and specific countermeasures set up as urgent and temporary measures until the complete repair and retrofitting of the building. As previously described, all the perimeter walls overlooking the public streets and the internal courtyard show wide cracks associated to the trend of the walls to overturn toward the exterior, particularly the condition along Sardi St. is very near to the complete collapse. To eliminate this collapse possibility a complex systems of Diwidag tendons has been installed that, going from one side to the opposite one, are able to close the masonry box and avoid the overturning. The tendons, passing through the aligned windows and openings, or through perforated holes, connect the walls of the opposite façades, equilibrating the outward pushing from the static loads of the vaults and from the lateral acceleration of an eventual earthquake. The tendons transfer the reaction to the masonry panels at the sides of the openings by means of steel beams and wood boards.

4. SEISMIC CAPACITY

4.1. Seismic hazard

According to the current Italian code (NTC 2008) the site is characterized by the hazard curve reported in Figure 8a in terms of PGA at the bedrock a_g versus the return period TR. The PGA at the bedrock with a 475 years return period is ag=0.261 g. For the site effect an amplification factor S=1.0 corresponding to a hard subsoil condition (subsoil type A) can be assumed. The ULS elastic response spectrum corresponding to the Life Safety ultimate state is reported in Figure 8b.



(a) (b)

Figure 8. (a) Seismic hazard curve at the site. (b) ULS elastic response spectrum (NTC 2008).

4.2. Seismic analysis

The seismic capacity of the building in its pre-existing configuration (not accounting for the damage undergone by the seismic event) has been evaluated through an analysis in two steps. A structural analysis of a FEM model of the whole building allows to account for the capacity related to the in-plane strength of the masonry panels. The analysis of a number of local collapse mechanisms, that a global model is not able to reproduce and evaluate, allows to evaluate the capacity associated to the out-of-plane behavior. The global analysis is performed through nonlinear static analyses (pushover) according to the provisions of the Italian codes. The local analyses are performed through the limit analysis with a linear cinematic approach. The capacity PGA from the worst case of global analysis results equal to 0.099 g, characterized by a return period of 46 years and defining a risk index of 0.381 (ratio between the capacity PGA and the ULS PGA). The capacity PGA from the worst local mechanism results equal to 0.057 g, characterized by a return period of 22 years and determining a risk index of 0.222.

5. BASE ISOLATION

The design of a base isolation system for the seismic improvement or retrofit of an existing building is substantially different from that of a new building. In the last case the main parameters of the isolating system, i.e. fundamental period and damping, are predefined and the superstructure is then designed to have the suitable strengths to resist the computed forces. On the contrary, for an existing structure the main goal is to avoid or strongly limit the retrofitting works on the elevation, therefore the first step consists of evaluating the seismic capacity of the structure and then the characteristics of the isolation system should be calibrated to limit the forces undergone by the structural elements below the strength levels. The design strategy provided by the base isolation allows to design the demand in such a way that it is lower than the capacity. In the practice it can happen that the capacity analysis of the existing building evidence the presence of structural elements having strength or ductility so low to lead to very low values of the allowed design acceleration. So low values could require so high values of the isolation period that are not compatible with the typologies of isolators available in the market and with the limits of their response. In these cases it is suitable to adopt local works to strengthen the inadequate elements to increase the capacity of the building and to allow the insertion of isolation systems having ordinary characteristics. Once outlined the design procedure, the main issue consists of the execution modalities of the base isolation of the existing building - that is a masonry building and in addition seriously damaged - that should be separated from the ground and, in the present case, also from the one-story portion present at one of the two heads. Figure 9 shows the main phases of the works for the seismic isolation of the palace. The operational modalities to apply the innovative isolation strategies are partially based on traditional operational methods widely applied to construct a sub-foundation of a masonry building showing a lack in foundation structures. The first execution phase provides for the repairing of the poorest masonry structural elements and for the insertion of ties to eliminate the risk condition and to contrast the outward reactions of arches and struts. The separation of the small one story portion is pursued creating a gap 250 mm wide on the floor and walls adjacent to the main construction and building a r/c frame supporting the floor previously stood on the wall of the higher building. Making the gap is not a relevant work, even for the artistic and historical aspects, indeed the portion to be separated is a recent one (dated at the beginning of the last century), the cut floor is made of concrete and masonry, and the spaces do not have relevance. The following phase, after a suitable shoring of floors and vaults, provides for the excavation at the base of the walls and the casting of twin r/c beams at the two sides of the walls according to the ordinary sub-foundation works. The works are carried out subdividing the operational area in sub-areas and executing the works in successive steps alternating the operational sub-areas. The successive phase consists of a second sub-foundation phase including works at a greater depth still operating for sub-areas (Figure 10): r/c cubes and the surrounding portions of the foundation slab are built. The cubes are devoted to host the isolating devices and a flat jack is provided to be placed below the isolators. After the curing of the cubes and slabs, the jack will be put in pressure, injecting epoxy resin, up to the load to be transferred. At this stage the vertical load pass through the isolator and the above masonry wall is effectively supported by the isolator. The phase is completed by casting a fluid mortar to compensate the space below the lower counter plate of the isolator and to seal its anchor bolts. The operation is repeated for all the isolators.

