Experimental Dynamic Analysis and Seismic Rehabilitation of Palazzo Margherita in L'Aquila

The studies carried out for the retrofit of Palazzo Margherita, the City Hall in L'Aquila, seriously damaged by the 2009 earthquake, are shown. The building and the tower were first analyzed by means of ambient vibration tests, in order to find out the dynamic characteristics of the structure even in a damaged situation. On the basis of the results obtained and of the microzoning analysis results, the base isolation was proposed as the most suitable solution for the seismic retrofit of the structure, because it allows to obtain a good structural result without altering the architectural features of the superstructure. The new isolation system is based on the realization of an isolated platform under the building foundation without any intervention on the building itself. The system can be used for single buildings but also for complex structures, typical of the Italian historical centres

Giacomo Buffarini, Paolo Clemente, Sandro Serafini, Alessandro De Stefano, Roberta Olivieri, Antonello Salvatori

Introduction

Historical structures have been built without accounting for the seismic actions and are vulnerable even to moderate events but, due to their historical importance and to the daily presence of tourists, their seismic rehabilitation is quite delicate, aiming at the protection of both human life and cultural heritage. Seismic preservation should be based on a good knowledge of the dynamic characteristics of the structure and a suitable choice of the intervention, if necessary.

The first step is very important in order to assess, also by means of a suitable numerical model, the possible dynamic behaviour of the structure during strong events. But it is not easy for several reasons: the structural size of the various elements (walls, floors, etc.) cannot be evaluated with the needed accuracy; the material characteristics, such as the tension-strain relationship, the strength, etc., are not known; structure and materials often exhibit inelastic behaviour; horizontal structures are not effective in joining the vertical ones; the depth of the foundations is often variable as well as their geometry and material properties, including the soil characteristics; buildings are often connected to other constructions, so that their behaviour is very complicated. For such kind of structures the experimental analysis is often the only way to improve our understanding about their dynamic behaviour [1, 2, 3, 4, 5].

Giacomo Buffarini, Paolo Clemente, Sandro Serafini
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale
Alessandro De Stefano
Politecnico di Torino
Roberta Olivieri, Antonello Salvatori
Università degli Studi dell'Aquila

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Speaking of interventions, it is worth noting that traditional techniques are not suitable for the seismic rehabilitation of cultural heritage buildings. In fact, these are based on the increasing in strength and ductility, and so are often not reversible, making use of materials different and incompatible with the original ones, and can determine changes in the original structural conception. Furthermore, under high-intensity earthquakes, traditional techniques can just guarantee against the collapse, but cannot avoid heavy damage both to structural and non-structural elements. Therefore, base isolation could be a suitable solution for the seismic rehabilitation of historical structures. It aims to reduce seismic actions, thus avoiding significant damage to the structure and its contents even under strong earthquakes, and presents very low interference with the structure itself.

In this paper the study carried out on Palazzo Margherita in L'Aquila is shown. First of all an experimental campaign was carried out in order to find out the dynamic characteristics of the structure. Then a conventional improvement intervention was defined, which allowed the structure to be able to support minimum horizontal actions. On the basis of the effective earthquake resistance of the restored structure and of the actual seismic input at the site, a suitable solution for the base isolation system was designed.

FIGURE 1 Palazzo Margherita: main façade and courtyard
Source: ENEA

Palazzo Margherita: History and Characteristics

The erection of the City Hall in L'Aquila started in 1294. A first important restoration was completed in 1541 (Fig. 1). Important works were done since 1573, when the building became the house of Margherita d'Austria, and most of the original characteristics were lost. At the beginning of the XX century another restoration intervention was made to realize a concrete ring beam under the roofing. The palace has three levels and a rectangular plan of about 40*60 m, with an internal court. The vertical structure is made of stone and brick masonry with good mortar. The horizontal structures are made of masonry vaults, some of them with chains, and steel decks.

The Civic Tower, built from 1254 and 1374 at the N-E corner of the building, was seriously damaged by the 1703 earthquake and then rebuilt with lower height. In 1937 it was consolidated by inserting iron T-beams at the floors. It has an almost square cross-section of about 6.30 m size. The thickness of the walls is about 2.0 m at the basement.

The building suffered heavy damage during L'Aquila earthquake of April 6th, 2009. Several cracks were apparent and local collapse mechanisms were activated. In more details the seismic events caused the disconnection between the orthogonal walls, the out-of-plane collapse of some masonry walls, the formation of large cracks, the collapse of some floors and important damage to the stairs.

