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BASE ISOLATION FOR SEISMIC RETROFITTING OF DAMAGED BUILDINGS

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The paper deals with the retrofitting of r/c buildings damaged by the earthquake adopting the base-isolation. The case of one building is analyzed in detail. The seismic vulnerability of the building in the original configuration is assessed. A classification of the possible conventional works concerning repair, retrofit, seismic enhancement is carried out dealing with the structural effectiveness, impact, control in application and lifetime, related indirect works, cost. The main result is a tentative classification of the issues related to the insertion of a base-isolation system below an existing building aimed at its seismic enhancement, avoiding or relied strongly limiting other works in the building elevation. The retrofitting strategies, the enhancement levels, the application solutions are critically revised statement under the experience of the real cases faced with, also paying attention to the cost-effectiveness ratios.

Keywords: Seismic isolation, Retrofitting strategies, Seismic enhancement.

1 INTRODUCTION

After the 2009 L'Aquila earthquake, not only the ancient masonry buildings of the historical center, but also a large amount of reinforced concrete (r/c) buildings resulted strongly damaged (EERI 2009). The design for the retrofitting and seismic enhancement of damaged buildings involves the vulnerability assessment of the buildings in their original configuration as well as the identification of the optimum technique for the seismic enhancement. A classification of the alternative seismic enhancement strategies should deal with the structural effectiveness, the impact in the application, the lifetime, the related indirect works, and the direct and future costs. Actually also the ambient and cultural conditionings and the explicit or latent reluctance to adopt innovative solutions influence the choice of the strategy to be adopted. Indeed also minimum constraints put by the actual situation of the preexisting building generally play a decisive role in assuming a design decision adverse to a non-traditional solution. The authors within their activities on the seismic design enhancement of r/c buildings damaged by the Aquila earthquake (Mezzi and Petrella 2013) adopted these techniques in some cases (Figure 1). A sample case is illustrated in this paper.

2 DESCRIPTION OF THE SAMPLE BUILDING

The sample building (Figure 2) has a rectangular plan with dimensions of approximately 28.90×15.05 m excluding the cantilevered balconies. The building has a basement with cellars and garages, four floors above ground and a loft. There is also a further "buried" basement below the basement floor. The structure is made of r/c beams and columns with floors made of hollow bricks and concrete. The columns are arranged in eight transversal alignments and four longitudinal alignments, but some of the facade columns are backward with respect to the alignment of facade. The perimeter beams are high, while inside, along almost all the alignments, there are beams with the floor thickness. The original project was made in 1969 but only one drawing, concerning foundations, was found.

Figure 1. Buildings retrofitted through base isolation.

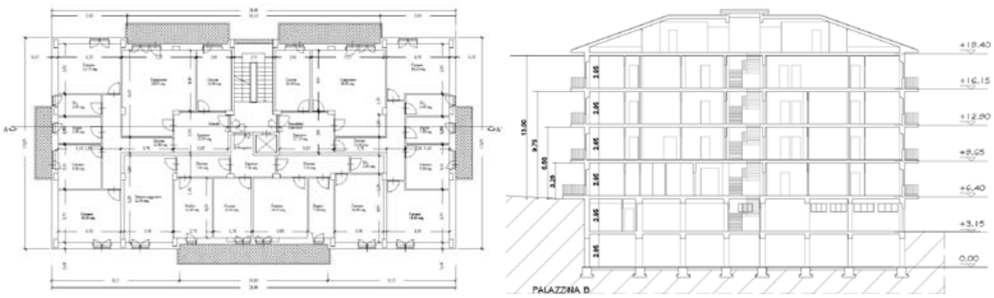

Figure 2. Plan of a typical floor and longitudinal section of the sample building.