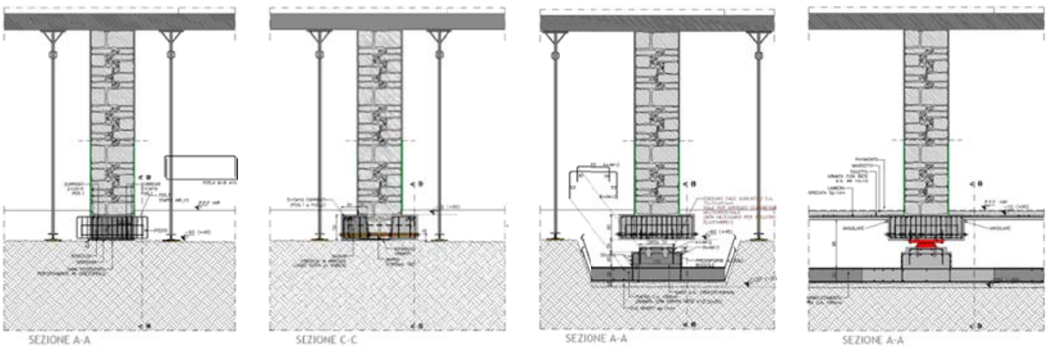


Figure 9. Phases of the works for the insertion of the base isolation system

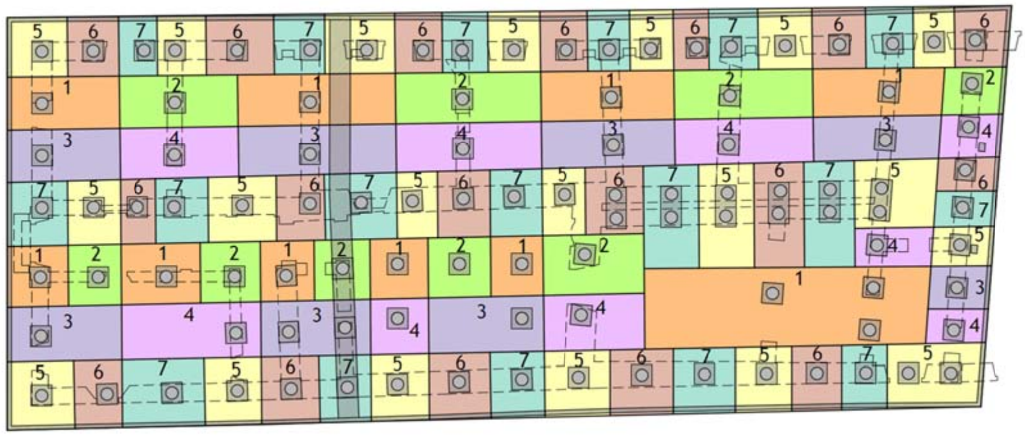


Figure 10. Operational sub-areas for casting the support r/c cubes and the surrounding foundation slab

After building all the cubes and slab portions, the foundation slab is completed on all the base surface casting the areas among the previously cast portions, new and old parts are closely joined thanks to the superposition of the reinforcement to devoted bars sticking out of the previous casting. The foundation slab represents the rigid diaphragm below the isolating interface. The rigid diaphragm above the isolating interface is made of a steel floor rigidly joined to the twin beams previously built and completed with the casting of a r/c slab. This floor will represent the new ground level floor. The space between the ground floor and the foundation slab is devoted to the maintenance and inspection of the isolators. Figure 11 shows the final scheme of the base isolated palace.

