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Seismic Analysis for the Structural Retrofit of "Palazzo della Civiltà Italiana" in Rome EUR, Italy

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Abstract The "Palazzo della Civiltà Italiana" is a monumental building characterized by a reinforced concrete structure composed of parallel (cast in situ) portal frames and composite (reinforced concrete + hollow bricks floors which spans between adjacent portals: a common construction technique in Italy. The floors being characterised by a large span of about 10.0 meters. The construction took place between 1939 and 1943, most likely according to the Italian building code published in 1939. The authors have coordinated a comprehensive experimental campaign aimed at (a) the identification of the characteristics of the structural materials and members, and (b) the identification of eventual damages. Based upon the experimental results a number of analytical and numerical investigations have been developed in order to assess the structural reliability of the "Palazzo" which up to date still ~~is~~ remains in its "original" configuration, as no substantial intervention of structural retrofit or rehabilitation have been implemented so far. These analysis allowed to identify two major reliability issues: (i) the load bearing capacities of the floors do not allow the intended use, and (ii) the seismic vulnerability of the building does not satisfy the reliability standards required by current codes. On the basis of all data acquired and investigations performed, a simple (non invasive) structural retrofit solution capable of bringing the "Palazzo" to the level of structural safety required by current codes is identified.

Keywords: Reliability analysis, numerical investigation, hazard analysis, historical building, retrofit design

Introduction

The "Palazzo della Civiltà Italiana" in Rome is a monumental symbol of the project for the "Esposizione Universale di Roma" programmed for 1941. The project for this exhibition was only partially built and the exhibition itself was never held due World War II. The construction works for this building started in 1938 and were completed (in almost all areas) by 1943. From a structural point of view the building is carried by a series of concrete frames with floors made of mixed (reinforced concrete-masonry) slabs. The span of the slab is quite large. The construction took place between 1939 and 1940, before World War II: at that time the use of steel for construction was considered a waste of money and resources, to such a degree that it was forbidden by law. This situation led to the structural concept of the building itself: oversizing of structural members in terms of concrete use, in order to contrast and supply the compulsory lack of steel reinforcement.

This peculiar structural concept endowed the "Palazzo della Civiltà Italiana" with:

- a particular and recognizable architectural appearance, with a consequent specific architectonic characterization (it is widely known as "the Modern Coliseum");
- a high durability;
- an ability to fulfill the different performances of design levels changing in times.

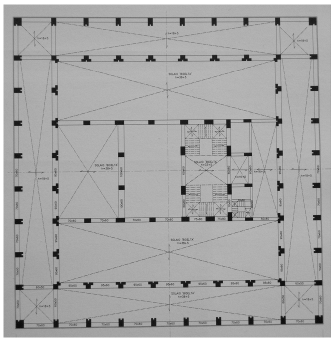
Thanks to such a robust and massive structural system, the strengthening and retrofit design performed by the authors is light and not much invasive, as the value of the intrinsic structures ductility is proper enough to nearly satisfy the levels of structural safety required by current standards.

The present work summarizes the evaluations that the authors have carried out regarding the safety and conservation state of this construction designed and built according to the knowledge and technology of about 60 years ago. In order to carry out the above mentioned evaluations it has been necessary to develop, on the basis of the available technical documentation, a series of experimental investigations regarding the materials used for the construction. Also a number of numerical analysis and simulations were developed with special attention devoted to the correct modelling of the non structural components of the building.

The Structure

The building (Fig. 1(a)) is characterized by a squared plan with sides measuring about 51,50 meters. The overall building height is about 65 meters. Externally the construction is characterized by 6 orders of arcades (porches). Each one composed of nine vaults on each side. An internal "cloister" (which starts at the second floor) provides light the central area of the building(Casciato and Poretti 2002).

(a)



(b)

Figure 1: (a) The external view of the "Palazzo della Civiltà Italiana", (b) the plan of the building

Fig. 1(b) shows the typical building plan with the position of the pillars, beams and direction of the floors. The floors (mixed in reinforced concrete + masonry elements – hollow bricks called "pignatte") over the porches span about 5,6 meters with a thickness of about 18 + 5 cm. The floors of the central part of the building spans about 10 m with a thickness of about 38 + 5 cm. The beams are characterized by a depth which varies (depending on the type) between 95 and 70 cm with a constant width of about 60 cm. All floor were originally designed to carry a live load of about 4 kN /m^2 . At the base the pillars are characterised by generous dimensions with a cross section of about 1,50 m by 0,80 m, while at the top show a square cross section with a side length of about 70 cm.