Dynamic Characterization of the Building

As already said, an experimental campaign was carried out, in order to find out the dynamic characteristics of the structure. Fifteen velocimeter sensors were

Freq. (Hz)	Building Description	Freq. (Hz)	Tower Description
2.24	Transversal	1.46	Transversal
2.74	Transversal + Tors.	1.46	Longitudinal
3.32	Longitudinal	2.83	Transversal
3.71	Torsional	3.22	Longitudinal

TABLE 1 First resonance frequencies of the building and of the tower
Source: ENEA

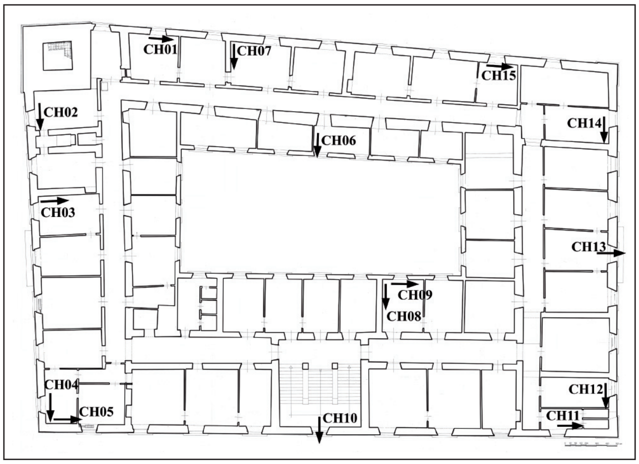

FIGURE 2 Second floor: sensor deployment in the first configuration
Source: ENEA

deployed in two different configurations. In the first one, the sensors were deployed in the building, in order to point out the global and local resonance frequencies (Fig. 2). In the second configuration, the sensors were deployed at different levels of the tower. For each configuretion three tests of about 300 sec were carried out, with a sample rate of 200 *point/sec* using ambient noise only as source of vibrations. With this low level of excitation the building showed a quasi-linear behaviour, and a spectral analysis was performed. As well known, peaks in the power spectral densities (PSD) could be associated to structural frequencies, while the same peaks in the cross spectral densities (CSD), with significant values of phase factor and coherence function, could confirm this statement and give some indications about the modal shape associated to each structural resonance [6, 7, 8, 9].

In Fig. 3, the PSDs and the CDS relating to sensors CH11 and CH13 in the longitudinal direction are plotted. The PSDs and the CDS relating to sensors CH04 and CH14 in the transversal direction are plotted in Fig. 4. The experimental analysis pointed out the resonance frequencies of the building and of the tower listed in Table 1 [10].

Design and Application of Seismic Isolation in Existing Buildings

Seismic isolation has already been used for the retrofit of historical buildings [11], among these:

- the Saint Francisco City Hall, whose retrofit was completed in 1998. The foundations were first reinforced with new beams and a new deck was realized above the isolation interface. Then, the structural elements were shored up and the foundations were cut at their top. Hydraulic jacks

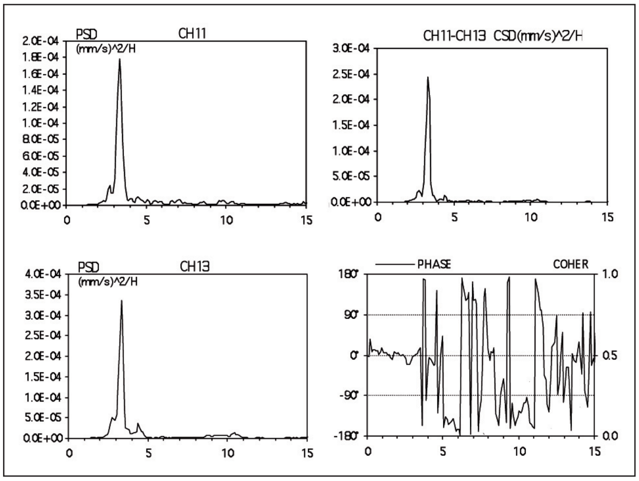

FIGURE 3 PSD and CSD of longitudinal sensors CH_{11} and CH_{13}
Source: ENEA

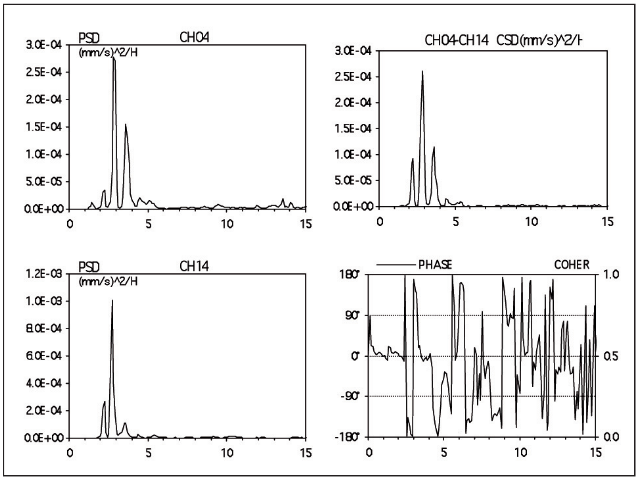

FIGURE 4 PSD and CSD of transversal sensors CH_{04} and CH_{14}
Source: ENEA

were used as temporary supports for steel columns and brick walls to install the lead rubber bearings under each column;