Figure 11. Longitudinal section of the palace in the isolated configuration

The designed isolation system includes two types of isolators: 53 soft compound HDRB and 49 sliders. The mechanical characteristics of the adopted devices are reported in Table 5.1. The relatively small number of HDRB devices with respect to the total derives from the fact that the total number of devices is high because of the need to locate them at reduced distances to limit the stresses in the masonry walls and to allow the works at the base previously described. The distances among the isolators are limited between 2,5 and 3,5 m to avoid that the base twin beams are too large and heavy. The number of isolators per unit in-plan surface of the building is therefore higher than for analogous retrofitting of r/c building where the distances are those among the columns, ordinarily 4,5 - 6,0 m. On the other side the total mass is not relevant, therefore the stiffness of the isolation system, required to obtain an optimum value of the isolation period, is not high and consequently the required number of HDRB isolators, provided with stiffness, is quite similar to that of the sliders, that practically have not stiffness. Figure 12 shows the in-plan arrangement of the two different types of isolators located to maximize the torsion stiffness of the system and to minimize the eccentricity between mass and stiffness center. The adopted solution allowed to limit the eccentricity values to 260 mm in the longitudinal direction and to 160 mm in the transversal direction.

Table 5.1. Properties of the isolating devices

Typology	Type	Maximum vertical load		Stiffness	Percent of critical damping	Maximum displacement	Number
		Seismic	Static				
		(kN)	(kN)	(kN/m)	(%)	(mm)	
HDRB	FIP SI-S 500/78	1800	5100	1010	15	150	53
Sliders	FIP VASOFLON VM 200/150/150	2000	2000	---	---	150	49

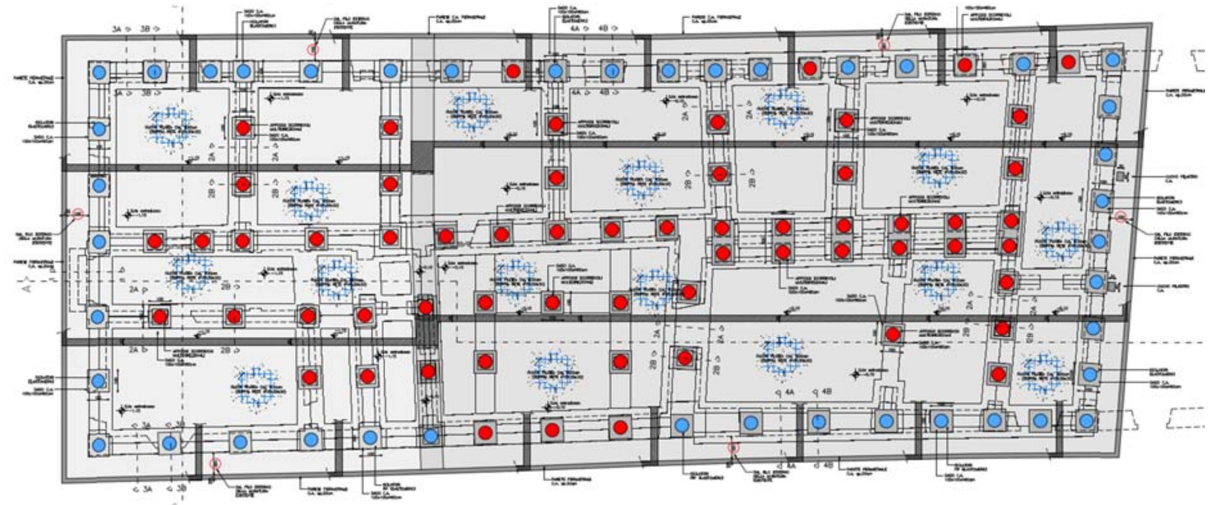


Figure 12. Plan layout of the isolating devices: HDRB (blue circles) and sliders (red circles)

5. ANALYSIS OF RESULTS

The design and the check of the building has been performed through linear analyses of a global model including substructure, isolation system and superstructure. Figure 13 shows the deformed shapes of the first three modes of the isolated structure, that is of the modes associated with the isolation system. The first and second modes result purely translational in the transverse and longitudinal direction, respectively; the third mode is a pure torsion. The dynamic characterization is the typical one of an optimum solution of base isolation and evidence the goodness of the solution designed.

