RESTORATION OF THE HISTORICAL ARCHBISHOP'S PALACE IN CAGLIARI (ITALY).

G. Concu and F. Mistretta

Department of Structural Engineering
University of Cagliari, Italy
Piazza D'Armi 2
09123 Cagliari, ITALY
fmistret@unica.it

KEYWORDS: masonry, repair, restoration design, NDT

ABSTRACT

This paper presents a case study in which an extensive restoration of an ancient stone masonry building – the Archbishop's palace of Cagliari (Italy) was conducted. In the last decades, degrade of floors and masonries has reached a fatal stage and has caused structural faults and a generalized lack of safety. To bring the building back to its original splendour a rigorous investigation on the structural integrity of the building was undertaken on the basis of an extensive on-site non destructive testing (NDT) campaign. The results of inspections and the consequent renovation project are reported.

INTRODUCTION

The oldest part of the city of Cagliari - named "Castello" (castle) - sits on top of the hill, gazing over the Gulf of Cagliari. This core of the town was built by the colonizing Pisans in the early Middle Ages. The ancient city walls are still largely intact, with two thirteenth-century's white limestone towers looking down over the port. Right in the heart of the "Castello" stands the historical Archbishop's palace, built adjacent to the Cathedral between XIII and XVII centuries (Fig 1-2). Despite its recently restored facade, the Archbishop's palace still has some traces of the original Pisa's pointed arch architecture. At the time of the Court the building was the residence of the Prince who became King Carlo Felice.

Design History and Background

Over the ages the four storeys high building had been partially modified with the addition of tile-lintel, iron and wooden floors, the opening of stairs and the closure of part of the courts. Last year it was decided to bring the building back to its original splendour through an extensive restoration consisting in the removal of all the recent addictions, the substitution of the ancient wooden-beam floors hardly attacked by humidity and termites and the rehabilitation of masonries. These seemed to be locally disconnected and showed macroscopic cracks requiring further analysis to understand what kind of work would be more suitable for the restoration.

Based upon a review and analysis of the original structural elements supplemented by an extensive on-site testing campaign, a rigorous investigation on the structural integrity of the building has been undertaken. Several non destructive tests have been carried out to determine the in-situ masonry condition in order to design the rehabilitation.

Fig. 1 Archbishop’s palace (left) and Cathedral facades (right).

