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SEISMIC RETROFITTING OF A STRATEGIC BUILDING THROUGH BASE ISOLATION AND TRANSLATION

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ABSTRACT

Besides introducing the building isolation system design, this paper draws the attention on some practical and accessory aspectes that characterize the building seismic retrofitting through base isolation. Particularly, critical issues such as pounding with an adjacent building and general accessibility for maintenance of the devices were deeply considered in the design, which eventually was strongly affected by the technical solutions adopted.

Among all the issues faced in developing an optimal design, one in particular deserves more attention, that is, the solution chosen for widening the existing technical joint, obtained by laterally displacing the building, so to avoid any pounding with the adjacent building. This was achieved in an innovative way: after cutting the columns bottom portion, pre-deformed-and-blocked isolating devices were installed under them. Once released, they recovered the undeformed position and were eventually able to displace the building of the designed amount, thus widening the joint with the adjacent building. The paper presents the details of the isolation intervention, with some details as to the calculations performed and the numerical models adopted.

INTRODUCTION

The building hosts the Florence headquarter of the Italian Highways Company, .

The construction of the building started at the end of the ‘50ies, without any seismic code, but especially without any basic theoretical background regarding antiseismic design. For this reason, given the strategic importance of the building, it was deemed necessary to perform an assessment of its seismic vulnerability and eventually retrofit its seismic performance.

This study shows that, in seismic conditions, the building is not able to withstand the seismic demand at the Life Safety Limit State (LSL), as prescribed in the Italian code NTC 2008.

Within the main requirements requested by the contracting authority, the continuous operativity of internal office activities during construction works has proved particularly challenging and has determined the choice of the type of intervention.

Having studied different strategies, base isolation was chosen as the more appropriate, especially for the possibility offered by the particular geometry of the building to easily create an isolation interface at the ground level.

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In addition, the base columns were shear-strengthened with the so-called CAM system (prestressed stainless steel strips), with the aim of improving their low shear capacity. In fact, the transverse reinforcement of the columns was largely insufficient and, most of all, heavily corroded.

The project is organized in phases, as described below, each comprising working activities carried out in parallel for their characteristics of repetitiveness and absence of superposition.

Since the building is constituted by two symmetrical ”wings” with respect to the central entrance hall, which only serves as vertical connecting systems of the entire building with its stairs and elevators, each working phase was carried out firstly on a wing and then, after its completion, on the other wing.

A very interesting and innovative aspect regards the approach followed to cope with the large displacements that base isolated structures usually undergo. To prevent pounding between hall building and lateral “wings”, the insufficient existing joints needed to be widened.

This was achieved by pushing the wings away from the central hall building. The initial solution foresaw using low-friction sliders under the elastomeric isolators and pushing the wings with hydraulic jacks contrasting against the central hall building. This approach proved very expensive. Subsequent studies have identified a non-conventional solution that proved extremely effective in terms of cost and practical advantages: the pre-deformed isolating devices.

The particular geometric configuration of the building has allowed realizing seismic isolation in ideal conditions, by placing the isolation devices under the columns at the ground floor of the two “wings”, thus avoiding the usual problems related to isolation of stairs. It is worth noticing that the central hall building, since it complies with the code requirements, was not retrofitted.

DESCRIPTION OF THE BUILDING

A panoramic view of the building is shown in Fig.1. Palazzo Fagnoni consists of three buildings, as shown in Fig.2. The retrofitting operations described hereafter refer to the two lateral buildings, in gray, called “wings”, which host the offices. The left one is represented in bigger scale in Fig.3.

The wings have the same rectangular shape and dimensions, the sides are equal to 11.50 x 32 m; they are about 12.80 m high above ground, made of a “pilotis” ground floor 5.00 m high, of two upper floors used as offices with height of 3.90 m each; there is also a basement area 3.40 m high, where equipment and plants are accommodated.

Access to the wings occurs only through the central building, where stairs are located. The structure is made of reinforced concrete frames, obtained by connecting precast columns.

A vertical cross section of the building is shown in Fig.4, while a detail of a wing with its columns at ground floor is shown at a bigger scale in Fig.5.