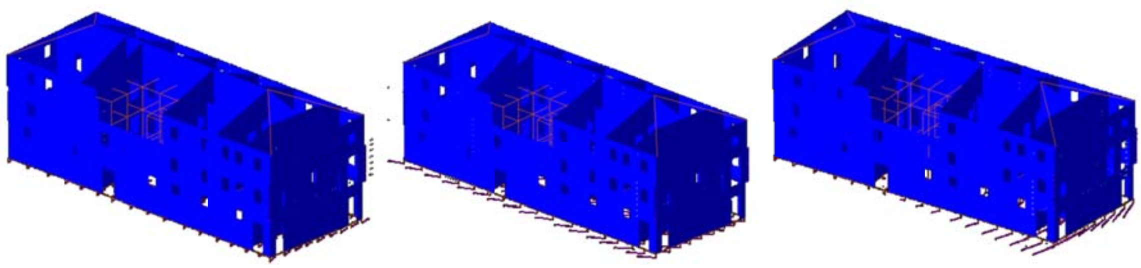
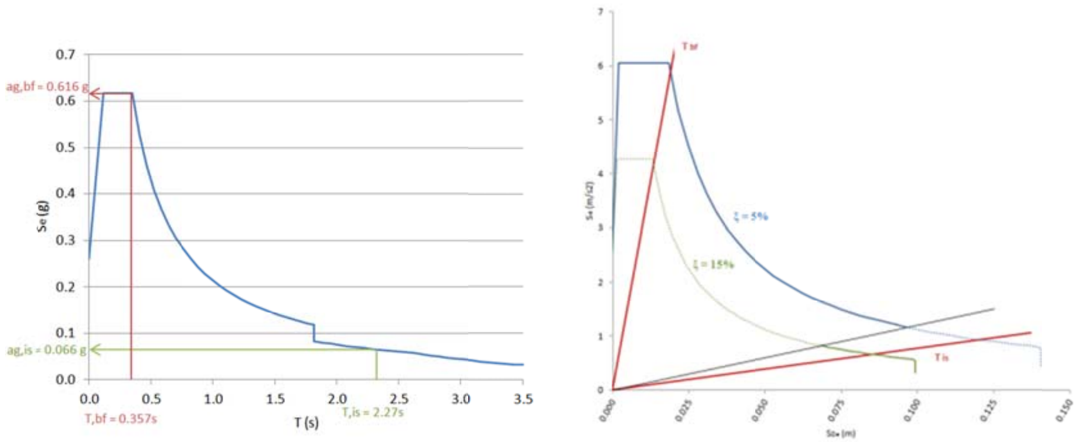


Figure 13. Deformed shapes of the first, second and third mode of the isolated structure

The performed numerical analyses show the optimum seismic behavior of the isolated building for which the integral protection and full fitting are obtained: the building results able to undergo the ultimate limit design earthquake without reaching the strength limits of the superstructure elements. Figure 14 gives a graphic representation of the design principle of the seismic isolation that allows to adjust the demand. Figure 14a shows, with reference to the elastic response spectrum, the reduction of the response acceleration (from 0.616 g to 0.066 g) resulting from the increment of the natural period of the building from 0.357 s (fixed-base option) to 2.27 s (base isolated option). Figure 14b shows the same effect when the representation in the plane ADRS (Acceleration Displacement Response Spectrum) is adopted. In this case also the displacement increase is evident. The increase in the percent of the critical damping (from 5% to 15%) allows a reduction of the response in terms of acceleration, that is less relevant, and, more significantly, of displacement.

The analysis of the graphs evidences the fundamental effects of the base isolation:
- quite complete decoupling of the behavior of the superstructure from that of the ground, thanks to a ratio between the fundamental periods of the isolated and fixed-base structures greater than 6;
- dramatic reduction of the response acceleration of the elevation resulting from the shift of the natural period of the building towards the range of periods in which the seismic action is characterized by very lower power;
- significant increase of the structure displacements that are not required to the superstructure but only to the isolation system, the superstructure remains quite undeformed, oscillating on the isolators;
- slight increase of the system damping from the values (about 5%) associated to the limited deformations of the fixed-base structures to the values (15% in the present case) associated to the lateral behavior of the isolating devices, reducing both acceleration and displacement.