Overall the structure in elevation is massive with "poor" reinforcing details, mainly in the pillars where, in spite of the large number of longitudinal bars it is inserted only one hoop to confine them and prevent lateral instability. Also the beams show little transversal (shear) reinforcement as well as short reinforcement overlaps and length of anchorage. Most likely the relatively sparse use of reinforcement is a consequence of the economic condition of the time.

Reasonably the design was carried out according to the construction code (for reinforced concrete structures) published 1939, design code that replaced the preceding one published in 1907.

The whole structure rests upon a soil of average bearing capacity. Due to the large self weight of the massive structure and of the marble cladding of the exterior the foundations rests upon piles. It is to be pointed out the building is characterized by the presence of extensive and thick marble cladding, internal brick partitions, and brick vaults (cross) inserted in all porches which structurally work in parallel with the columns and beams. The "Palazzo" acts as a connection between the ancient ("heavy") conceptual design (the most relevant example of which is the Coliseum) and the modern ("light") conceptual design (i.e. the shear type structural system, with the presence of a full exploitation of the concrete material). The "Palazzo" structural concept, in fact, is "lighter" than a shear type system in terms of member sizing, but it's not so light as a real shear type structure.

Characteristics of the Materials, Their Conservation and the Working Condition of the Structure

In order to obtain the characteristics of strength for the concrete of the pillars use was made of a combined approach ultrasound / sclerometer at one storey. This was used to calibrate the results obtainable from the use of the sclerometer only. After this "calibration" effort and extensive campaign was carried out using the sclerometer upon all pillars at all floors. Using Brinnell hardness tests upon the reinforcing steel of the columns and beams (exposed by removal of the cover), it was possible to estimate the strength of the re-bars. The concrete of the structure was also extensively investigated in order to evaluate its possible carbonation. Also a number of tests were performed in order to check the correspondence between the reinforcement prescribed in the original technical drawings and the what was actually placed in the construction. Similar verifications were developed to check the reliability of the geometry described in the original design. Finally a number of dynamic tests were performed in order to evaluate the properties of the floors characterized by the large spans.

As far as the materials are concerned the good quality of the concrete has been verified (with respect to their working load) and, tracing back to the original technical literature it was possible to estimate the yield strength of the steel to be equal to 350 N/mm^2. The practical absence of carbonation in the concrete is probably to be ascribed to the "generous" marble cladding and mortar. The dynamic tests indicate that all floors are characterized by a homogeneous behavior with a fundamental frequency of vibration of about 12 Hz.

Comparison with the analytical/numerical counterparts clearly indicates that the masonry inserted in the floors mainly as non load bearing elements (they are characterized by the presence of voids to reduce weight) do actually contribute to the structural functioning of the reinforced concrete system. Also the thin layer of concrete (about 5 cm) positioned above the floor for construction reasons (non load bearing element) together with the thick marble flooring seems to collaborate to the structural functioning of the floor system. Overall, after more than 65 years of or service work and in the absence of significant maintenance and retrofitting works, the structure in elevation seems to be in good condition.

There is no evidence of differential foundation settlements. The structural design of the time was carried out using conventional methods, nonetheless the structures, as verified by the authors, show level of stress (under working condition) which are fully compatible with reduced deformations and limited cracking. The over strength of the floors, beams and columns, has allowed the building to accommodate easily the unavoidable deformations due to creep which occurred in the reinforced concrete members.

The Analysis of Seismic Hazard

A Probabilistic Seismic Hazard Analysis (PSHA) has been carried out with reference to the site of Roma EUR. The PSHA procedure, based upon the consolidated approach suggested by Cornell(Bertero and Bertero 2002), is here carried out through the identification of the Probability Density Function (PDF) and the Cumulative Distribution Function (CDF) of the Peak Ground Acceleration (PGA), as computed over a given observation time *t*. It consists of the following basic steps:

1. choice of an appropriate earthquake catalogue and identification of the areas of homogeneous seismic activity;
2. definition of an appropriate recurrence law, which gives, for example, an analytical relationship between a quantity describing the seismic event (e.g., the magnitude) and the return period of the seismic event for each seismic source zone;
3. definition of an appropriate occurrence law (e.g., Poisson process or other different laws), which statistically describes the number of events in any time period for each seismic source zone;

4. development, from the above assumptions (steps 1 to 3) and from basic probability theory, of the PDF and the CDF of the parameter describing the seismic event (e.g., the magnitude) for each seismic source zone;
5. identification of the appropriate ground motion prediction model (attenuation law) for the territory and the site under investigation;
6. development, from the above assumptions and results (steps 1 to 5) and from basic probability theory, of the PDF and the CDF of the prediction of the peak ground acceleration PGA' due to the seismic action of each seismic source zone;
7. development, from the above results (step 6) and from basic probability theory, of the PDF and the CDF of the prediction of the peak ground acceleration PGA' due to the seismic action of all seismic source zones considered;
8. derivation, introducing the epistemic uncertainty, of the PDF and the CDF of the peak ground acceleration PGA due to the seismic action of all seismic source zones considered.

