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BASE ISOLATION IN SEISMIC RETROFITTING OF R/C BUILDINGS

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The paper, based on the authors' direct involvement in managing actual retrofitting design, reports on seismic vulnerability assessment, design and implementation issues related to the seismic retrofit of reinforced concrete buildings through base isolation. The retrofitting interventions design of damaged buildings involves three aspects: the damage survey, the assessment of the vulnerability of building in its original structural configuration, the design of intervention needed to reduce the building vulnerability up to a conventional level, normally indicated by the seismic standards. In the first part of the paper, the experience achieved in the retrofit of reinforced concrete buildings damaged by the Italian 2009 L'Aquila earthquake is presented by referring to a typical intervention designed by the authors. Topics related to conventional vs base isolation retrofitting strategies, structure's performance, safeguard of human life, construction efficiency and repairing cost are analyzed with reference to actual case study. Lessons learned from the Italian experience have been critically applied to the design of retrofit intervention of a building, designed according to the current Nepal set of codes and under completion at the time of the earthquake, damaged by the Gorkha 2015 earthquake. In the second part of the paper activities carried out for the definition of a specific site seismic input, for the dynamic characterization of the building and for the design of the base isolation retrofit are presented.

Keywords: Earthquake damage, Seismic isolation, Retrofitting intervention, Dynamic characterization, HVSR technique.

1 INTRODUCTION

Seismic (or base) isolation is a design technique that reduces the force demand on structures by isolating them from the damaging effect of the ground motion (Martelli *et al.* 2011). It functions primarily by lengthening the period of the structure (Skinner *et al.* 1993). This approach contrasts with conventional design schemes that rely on inelastic action of various structural elements to dissipate earthquake energy. It provides a level of performance well beyond the normal code requirements with potential for substantial life-cycle cost reduction. Base isolation offers important advantages over conventional protection methods because it reduces the earthquake forces transmitted into a structure, thus it protects not only the structure itself but also the contents and secondary structural features.

Isolation is achieved with specially designed bearings placed between the building and its foundations that provide flexibility and energy absorption capability while supporting the weight of the structure. These bearings can be replaced if such need arises. The design of the retrofitting and seismic improvement of the damaged buildings involves the vulnerability assessment of the buildings in their undamaged conditions and the identification of the most effective techniques for the seismic enhancement (Mokha *et al.* 1996). Ranking of the different seismic enhancement strategies should be based on their structural effectiveness, impact in the application, lifetime, related indirect works as well as their direct and future costs. However, also ambient and cultural conditionings and the explicit or latent reluctance to adopt innovative solutions have a significant influence on the choice of the retrofitting strategy to be adopted. Very often even minimum constraints put by the actual situation of the existing building play a decisive role in opting for a retrofit design strategy adverse to a non-traditional solution. This is also the case of base isolation (BI) that is applied in a limited number of cases despite its well-known effectiveness.

Two of the cases in which the BI technique has been proven to be more effective and convenient than conventional strengthening, and therefore adopted for the seismic improvement, are illustrated in the paper.

2 APPLICATION IN ITALY

A huge number of r/c buildings were strongly damaged by the 2009 L'Aquila earthquake (EERI 2009). Many of these buildings, designed and built more than twenty years ago, were characterized by insufficient resistance against lateral forces, as well as by insufficient ductility and resilience due to inadequate structural configuration and structural detailing. In the following are reported the conventionally based and the base isolated design retrofit of a typical Italian residential building.

2.1 Building Description and Vulnerability

The building, in its as built condition (Figure 1), has an L-shaped plan resulting from the presence of two blocks, independent from the structural point of view and separated by an insufficient seismic gap of 4 centimeters. The building has a basement with cellars and garages, five floors above ground and a loft. The structure is made of r/c beams and columns with floors made of hollow bricks and concrete.

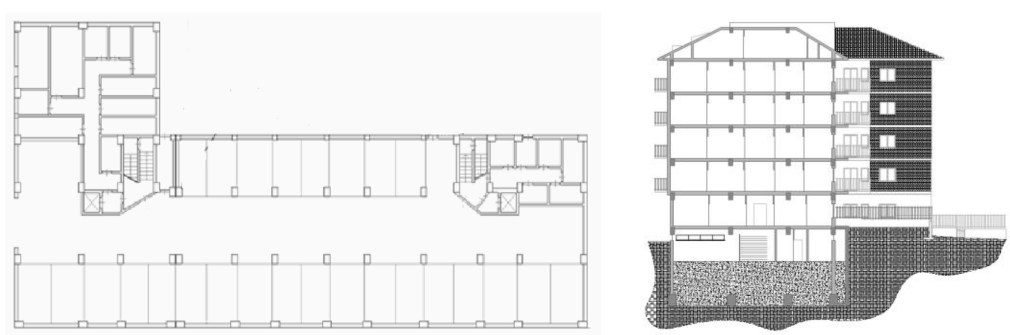

Figure 1. Basement floor plan view and building longitudinal section.