(a) (b)

Figure 14. Comparison of the seismic performance of the fixed-base and base isolated solution: (a) pseudo-acceleration response spectrum; (b) Acceleration-Displacement Response Spectrum (ADRS)

6. CONCLUSIONS

The fundamental problem of the seismic retrofitting consists of an optimum calibration of the "distance" between seismic demand and seismic capacity. The calibration is more critical when a historical construction is involved, due to the contrasting requirements deriving by the preservation need: to increase the safety and the life of the construction, to limit the strengthening works that can alter the integrity of the worth. Base isolation allows to satisfy the preservation requirements sometimes allowing for an integral protection of the construction, without significant strengthening works on the elevation.

The situation of the Gagliardi-Sardi Palace has been illustrated as emblematic case of a real situation of historical construction located in a high seismicity area. The designed works concern almost only the foundation of the building, while the works on the elevation, not described here for the sake of brevity, consist of repairing and restoring works required by the damage induced by the earthquake and of strengthening works related to the weakness, even for the static loads, of local structural configurations characteristic of the construction. The works provided on the elevation are the same restoration works that would have been performed on the building even if it was located in a region without seismic hazard. No seismic strengthening is required on the superstructure, while the construction, once isolated, can undergo the maximum expected quake (ultimate limit design earthquake) within the strength limits of all the structural elements and practically also within the structural and artistic damage limits. Therefore the historical construction results integrally protected against the future earthquakes.

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REFERENCES

Allen E.W., Bailey J.S. (1988). Seismic Rehabilitation of the Salt Lake City & County Building Using Base Isolation. *9th World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan.

Centofanti M., Colapietra R. (1992), L'Aquila città di piazze, spazi urbani e tecniche costruttive, Carsa Edizioni, Guastalla, Italy.

Clementi A., Piroddi E. (2009), La città nella storia d'Italia, L'Aquila, Edizioni Laterza, Bari.

Davis H.A., Robertson D.R. (2000). Hearst Memorial Mining Building Seismic Improvements, University of California, Berkeley. *12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

Indirli M., Forni M., Martelli A., Spadoni B., Venturi G., Alessandri C., Bertocchi A., Capelli C., Baratta A., Procaccio A., Clemente P., De Canio G., Carpani B., Bonacina G., Franchioni G., Viani S., Cesari F., Mucciarella M. (2001). ENEA activities for the development and application of innovative techniques for the seismic protection of cultural heritage. *5th World Congress on Joints, Bearings and Seismic Systems for Concrete Structures*, Rome.

Mezzi M., de Nunno R., Marimpietri A. (1989). Ipotesi per l'Isolamento Sismico di Due Complessi Monumentali di Perugia: la Fontana Maggiore e la Chiesa di San Bevignate. *Intern. Meet. on Base Isolation and Passive* .... Assisi, Italy.

Mezzi M., Parducci A. (1998). Base Isolation in Retrofitting Historic Building. *MONUMENT-98*. Lisboa.

Mezzi M., Comodini F., Rossi L. (2011). Base Isolation Option for the Full Seismic Protection of an Existing Masonry School Building. *13th Int. Conf. Civil, Structural and Environmental Engineering Computing*. Chania, Greece.

Moretti M., Dander M. (1974), L'architettura civile aquilana dal XVI al XIX secolo, Japadre Editore, L'Aquila.

NTC (2008), Norme tecniche per le costruzioni. D.M. Ministero Infrastrutture e Trasporti 14 gennaio 2008, G.U.R.I. 4/2/2008, Roma, Italy.

Poole R.A., Clendon J.E. (1992). New Zealand Parliament Buildings Seismic Protection by Base Isolation. *Bulletin of the New Zealand National Society for Earthquake Engineering* **25(3)**, 147-160.

Seki M., Miyazaki M., Tsuneki Y., Kataoka K. (2000). A Masonry School Building Retrofitted by Base Isolation Technology. *12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

Spagnesi G., Properzi P. (1972), L'Aquila problemi di forma e storia della città, Dedalo Libri,Bari.

Stockel G. (1981), La città dell'Aquila, il centro storico tra il 1860 e il 1960, Edizioni del Gallo Cedrone, Rieti.