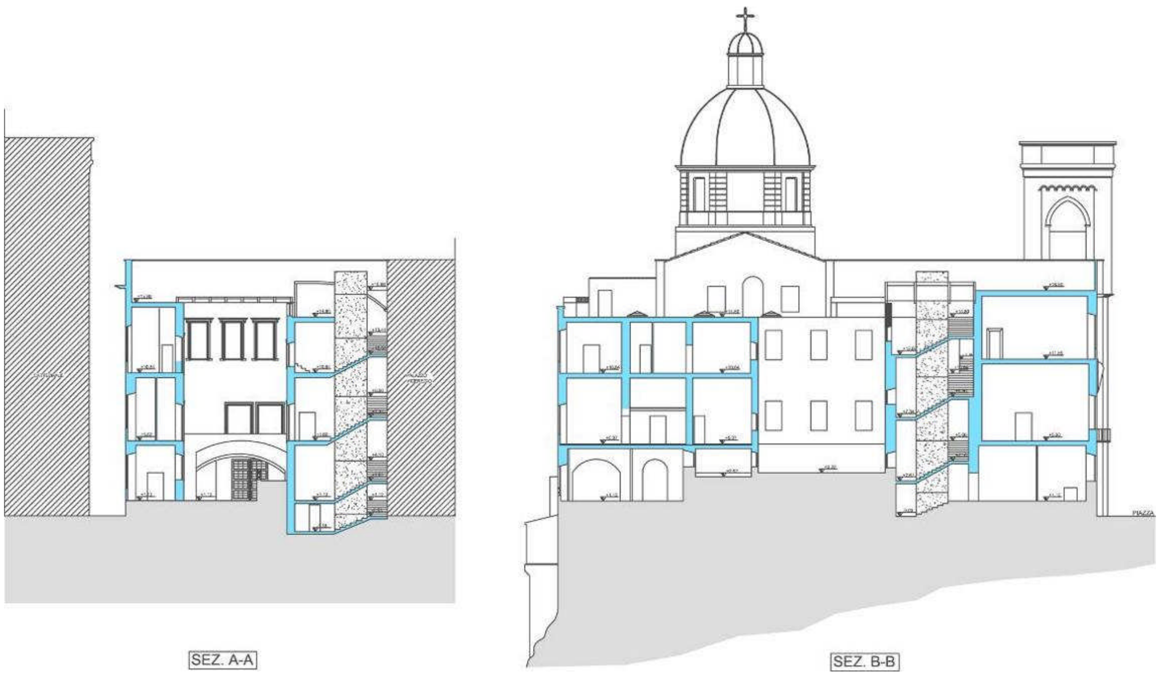


Fig. 2 Sections of the palace.

NDT TESTING

Limestone masonries of the Archbishop’s palace have been tested by several non-destructive analyses with the purpose of getting reliable data for evaluating the actual static condition, the degradation level and the structural safety. This would make possible to correctly design the restoration works.

The non-destructive diagnostic surveys included: Sonic Methods, Endoscopy, Monitoring of Cracks.

Sonic Methods

Generalities on Sonic Methods

Sonic Methods (SMs), based on measurements of the velocity V of sonic waves propagating through the material, seem to be very suitable for evaluating a buildings condition because they give information with immediacy, rapidity and relatively low cost (Cianfrone, 1993; Concu, Mistretta, De Nicolo, Valdes, 2003). When there is the need of investigate buildings characteristics, and buildings consisting of ancient masonry, which is a very diffuse situation, SMs should be appropriate because they involve low frequency signals, thus they can better bypass masonry intrinsic non-homogeneity because of the wave's high energy content (Binda *et al.*, 2000; Concu, 2003; Concu, Mistretta, De Nicolo, 2003). SMs are preferentially carried out applying the Through Transmission Technique, in which the sonic wave is transmitted by a transducer through the tested structure and received by a second transducer on the opposite side. This approach consents to measure the time T that the wave needs to travel from the emitter to the receiver, along the path of length L; the velocity V of the sonic wave is then obtained from the ratio L/T. From wave's propagation theory it is known that V is a function of the following material's characteristics: dynamic elastic modulus Ed, Poisson's number ν and density ρ. Several efforts have been made in order to estimate the material strength S from V measurements, starting from the assumption that V is directly related to Ed, and Ed is directly related to S. Nevertheless, the S estimation is acceptable only when a direct correlation between V and S is available, for example by measuring the velocity of cores extracted from the structure and then tested for S determination, or by measuring V in masonries' portions successively tested with flat jacks. However, even if this direct correlation is available, it is valid only for the tested materials or buildings portions, and it shouldn't be extended to the entire structure. Therefore, the use of sonic velocity for the determination of a building residual strength is not a correct procedure and should be avoided. Instead, the relation between V and Ed, ν, ρ, can be exploited for achieving data regarding the structure's health in terms of elasto-mechanical conditions. In fact, the measurements of V along a proper grid of paths leads to define the level of homogeneity of the tested area, thus emphasizing zones where anomalies are located; moreover, the knowledge of V values distribution consents to express a qualitative remark on the mechanical effectiveness of the structure, since it is empirically known that the higher the strength the higher the velocity. Therefore, V analysis should be a useful tool in masonries diagnosis and testing, but the experience of the operator in running the tests and in interpreting the results is still of fundamental importance (Concu & Valdes, 2005; Concu & De Nicolo, 2005).