The mechanical characteristics of the materials were estimated on the basis of testing campaigns including core sampling and SonReb tests for concrete and tension tests on samples of steel bars. Tests indicated an average cubic strength of concrete R_{cm}=22.0MPa and a characteristic yield strength of steel f_{yk}=305MPa. According to the Italian code provisions on the knowledge of the existing constructions concerning geometry, constructive details and mechanical properties of materials, it results an intermediate knowledge level (adequate knowledge); this implies the application of a confidence factor FC=1.2 reducing the mechanical parameters of materials to be used in numerical calculations. The performed geological investigations pointed out that the subsoil was characterized by a reference shear wave velocity greater than 360 m/s and lower than 800 m/s and so classifiable as "Category B" according to European (EN1998-1 2004) and Italian (NTC 2008) standards. The seismic hazard is then expressed in terms of demand peak ground acceleration for different limit states: $PGA_{D,LD}$=0,125g for the Limited Damage (LD) limit state, $PGA_{D,LS}$=0,301g for the Life Safety (LS) limit state, $PGA_{D,CP}$=0,361g for the Collapse Prevention (CP) limit state.

The seismic capacity of building in its original undamaged state was assessed by nonlinear static analyses. The minimum value of bedrock acceleration for the attainment of the LS limit state is $a_{g,C,SLV}$=0.078g. The vulnerability of the construction is expressed by the ratio $a_{g,C,SLV}/a_{g,SLV}$=0,299 between the capacity and demand accelerations ("risk index" in the Italian guidelines). Since this value is less than the minimum of 0.60 prescribed by the guidelines for the repair of damaged buildings, works are required to improve the seismic capacity up to a Capacity/Demand (C/D) ratio higher than 0.60 but less than 0.80. The collapse scenario associated with the attainment of the limit state in pushover analyses shows that it is connected to the shear failure of columns together with flexural damage of beams. Actually, the building suffered damage in the 2009 seismic event, especially at the lower levels, to both nonstructural (claddings and internal partitions) and structural elements (cracking of r/c elements). In the post-earthquake survey of damaged buildings, the building was classified as class E "unfit for use – to be evacuated".

2.3 Improvement of Seismic Capacity through Traditional and Innovative Approaches

The adopted enhancement solution foresees the insertion of a base isolation system, but for the purpose of comparison, also a traditional enhancement strategy based on the reinforcement and stiffening of the structural components has been considered.

Within the framework of a traditional seismic improvement the following interventions should be made: (a) insertion of r/c walls to increase the seismic resistance and reduce the lateral and torsional deformability; (b) construction of a r/c slab to strengthen the floors, damaged by the earthquake, and ensure a diaphragm behavior; (c) steel jacketing of unconfined internal joints; (d) bonding fiber composites tapes to strengthen the external joints; (e) strengthening of local critical elements (i.e. landing beams of stairs); (f) widening of foundation beams under the walls. The traditional seismic improvement allows the structure to reach a capacitive acceleration $a_{g,C,SLV}$=0.211g, that is an acceptable C/D ratio equal 0.649>0.60. However, it has to be noted that the aforesaid works are characterized by a high impact on the construction since almost all the nonstructural elements should be demolished; furthermore, the standard protection levels cannot be reached, due to the inherent low capacity of the construction itself, not to mention the fact that they a high cost with respect to the benefit achieved.

The base isolation option was considered as the preferred solution since the very beginning of the design for the seismic improvement of the building. This was mainly due to the possibility to do most of the works at the basement level only, almost completely avoiding strengthening works at the elevation in spite of the generalized low seismic-resistant capacity of the primary structural system. The following interventions have been conceived: cutting of the top portions of the columns at basement level, insertion of isolating devices, strengthening of the columns below the cut and of the joints above the cut, demolition and reconstruction of the first flight of the stairs. Figure 2 shows some details of the base isolation works. The isolating system, consisting of one type of High Damping Rubber Bearings (HDRB) 650mm diameter and sliders, allowed to reach a base isolated period of 2.62 s and participating mass percentage almost equal to 99%.

Figure 2. Pictures of works for the base isolated retrofit.

As far as the building elevation (existing superstructure) is concerned, the resistant sections of beams and columns have been proven to be sufficient to sustain the stresses induced by the earthquake; this turned out to be the only safety check since for base-isolated constructions the detailing design rules of seismic-resistant structures are not prescribed. For the substructure the strengthening, consisting of jacketing with r/c and steel profiles of the columns below the isolators, has been designed taking into account the P-delta effect caused by the isolators' displacements. No strengthening of foundations was required. The base isolation approach allows the structure to obtain a C/D ratio equal to 0.797>0.60.

2.4 Cost Comparison

The comparison of the retrofitting costs of the two solutions is reported in Table 1 from which it can be seen that the base isolation approach allows to achieve an immediate saving of 34%, saving that in the building lifetime will be even greater. As a matter of a fact, the base-isolated building will not suffer, under the maximum expected earthquake any structural damage, while, at the same time offering full protection to the contents and secondary features (such as cladding and windows) thus improving the safety of occupants and passers-by.