Following these steps, a PSHA is developed which makes use of the following assumptions:

- the surface-wave magnitude (M) as magnitude measure;
- the CPTI2 earthquake catalogue of the Italian territory (2004). This catalogue accounts, independently of the intensity (Io) and the surface-wave magnitude (M), only for the largest event within time-space frames of +/- 90 days and radius of 30 km of each seismic event;
- the ZS9 seismic subdivision for the Italian territory (2004) which refers to 40 area source zones;
- the "completeness analysis" proposed by Mulargia, Gasperini and Tinti (Mulargia Gasperini and Tinti 1987) to filter the historical data;
- the PGA attenuation law by Sabetta and Pugliese (Casciato and Poretti 2002, Cornell 1968) specifically developed for the Italian territory, which provides the values of the PGA', together with the values of the standard error $SE_{\log 10 PGA}$.

The CDF curve of the PGA, as obtained over an observation time of t = 50 years, (Bertero and Bertero 2002) allows to identify the numerical value of PGA corresponding to $\overline{P}$ = 10% in 50 years: $a_g \cong 0.10g$.

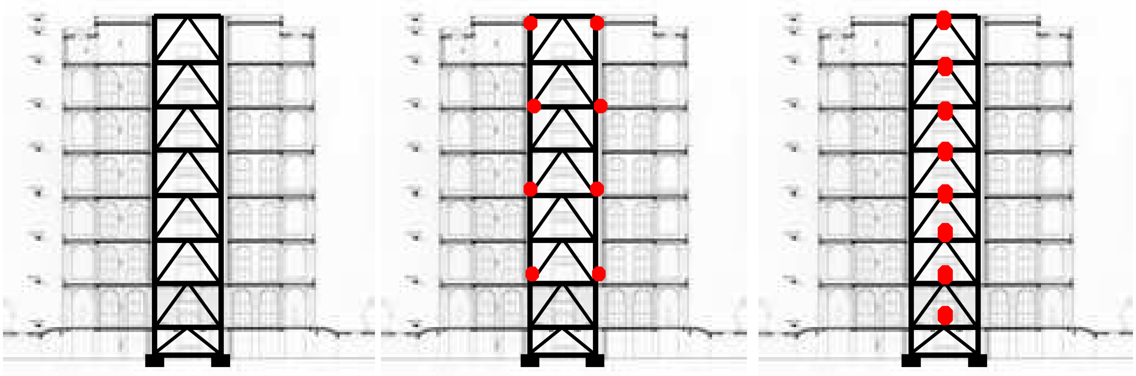
The Seismic Behavior of the Structure and Its Retrofit

Analysis of the seismic behaviour of the structure were developed with the support of numerical models. The fundamental period of vibration of the system is estimated to be about 1,7 second, with the first two mode of vibration being characterised by a lateral deformation and the third mode of vibration by a torsional deformation. The relatively large value of the first period being due mainly to the large masses of both load bearing and non load bearing elements.

The seismic response of the system under the input corresponding to the PGA of 0,1 g (which corresponds, according to the probabilistic seismic hazard analysis summarised above, to the design ultimate limit state - ULS) lead to structural action which are approximately the double of the structural system capacity. In particular the beams showed an insufficient reinforcement at their intrados in correspondence of their connection to the columns. On the other hand, the columns, thanks to their massive size shoed larger capabilities to carry the seismic loads. The capacity of the beams was estimated considering a ductility of the system of about 3.5, this estimation being made taking into account the fact that the poor reinforcing details leads to a reduced ductility of the elements, and the limited amount of reinforced used in the system, lead to an increased ductile behaviour of the elements.

Overall, with respect to the seismic hazard the building shows a level of vulnerability which is not capable to meet the current (high) standard of structural reliability required for the new construction. Considering the historical value and nature of "Palazzo della Civiltà Italiana", the level of seismic protection (for specific use of the building) can be considered acceptable. However, in light of a possible (but not programmed) retrofit of the building in order to bring it to the same level of safety of newly built construction, the retrofit solution described below was developed.