- the City Hall of Oakland, where 112 devices were installed and the superstructure was strengthened by means of reinforced concrete shear walls. Structural details were studied to protect the structure from earthquakes during the works, and the construction phases guaranteed the symmetry. The works were completed in 1995.
- the City and County Building in Salt Lake City, a massive unreinforced masonry structure completed in 1894. The isolation system is composed of 443 lead-rubber bearings, installed underneath the building on top of existing foundations.
- a masonry school building in Vanadzor, Armenia, after the 1988 earthquake; the construction phases are shown in Fig. 5.

Among the proposals, not realized at the moment, it is worth reminding the seismic retrofit of the Iran Bastan Museum in Tehran [12] and the seismic retrofit of a residential building in Belluno, Italy.

The isolation system must be designed in order to reduce the seismic action in the superstructure to the value that the restored building will be able to support in the elastic range. More in detail, the first period of vibration of the isolated building should be chosen as the one corresponding, in the elastic spectrum relating to the superstructure, to the acceleration value that the superstructure is able to bear. Then the corresponding displacement values in the elastic spectra relating to the isolation system, are evaluated.

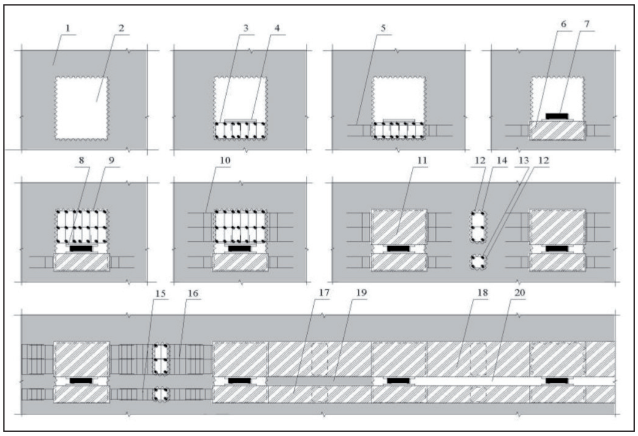

FIGURE 5 Construction phases for the isolation system in the school in Vanadzor
Source: M. Melkumyan

In the case study, a preliminary analysis allowed to fix 0.10g as the maximum spectral acceleration tolerable by the superstructure and the corresponding period was tentatively assumed as period of vibration of the isolated building. This value was first compared with those obtained during the experimental analysis. In fact, a suitable decoupling between the motion of the building and the motion of the soil is obtained only if the frequency of the isolated building is lower enough with reference to the frequency of the superstructure assumed as fixed at its base. Besides, it is important reminding that the seismic microzoning, carried out by the Italian National Civil Protection Department, pointed out the presence of seismic amplifications in the range 0.4÷0.6 *Hz* in a wide area, which also

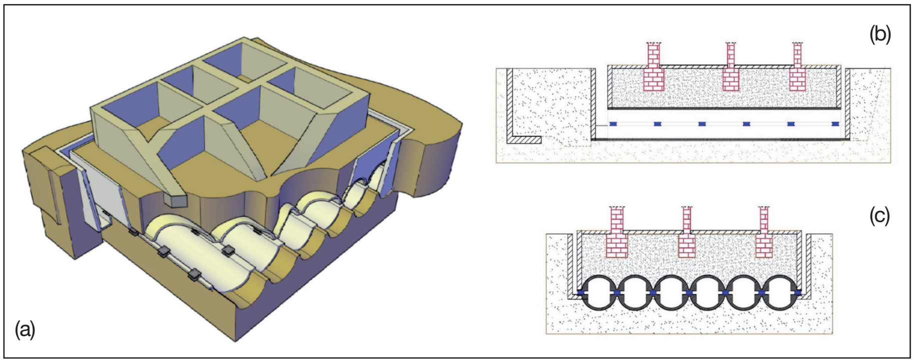

FIGURE 6 The new isolation system: (a) view, (b) longitudinal and (c) transversal sections
Source: ENEA