On the contrary the traditionally retrofitted building will start undergoing serious consequences for an earthquake having an intensity lower than 70% of the maximum expected one and a 25% probability to be exceeded in the building life. Moreover, for the maximum expected quake, i.e. the one a probability of 10% in the lifetime, the building will suffer extensive damage with an expected reparation cost comparable with the reconstruction cost.

Table 1. Cost comparison for conventional and base isolated retrofit.

Work category	Traditional		Base-isolated		Diff.
Type A - Repair	€ 2.002.536	40.7 %	€ 199.000	32.9 %	-47.2 %
Type B - Seismic enhancement	€ 1.597.770	32.5 %	€ 646.000	36.4 %	-26.7 %
Retrofit due to Type B works	€ 620.068	12.6 %	€ 356.000	6.7 %	-65.1 %
Hygienic sanitary conformity	€ 232.783	4.7 %	€ 232.783	7.2 %	=
Energy saving conformity	€ 354.456	7.2 %	€ 354.456	11.5 %	=
Lifts	€108.863	2.2 %	€ 178.723	5.6 %	+67.1 %
Total	€ 4.916.478	100.00 %	€ 3.029.118	100.0 %	-34.3%

3 APPLICATION IN NEPAL

The April 25, 2015 M 7.8 Nepal earthquake, also known as the Gorkha earthquake had his epicenter approximately 80 km to the northwest of the Nepalese capital of Kathmandu. A number of buildings also located in the so called Kathmandu valley and designed according to the current Nepal National Building set of codes were damaged.

A damage survey has been carried out and a number of r/c buildings, representative of currently used Nepalese earthquake resistant structural schemes, have been selected by the authors for the vulnerability assessment and retrofit intervention designs. In the following the focus is on a building complex, hereinafter referred to as the “Downtown complex”, made of two towers of 15 floors each resting on a common underground basement (Figure 3). The “Downtown complex” was in an advanced construction stage at the time of the earthquake and suffered damage to both structural and nonstructural elements.

Figure 3. The “Downtown building complex”.

On the selected building, a set of instruments have been installed by the Seismological Research Centre of the Italian National Institute of Oceanography and Experimental Geophysics for the acquisition of accelerometric data, while estimates of site amplification of seismic ground motion have been obtained from application of HVSR technique (OGS 2016). In Figure 4 the average H/V curves at different floors are reported.

Seismic site study results showed that no amplifications are to be expected at typical isolation periods, therefore base isolation has been considered as retrofitting strategy. The seismic behavior of the buildings has also been analyzed by means of Finite Element Model that has been suitably adjusted to match the frequencies identified through the site tests. Indeed the first two frequencies identified on site are equal to 0.96Hz and 3.7Hz and the corresponding frequencies computed on the FE model are 0.97Hz and 3.6Hz. Analyses showed that the insertion of HDRBs at the top of the basement columns gives an isolated period of 3,5s with consequences in term of performance increase and cost reduction similar to those obtained in the Italian application.

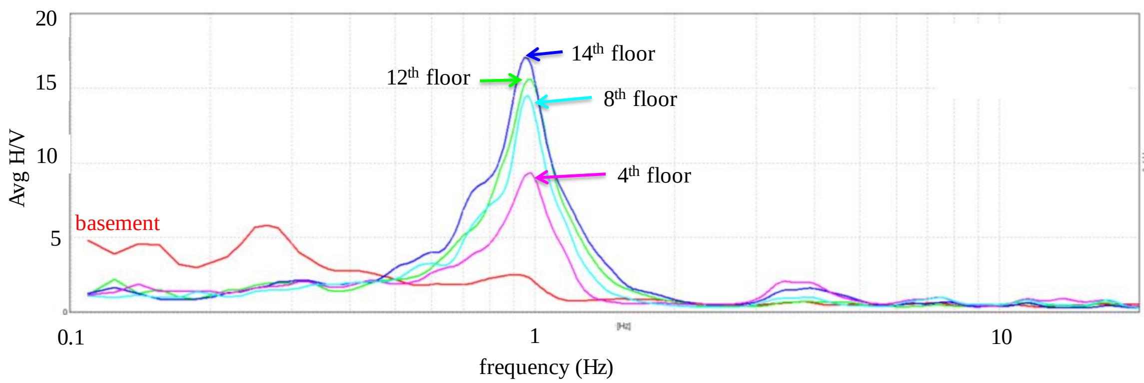

Figure 4. Average H/V curves at different floors.

4 CONCLUSIONS

Base isolation application in retrofit of r/c structures has been proved to be effective and economically convenient. The cost comparison carried out shows that base-isolation choice allows to obtain an immediate saving of 34%; savings that in the building's lifetime are actually even greater. Experiences achieved in the design and retrofit works can be extended to seismic prone area worldwide.

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