The mechanical characteristics of the materials were estimated on the basis of two campaigns of tests including core sampling and SonReb tests for concrete and tension tests on samples of steel bars drawn in situ. The average cubic strength of concrete is R_{cm}=12.5 MPa and the characteristic yield strength of steel is f_{yk}=380 MPa (steel type FeB38k). With reference to the 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 involves the application of a confidence factor FC=1.2 reducing the mechanical parameters of materials to be used in numerical calculations.

The seismic hazard of the site, expressed in terms of peak bedrock acceleration as a function of the return period, is derived from the maps defined for the Italian territory. The performed geological and geotechnical investigations show a situation of very stiff subsoil, characterized by shear wave velocity $V_{s,30}$>800 m/s and so classifiable within the "Category A" according to EN1998-1 (2004) and Italian standard NTC (2008).

Hence local amplification effects does not exist and the peak ground acceleration (PGA) is equal to the bedrock acceleration, in particular: $PGA_{SLD}=a_{g,SLD}=0{,}104$ g for the damage limit state (SLD), $PGA_{SLV}=a_{g,SLV}=0{,}261$ g for the life safety limit state (SLV), $PGA_{SLC}=a_{g,SLC}=0{,}334$ g for the collapse limit state (SLC).

3 ASSESSMENT OF SEISMIC VULNERABILITY

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 SLV is $a_{g,C,SLV}=0.098$ g. The vulnerability of the construction is expressed by the ratio $a_{g,C,SLV}/a_{g,SLV}=0.377$ 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 (Figure 3) shows that it is associated with the shear failure of a column together with minor flexural damage of beams. This condition concerns a single structural element and is a fragile collapse condition without the structure can get a ductile behavior. Moreover also any factor of intrinsic vulnerability of the building should be taken into account: in this case the variation in height of the beams and the presence of beam-column joints not fully confined involves values of risk indexes still lower than that estimated at the global level.

The building suffered many damage in the seismic attack, especially at the lower two or three levels. Almost all the claddings were damaged as well as many of the internal partitioning. A number of cracks were observed on the r/c elements of the basement story where the surface of the structural elements was not plastered.

The project for the seismic enhancement must have two goals of seismic protection: to eliminate situations of vulnerability and fragility related to structural and constructive configurations also highlighted by the damage undergone in the earthquake; to increase the overall seismic-resistant capacity up to C/D values greater than 60%. In addition all necessary works to restore the integrity of the damaged elements must be provided.

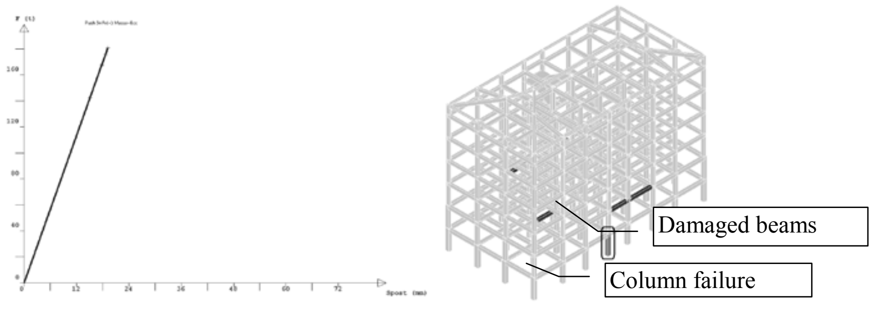

Figure 3. Example of pushover curves (left) and damage state at SLV limit state.

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

4 CONVENTIONAL SEISMIC ENHANCEMENT

Within the framework of a traditional seismic improvement the following classes of works should be provided: (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 get a capacitive acceleration $a_{g,C,SLV}$=0.181g, that is an acceptable C/D ratio equal 0.696>0.60. These works: (a) are characterized by a high impact on the construction; (b) cannot reach the standard protection levels, due to the basic low capacity of the construction; (c) have a high cost with respect to the benefit achieved.