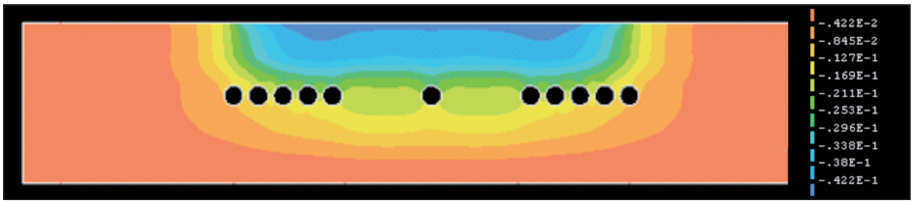

FIGURE 7 Filling the layer of pipes (strategy 1)
Source: ENEA

included the site of Palazzo Margherita. So the main resonance frequencies of the isolated structure should be lower than the minimum value of this range. Taking into account all these considerations, a period of the isolated building equal to 3.0 s was fixed. At this period, the spectral acceleration and displacements were S_e=0.07g and S_{De}=0.30 m, respectively.

A New Isolation System

An innovative solution has been proposed for Palazzo Margherita, which consists in the realization of an isolated platform under the foundations of the building, without touching the building itself (Fig. 6). A discontinuity between the foundations and the soil is created by inserting horizontal pipes, by means of auger boring or micro-tunnelling technique, the positioning of isolation devices at their horizontal diametric plane and the realization of a double system of vertical walls around the building. The pipe diameter should be ≥ 2 *m*, in order to allow the inspection and the substitution of the devices. The pieces of pipe have a particular shape, composed of a lower and an upper sector, connected by means of removable elements. The removable elements, placed in correspondence of the isolator locations are first removed, and the isolation devices are positioned also joining each pipe with the two adjacent ones by means of reinforced concrete elements. Then, also the other connection elements along the pipe are removed, other reinforced concrete elements are casted to connect adjacent pipes, so the lower sectors are definitely separated from the upper ones. Finally, vertical walls are built along the four sides of the building [13, 14].
The structure is seismically isolated but not affected by any interventions that could modify its architectural characteristics, which is very important for historical buildings. Even underground level are not modified but can be part of the seismically protected building. The system also allows the realization of a tunnel for pedestrians or vehicles.
During the micro-tunnelling operation two problems can arise: the soil settlement and the vibration induced at the surface level [15]. Analogue experiences suggest that minor threats should be expected from induced vibrations, but theoretical and experimental in-depth studies are needed. More serious problems can arise by settlements [16]. A FE 2-D model was set up and then exploited in a *Diana 2* environment. The vertical edges of the model are kept far enough from the perturbed zone, to reduce their influence as much as possible. The nodes belonging to those edges are restrained by means of springs and dampers able to cut-off the wave reflection. In the model the soil is described as a layered continuum indefinitely extended, supported by the bedrock at 17 m depth. The building imposes a load of 3000 kN/m uniformly distributed along its base width. That load induces a local settlement. Then micro-tunnels, later named simply "pipes", are included in the model, following two different alternative strategies: i) strategy 1: one central pipe, then the two most external ones and all the others filling the layer from the external pipes to the centre (Fig. 7); ii) strategy 2: one central pipe, then the two most external ones; other pipes are then inserted in intermediate positions, regularly spaced, gradually filling the layer.
The settlement due to the insertion of pipes, originated by a stress release process, was computed as the difference between the settlement due to the weight of the building and the insertion of the pipes and the settlement due to the weight of the building alone. The three-dimensional mechanism of the stress release during micro-tunnelling was described by a

plane-strain two-dimensional model by means of a conventional hole-boundary force reduction approach known as "β-value method", or Convergence-confinement method using the stress-release factor λ, varying inside the 0-1 range. For the case of $\lambda = 0.4$ and $H/D = 3.5$, where H is the depth of the pipe axis and D is the diameter of the pipe, the final computed value of the settlement is about 6.8 *mm* for the strategy 1, and about 5.6 *mm* for the strategy 2. Increasing the stress release factor λ to 0.6 the settlement values increase of about 1.2. A larger H/D ratio reduces the problem but increases the cost of the trenches. Technologies to contrast the settlements exist and are consolidated but, of course, they push the cost up.

Conclusions

For the seismic retrofit of Palazzo Margherita, the City Hall in L'Aquila, seriously damaged by the 2009 earthquake, an isolation system has been proposed. It is based on the realization of an isolated platform under the building foundation without any intervention on the building itself and can be used not only for single buildings but also for complex structures, typical of the Italian historical centres. The structure was first studied by means of the dynamic experimental analysis, the results of which were determinant for the design of the isolation system as well as the seismic response at the site.

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