Considering the monumental characteristics of the "Palazzo della Civiltà Italiana" a direct intervention upon the structure itself (beams) was considered infeasible. For this reason a retrofit strategy aimed at reducing the actions imposed by the seismic input upon the structure was followed. Seismic isolation was not taken in consideration due to the specific problems connected to the insertion of the bearing under such (massive) building. On the other hand, the presence of a cloister (light well) in the centre of the building plan has suggested the insertion in this position of an additional steel structure that, from an architectural point of view, could be realized as a totally distinct and removable way (Fig. 2) to which seismic viscous dampers could be inserted. This solution allows to increase (in a totally reversible way) seismic dampers to the structural system, thus reducing the actions imposed by the ULS earthquake input.



(a) *(b)* *(c)*

Figure 2: (a) Transversal section of the building with the additional steel structure inside the cloister, (b) MPD placement: dampers (schematically represented with red dots) connect the new steel structure to the historical building, SPD placement: The SPD placement: dampers placed between adjacent stories of the new steel structure which is linked through axially inextensible beams to the historical building

The use of an additional steel structure (connected to the historical building through horizontal members pinned at both ends) to insert the dampers allows exert only beneficial horizontal action on the original construction (which in this was is somehow "re-strained" in its horizontal motion) without introducing other undesired actions. Also, the use of viscous dampers is selected for their capability of providing non degrading actions as well as a calibration of their maximum effect.

Two solutions were envisaged for the introduction of the dampers in the new system (Trombetti and Silvestri 2007):

- MPD implementation (which sees the dampers placed horizontally between the historical building and the steel frame, as represented in Fig. 2(b))
- SPD implementation (which sees the dampers placed between adjacent stories in the additional frame structure and this latter connected to the historical building through pinned beams, as represented in Fig. 2(c)).

All analysis developed indicate that the insertion of two viscous dampers per floor for each direction (each one characterized by a damping coefficient c = 40 t s/cm) lead to a reduction of the seismic response of the historical building (with respect to the undamped solution) of about ½ for the SPD solution. On the other hand the more efficient MPD solution leads to a reduction of the seismic response of the historical building to ¼ of that of the building without the insertion of any devices.

This result is summarized in Fig. 3 where the red line represent the profiles of the storey shear for the historical building in the case of the SPD solution, the blue and black lines represent the profiles of the storey shear in the historical building (in the case of MPD solution, with two slightly different solution of damper sizing), and the green line represent the profiles of the storey shear of the historical building in absence of seismic retrofit. It is clear how in the light of the preceding considerations, in order to bring the "Palazzo della Civiltà Italiana" to the same levels of structural seismic safety of new building constructions, the SPD solution is sufficient.

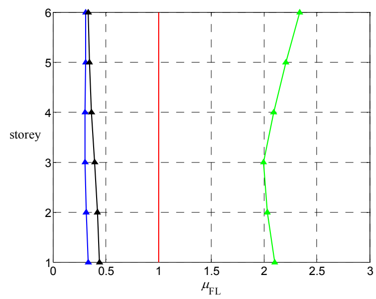


Figure 3: The storey shear profiles (relative values) for the different structural systems considered (green line = undamped system, red line = SPD system, blue and black lines = MPD systems)

Conclusions

The extensive experimental and analytical campaign developed for the "Palazzo della Civiltà Italiana" in Rome indicates that the building in its present condition shows sufficient levels of safety as far as the static and dynamic (not seismic) actions. The "sparse" use of reinforcement (indirectly imposed by the social conditions of the time) i.e. large use of concrete has led to a structure which is intrinsically more durable and more ductile (improved seismic behaviour). Only with regard to the seismic effects its level of safety (acceptable for an historical building structure) does not matches that required for new building construction. A seismic retrofit solution which encompasses the addition of viscous dampers to the structural system (placed in an additional steel structure to be realized in the light well positioned in the centre of the building) allows to raise the level of seismic safety of the historical building to values comparable to those required for new constructions. The oversizing of structural concrete members allowed to solve ahead in time, before it could appear, the problem of durability: when approaching a conceptual design, at its preliminary steps, it can be very useful to pay attention to the different aspects or problems which could appear in the future, and not to focus only on the actual difficulties. It is strongly recommended to take care of this design problems using adequate or oversized safety factors, because often the optimization of a single aspect of the planning process doesn't consider any possible future problems due to the changing of different conditions (i.e. all the Italian territory became seismic zone). In an historical perspective of structural functioning is fundamental to consider how the environmental actions, such as seismic actions, could change: the punctual optimization of a single aspect doesn't guarantee the flexibility of the structure. The historical buildings can have the prerogative to be defined as "monumental" even from the point of view of flexibility and functionality.

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