Figure 1. Aerial view of the building.

Each ground floor consists of 24 columns having a hollow-core circular section, with variable diameter along the height, from 400 mm at the bottom to 600 mm at the top; this latter is connected to the first floor slab with a conic portion, as shown in Figure 6, with outside diameter ranging from 600 mm up to 4.00 m, which gives the column a characteristic “mushroom” shape.

The hollow core has a constant diameter of 150 mm and is used to host the drain pipes. It is worth to notice that the internal hole produces a significant reduction of the column shear capacity, especially in the bottom portion, where the thickness of the circular crown is only 125 mm.

The first level floor is made of a concrete slab with depth of 0.50 m, while those at the second and roof floor are made of concrete and masonry, with depth of 0.12 m and joists with wheelbase of 0.40 m.

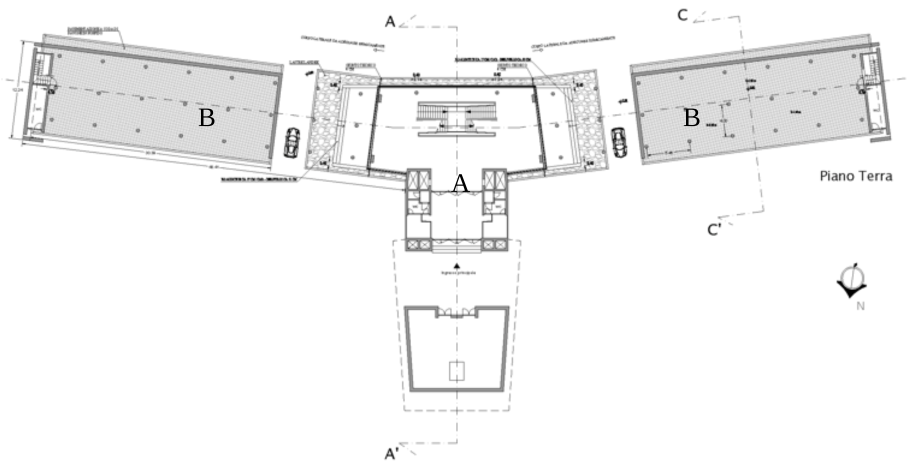

Figure 2. Ground floor of the building. A,   switching area, _B, wings.

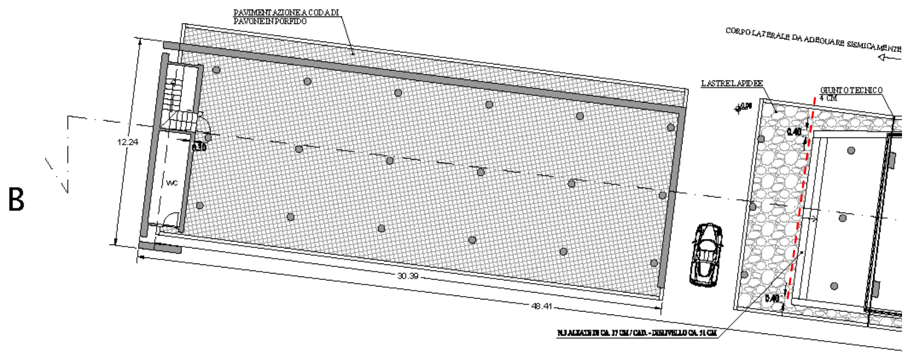

Figure 3. Est wing of the building. In evidence with red dot line the joint between the central and lateral building. The same technical solution was adopted in the Ovest wing.