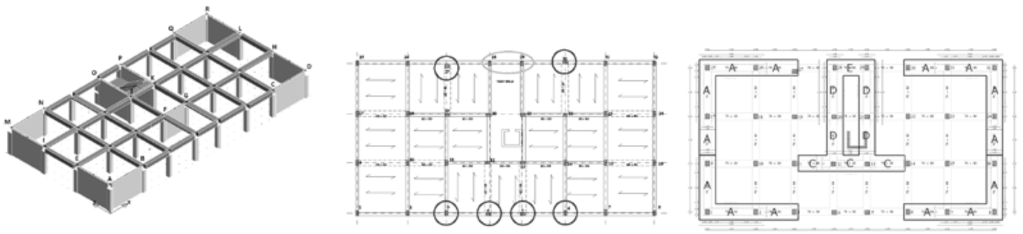

Figure 4. Traditional operations: walls insertion, joints strengthening, foundation widening.

5 ENHANCEMENT THROUGH BASE ISOLATION

Considering the low seismic-resistant capacity of the primary structural scheme, the relevant direct and indirect costs of a conventional design, the presence of a buried second basement, the improvement project provided for the insertion of a seismic isolation system at the top of the columns of the buried story. This allows to operate exclusively at the basement level and almost completely eliminates the need for strengthening the elevation. The following works are required: controlled cutting of the columns of the second basement floor, insertion of isolating devices, strengthening of the columns below the cut and of the joints above the cut, building of perimeter retaining walls. The isolating system consists of friction-controlled curved-surface sliders produced by FIP Industriale and having the following relevant characteristics: radius of curvature 3100 mm; conventional dynamic friction coefficient 2.5%; displacement capacity ±200 mm. Devices FIP-DL370/400(3100) with a maximum vertical load (seismic) N_{ed}=1500 kN are located under the columns of the stairs; devices FIP-DL280/400(3100) with N_{ed}=1000 kN are arranged below all the other columns.

Figure 5 shows some details of the base-isolation solution. The devices are characterized by the initial sliding force $F_y=\mu \cdot N$ and stiffness in sliding phase $K_p=N/R$, where N is the vertical load in seismic condition. The nonlinear behavior is then described by a rigid-plastic hardening curve, while the equivalent elastic-viscous behavior can be characterized by the stiffness $K_e = N \cdot \left(1/R + \mu/X\right)$ and percentage of critical damping $\xi_e = 2/\pi \cdot 1/\left(X/\mu R + 1\right)$, being X the maximum displacement for which to evaluate the parameters. The effective friction coefficient corresponding to the actual average vertical load N, with respect to the maximum nominal value, N_{ed}, can be computed as $\mu_{eff} = 2.5\ (N_{sd}/N_{ed})^{-0.834}$.

The building has an isolated mass M = 2576t and is characterized by two fundamental translational modes with periods of 2.5s and participating mass percentage almost equal to 99%. The seismic response of the isolated building is calculated through nonlinear dynamic analyses using as seismic input artificial acceleration time-histories having a duration of 25s generated in accordance with EN1998-1(2004) and NTC (2008). Fourteen acceleration time-histories were generated: seven fitting the SLV response spectrum and seven fitting the SLC spectrum. In SLC conditions, the maximum displacement of isolators is 88mm (< 200mm); the maximum axial force is 940 kN (< 1000 kN) for devices type FIP-DL280/400 and 1208 kN (< 1500 kN) for devices type FIP-DL370/400; the minimum vertical load is 410 kN (>>0) ensuring the safety against the uplifting. Figure 6 shows, for one of the dynamic analyses, the force-displacement histories of the two orthogonal components of an isolator. Concerning the building elevation (existing superstructure) the resistant sections of beams and columns are sufficient to sustain the stresses induced by the earthquake. This is 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 cut to insert the isolators, is designed taking into account the P-delta effect caused by the isolators' displacements. No strengthening of foundations was required.