Areas tested by Sonic Methods

SMs in Through Transmission mode have been carried out on the limestone masonries of the Archbishop's palace with the aim of qualitatively establishing the integrity of the materials and the static condition. The sonic surveys have been run extensively on the first and second floors' masonries. In the detail, the sonic tests have interested 7 wall's portions located on the first floor and 4 located on the second floor (Fig. 3). The characteristics of the tested areas are reported in Table 1. The sonic velocity V has been measured along paths crossing the thickness of the walls and located at the edges and in the centre of an ideal rectangle that identifies the tested area (Fig. 4).

Measurement Setup

As previously mentioned, tests were carried out applying the Through Transmission Technique, in which the signal is transmitted by a transducer through the test object and received by a second transducer on the opposite side. The testing equipment, developed and assembled by the Department of Structural Engineering, University of Cagliari, included:

- a impact hammer with piezoceramic sensor for generating the signal;

- a 55 kHz piezoelectric transducer for receiving the signal;
- a Velleman Instruments digital oscilloscope for signal visualisation and preliminary analysis;
- a PC for data storage and signal processing.

Transparent Vaseline was used to couple the transducer to the masonry, in order to reduce the energy dissipation due to the different acoustic impedance between materials in contact.

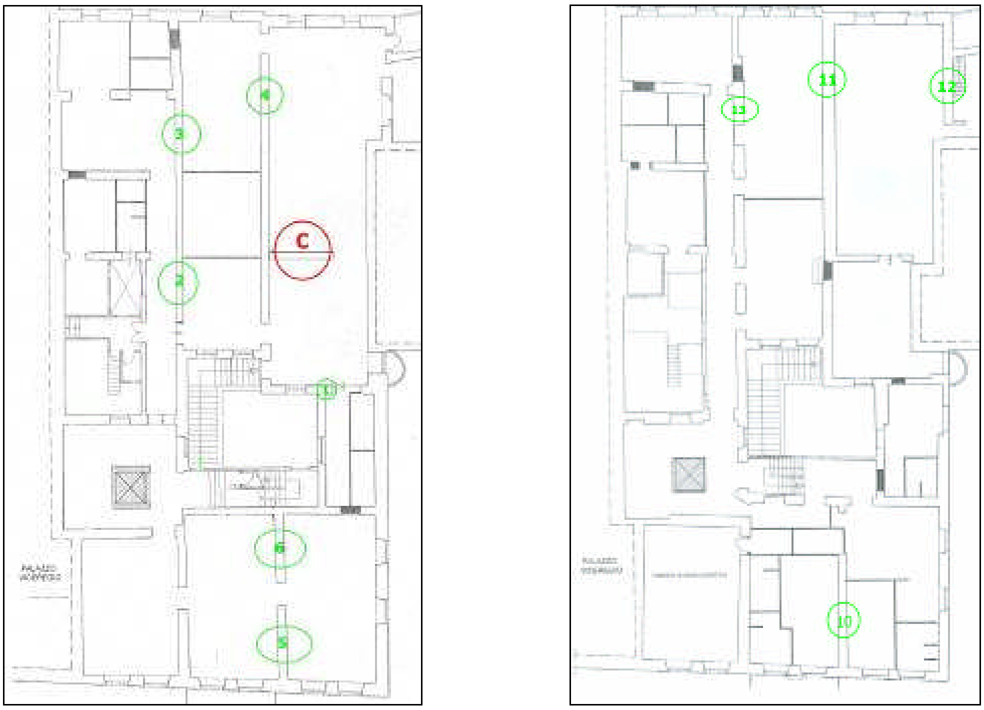


Fig. 3 Areas tested by sonic methods. First floor (left) and second floor (right)

Table 1. Characteristics of tested wall's areas

Area	**C**	**1**	**2**	**3**	**4**	**5**	**6**	**10**	**11**	**12**	**13**
Height (cm)	70	80	70	70	80	70	70	70	115	70	80
Width (cm)	100	90	60	70	70	70	100	70	100	100	70
Location (floor)	1st	1st	1st	1st	1st	1st	1st	2nd	2nd	2nd	2nd

Fig. 4 Schema of measurements points

Results and discussion

The velocity's values acquired on the crucial points (as shown in Fig. 4) have been processed and their histograms have been elaborated. As an example, the V histograms relative to two of the tested areas are shown in Fig. 5.