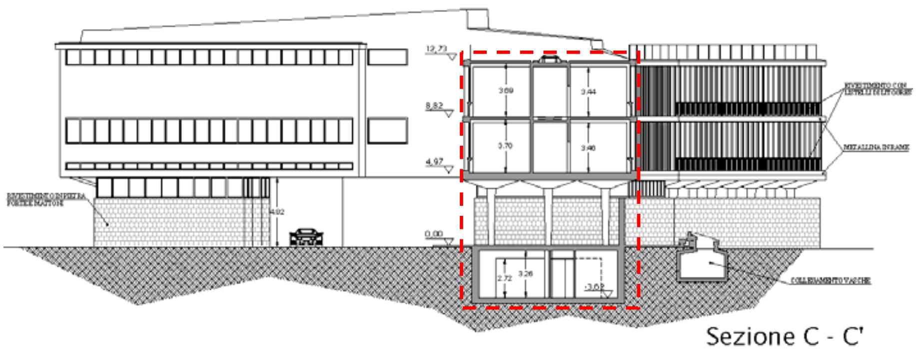

Figure 4. Section C-C of fig.2.In evidence with red box the Ovest wing.

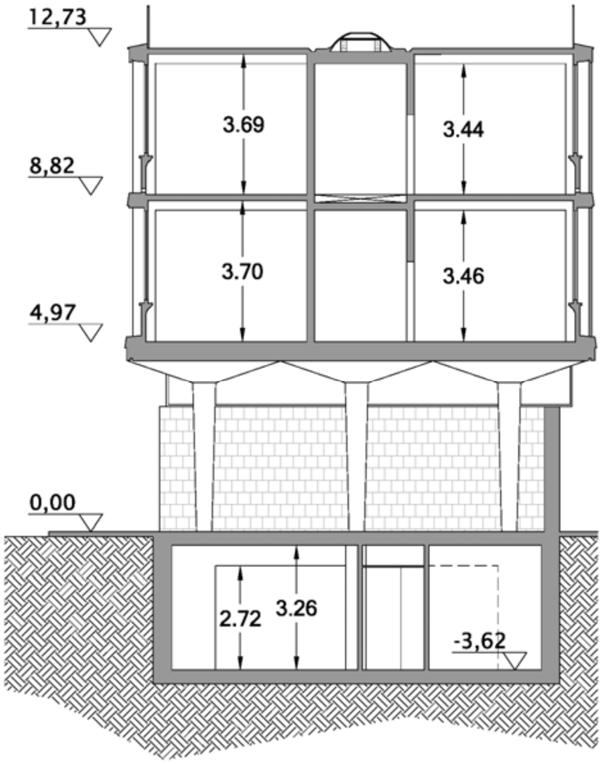

Figure 5. Detail of the section C-C of the Ovest wing.

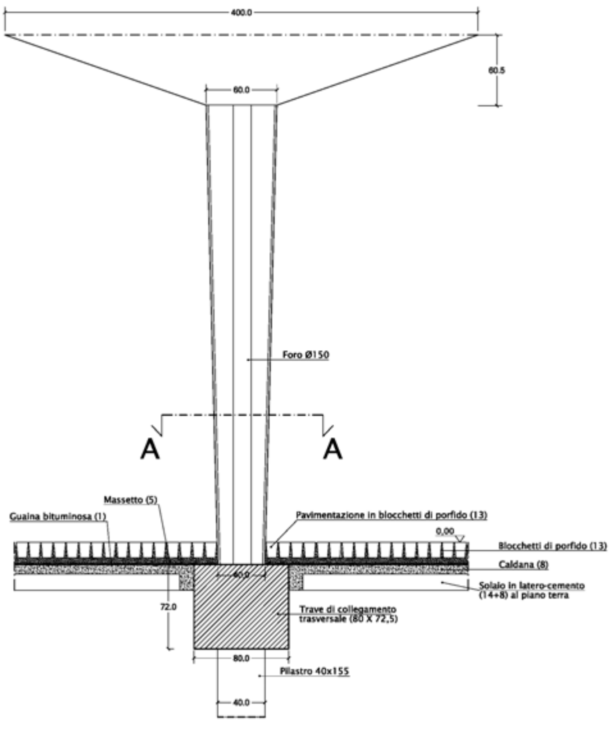

Figure 6. Mushroom shape column. Note the hollow-core circular section along the symmetric axis.

Note that the feasibility and success of the base isolation solution adopted depend on the characteristics of the basement area. In fact, under the ground floor columns there are reinforced concrete columns of considerable size, placed along the perimeter and the central alignment.