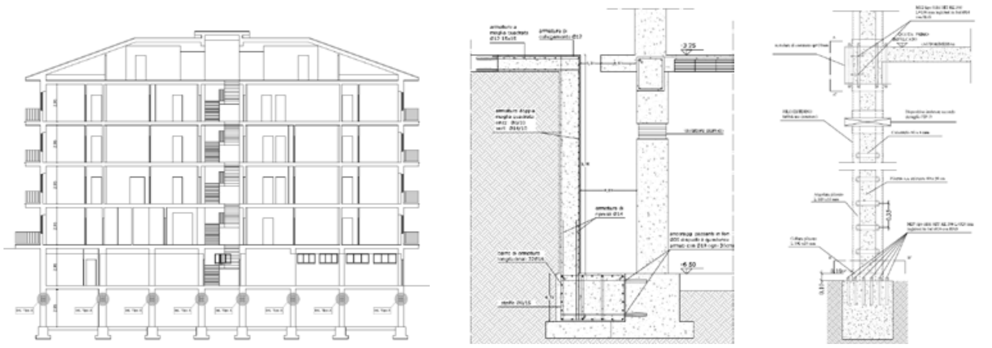

Figure 5. Details of the base-isolation solution.

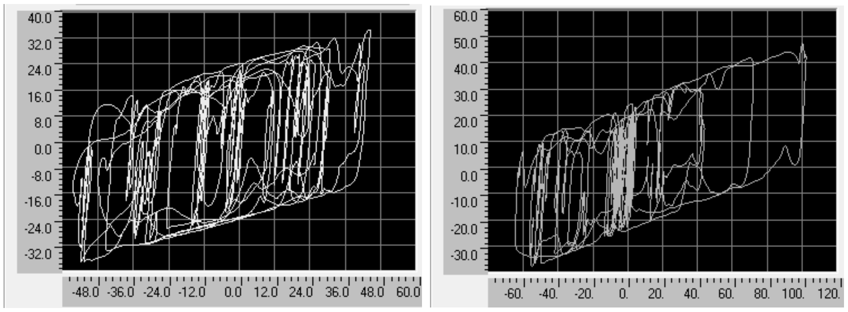

Figure 6. Force-displacement response in two orthogonal directions of an isolator.

6 CONCLUSIONS

Figure 7 reports pictures concerning some of the most typical works done for the seismic isolation of the building. The cost comparison reported in Table 1 shows that base-isolation choice got an immediate saving of 34% but in the lifetime the saving is much greater. Indeed the base-isolated building will not suffer any damage, nor any consequence to the occupants, under the maximum expected earthquake. On the contrary the traditionally retrofitted building will start to undergo serious consequences for an earthquake having 70% the intensity of the maximum expected one and a 25% probability to be overridden in the building life. Moreover, for the maximum expected quake, that is with a probability of 10% in the life, the building will suffer a complete damage with a cost of consequences comparable with the reconstruction cost.

Table 1. Cost comparison between base-isolation and traditional solution.

Work category	Traditional		Base-isolated		Diff.
Type A - Repair	€ 891.892	39.40 %	€ 667.570	44.72 %	-25.2%
Type B - Seismic enhancement	€ 555.347	24.53 %	€ 185.487	12.43 %	-66.6%
Retrofit due to Type B works	€ 132.928	5.87 %	€ 3.786	0.25 %	-97.2%
Hygienic-sanitary conformity	€ 81.023	3.58 %	€ 57.072	3.82 %	-29.6%
Conformity of plants	€ 190.959	8.44 %	€ 18.270	1.22 %	-90.4%
Energy saving conformity	€ 251.118	11.09 %	€ 141.866	9.50 %	-43.5%
Overflow	€ 160.307	7.08 %	€ 418.756	28.05 %	+161.2%
Total	€ 2,263,575	100.00 %	€ 1,492,806	100.00 %	-34.1%

Figure 7. Images of the works performed for the base-isolation of the building.

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