Moreover, the top side of each column of the basement area is rigidly connected to beams having depth of about 0.70 m and width of 0.80 m. Thereby, the structure of the basement area provides a continuous bearing surface, in the neighborhood of each column, where it is possible to place the sliding devices and to insert the seismic isolators under the columns.

Figure 7. Archive picture of underground structure.

Figure 7. shows an archive picture taken during construction of the basement area; the reinforced concrete columns that will support the isolating devices are clearly visible.

CONSTRUCTION DETAILS AND MATERIALS

The size of the structural elements and their reinforcement were found from the original drawings (dated 1959) and then verified directly on site. The columns are reinforced, from design, with 27ϕ24 longitudinal bars; transversal reinforcement is made by stirrup of ϕ10/80 mm. As it often happens, the actual reinforcement found on site was quite different: the vertical bars are instead 24ϕ22 and the transverse reinforcement is made of spirals ϕ5/50 mm, which are very corroded and ill-distributed, as seen in Fig.8.

Figure 8. At left, mushroom shape column damaged by corrosion of bars. At right, particular of the high level of corrosion of longitudinal bars and stirrups.

With this transverse reinforcement, the shear capacity is provided by non-conventional mechanisms, including the “dowel action” guaranteed by the almost continuous longitudinal reinforcement cage. Regarding the concrete strength, it has been observed that the very construction technique of these hollow columns, made by centrifugation, has produced the segregation of the heaviest aggregates towards the external surface, so that the concrete properties change dramatically within the thickness of the column cross-section. Thus, in the seismic assessment carried out, the actual reinforcement found during the survey was adopted and a reduced concrete strength was considered.

THE CURRENT LEVEL OF SEISMIC RETROFITTING

The structural configuration with *pilotis* floor has often shown poor performance to horizontal actions. In fact, the upper part remains substantially rigid, so that the displacement demand localizes on the columns of the ground floor. In this situation, plastic hinges can only develop at the base of the columns, which are not able to adequately dissipate the earthquake energy input. This is because columns are subjected to high axial load that reduces their available ductility and are also affected by significant P-delta effects.

The safety assessment is carried out by evaluating the demand on the structural elements, using modal analysis with linear elastic response spectrum at the Life Safety Limit State (LSL); the seismic hazard is determined from the local parameters for (stiff) soil class A. For a 10% probability of exceedence in 75 years (reference period for strategic buildings), which corresponds to a return period of 712 years, the PGA is equal to 0.154g.

The type of analysis adopted is due to the fact that, as shown in the next section, the building clearly shows elastic-brittle behavior. In these conditions, a low dissipation behavior is expected, which implies a low behavior factor q.

THE ASSESSMENT OF SEISMIC RETROFITTING

The Capacity/Demand comparison obtained from the analysis has highlighted that, as largely expected, the critical elements are the columns at the ground floor. Their transverse capacity has been evaluated with respect to the resisting mechanisms of bending and shear. Particularly, it was observed that the shear capacity, determined by the method of the variable-angle truss, was lower than the flexural capacity.

The outcomes in term of capacity-demand ratio prove that the columns would collapse in shear before developing the plastic hinge, thus showing a brittle behavior. This is reflected on the entire building, which shows an unacceptable elastic-brittle behavior overall. For this reason, it was decided to take action and improve the building seismic performance by retrofitting the columns to meet the code requirements pertaining to new constructions.

DESIGN APPROACH

Whichever the design strategy chosen, it anyway had to respect practical and formal requirements:

a. the work activities on the upper floors had to continue without interruption during construction operations,
b. the peculiar “mushroom” shape of the columns could not be changed, therefore the retrofitting measures had to preserve their shape and their architectural value.

The initial solution proposed to increase the columns capacity by concrete jacketing them. This intervention would greatly modify the architectural value of the columns, by changing the formal equilibrium of the building that constitutes its real intrinsic value.

Therefore an alternative solution has been searched, oriented to reducing the demand of the earthquake, rather than to increasing the capacity of the structural elements. Base isolation immediately appeared as the best solution for this case, with the insertion of isolation devices under the existing mushroom-shaped columns; in this way they are protected without changing their appearance. This strategy is proved to be optimal under all points of view - technical, architectural, functional, economical – and therefore it was adopted for the seismic retrofitting of the building.

CONSTRUCTION PHASES

The adopted strategy consists of three phases in sequence:
R. Strengthening of the columns,
I. Base isolation of the wings,
T. Translation of the wings.

Each phase is articulated in the sequential operations described below:
R1. Restoration of the external surface of the columns and passivation of corroded steel bars,
R2. Application of pre-tensioned confinement strips (CAM system) to all columns and surface finishing with structural plasterwork.

I1. Laying of equipment and carpentry for load transfer from the columns,
I2. Cut at the base of the columns,
I3. Laying of the isolators and tripods.

T1. Laying of the anchorage devices for the translation,
T2. Laying of the hydraulic jacks for the power-assisted release of the isolators,
T3. Release of the jacks and translation of the building with continuous monitoring,
T4. Protection of the devices with covering steel cases.

IMPLEMENTATION OF THE INTERVENTIONS

Strengthening of the mushroom-shaped columns

The first phase consists in the restoration of the outer layer of concrete and in the replacement of the stirrups with high resistance metal strips. This technique is commonly known as CAM (Italian acronym for Active Confinement of Members) that consists of the application of pre-tensioned stainless steel strips.

The steel strips have thickness of 0.9-1.0 mm and width 19 mm; the design strength is 532 MPa. The lower part of the columns, except those with drain pipe, has been filled with expansive mortar, to increase the effectiveness of the confinement supplied by CAM, by changing the section from hollow to full. Fig. 9 shows a column after the strengthening.

Figure 9. View from bottom of the column after the strengthening with CAM system.

Seismic isolation at *pilotis* floor

The second implementation phase consists in the insertion of high-damping elastomeric isolation devices (HDRB) under the existing mushroom-shaped columns.

In some columns it has been necessary to adopt sliders, characterized by low values of friction coefficient. Such devices were named "tripods" because made from an assemblage of three smaller sliders shows in Fig.10. Fig.11 shows their placement under a column, after removing its lower portion. The tripods have strength and horizontal stiffness virtually equal to zero, as a consequence of a low friction coefficient of the sliding surface (generally <0.003). They are installed under the columns that have the drain pipes to allow them go down to the sewage system. For this reason, the tripods were conceived with three support points at the vertices of a triangle around the column base section.

Figure 10. At left, support points at the base of tripods. At right, the internal flexible joint.

Figure 11. Tripod during the assemblage phases.

Translation of lateral buildings

The current Italian code NTC-08 allows, among the various intervention techniques, also the widening of technical joints. This operation is carried out by pushing the two lateral buildings away from the central one, after installing the isolator devices, blocked in the deformed configuration with specific steel locking devices. Fig.12 shows the assembled system.

Figure 12. Isolator device with its locking system.

After removing the locking devices, the isolators tend to elastically return to their un-deformed position, thus translating the building above. The translation speed is controlled by a system of tie rods placed on two alignments, shows in Fig.13. After the final configuration is reached, the last operation is the installation of protection cases around the devices and the surface finishing of the columns.

Fig.14 shows an image of two elastomeric isolators at the moment of removal of the locking devices. In this configuration, the isolators are at their maximum displacement corresponding to CLS; this already represents an on-site test on the deformation capacity of the system and its stability against the vertical loads.

Fig.15 instead shows the lower portion of a mushroom-shaped column, in which the elastomeric isolator has finally returned to the undeformed position: the building above has therefore shifted by the same amount.

Finally, Fig.16 shows the visual impact of the intervention at the end of work. Note that all isolator devices were covered with the same metal case.

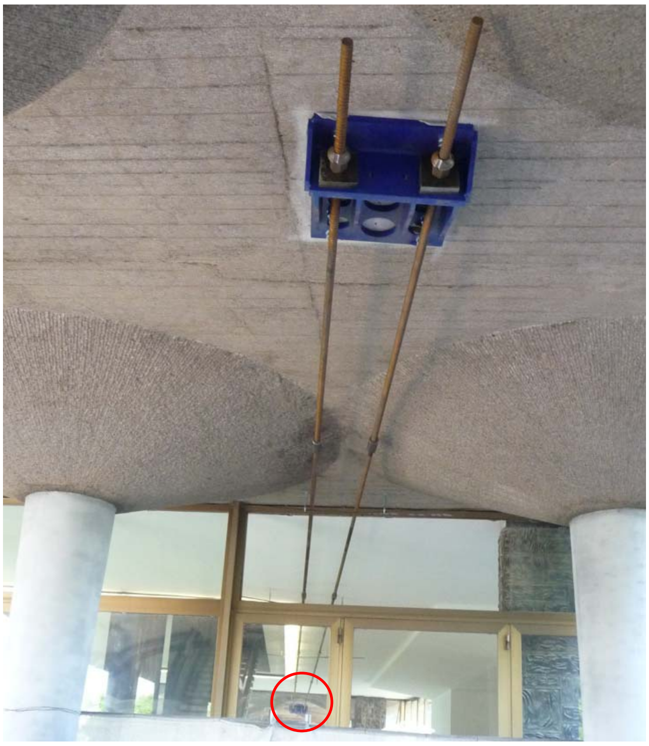

Figure 13. One of the two alignments of the displacement system control.
With the red circle the anchorage of Est wing.

Figure 14. Two of the elastomeric isolators in the deformed configuration,
before return to the vertical position.

Figure 15. Final configuration of elastomeric isolators.

Figure 16. Final step of the work. The isolator devices are covered by metal protection cases.

CONCLUSIONS

The seismic retrofitting of Palazzo Fagnoni, a strategic building owned by the Italian Highway Company "Autostrade per l'Italia S.p.A." built in the 50ies, has been presented.

The building is built with mushroom-shaped columns with hollow section at the *pilotis* floor, which makes them particularly vulnerable to shear.

It was therefore decided to design a seismic isolation system at the base of the building, by inserting the isolation devices under the existing columns at the *pilotis* floor.

The main benefit of this solution is the possibility to operate exclusively at the *pilotis* level, without interruption of work activity at the upper floors. In fact, the installation of the devices, the positioning in the final configuration of the lateral buildings, the covering of the technical joints between the three buildings and the re-connection of the water disposal system with flexible joints at the ground floor, have been all performed during normal working time.

The isolation system is made of 13 sliding devices (called tripods) under the columns where there are the drain pipes, and 11 elastomeric devices under all other columns.

For the numerical analysis, the stiffness of the tripods has been taken equal to zero, as a consequence of a low friction coefficient, generally lower than 0.003; stiffness of the elastomeric devices has been calibrated in order to have a first period of the isolated system equal to about 2.4 seconds, while the percentage of equivalent viscous damping has been taken equal to 16%. The efficiency of the studied solution was verified by modal analysis with response spectrum, from which it is seen that the shear demand on the columns is reduced to about 1/3 with respect to the original situation, thus remaining below of the corresponding capacity.

Therefore the isolation system has proved to be an effective measure to reduce the demand on the ground floor columns; this required minimal strengthening interventions by the so-called CAM system, to increase the columns capacity.

The efficiency of the isolation system during the earthquake depends on the width of the joints to the adjacent building, that must allow for the displacement in seismic conditions. However, the existing joints were found to have a small width, incompatible with the foreseen displacements.

Therefore, the project involves also the widening of the joints, as indeed allowed in the current Italian code NTC-08. This is achieved by slowly translating the two lateral buildings away from the central one, using hydraulic systems and special tendons anchored at the intrados of the first floor.

This operation is followed by the removal of the locking devices used to re-deform the elastomeric isolators. At translation completed, protection cases are installed to cover the isolation devices.

The preliminary studies have permitted to assess the intervention feasibility and have gradually reduced the uncertainties (and doubts!) that initially accompanied the proposal, to finally make it possible. The chosen solution proved to be extremely sensitive as to its realization phases, but it was eventually the only one that could meet the requirements of achieving total protection with no disruption of the normal strategic activities.

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