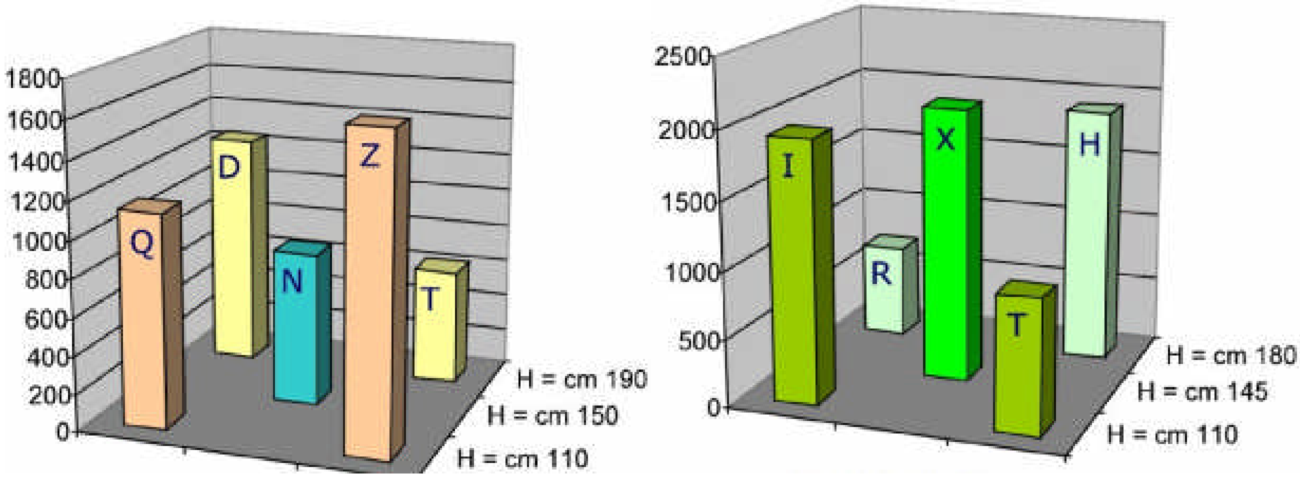


Fig. 5 Histogram of V(m/s). Area 4 (left) and area 5 (right). H is the height from the floor.

V data analysis pointed out the following outcomes:

- in the most of the tested areas V average value ranged between 900m/s and 1400m/s;
- areas 2, 3 and 12 showed V average value lower than 700m/s;
- area 1 showed a V average value higher than 2000m/s;
- V values scattering was extremely high in all the tested areas;
- the acquisition of the transmitted sonic signal in area 11 was impossible to perform.

Thus, results highlighted the highly irregular distribution of the velocity, that is symptomatic of a high level of non-homogeneity. As expected, the higher V values were measured in the large stones, while the decreasing of the values could indicate an internal detachment between the stones, or the presence of cracks and damages. The areas where V is lower than 700m/s should be looked at in special concern, because the de-cohesion degree could be serious. Additional surveys have been carried out on area 11 in order to ascertain which defects disturb the signal transmission and establish the real inner condition of the masonry.

<u>Endoscopy</u>

Generalities on Endoscopy

Endoscopy is a very practical technique in structural diagnostics as it offers the chance to see directly shape and appearance of elements otherwise inaccessible to direct observation, making it possible to carry out useful evaluations. The endoscopes can therefore be used in the on-site examination of both natural and artificial cavities, in order to directly observe morphology, type and state of conservation of materials and structures or structural elements that can be conveniently surveyed through small-diameter holes.

The endoscopic survey

A endoscopic survey has been carried out on tested area 11, in which the acquisition of transmitted sonic signals was impossible to perform due to the total dissipation of signal’s energy. The inspection has been run through holes drilled in correspondence of the crucial points described in the previous section.

Some pictures acquired during the survey are shown in Fig. 6. It can be noticed that the inner masonry has several discontinuities, cavities and lack of material.

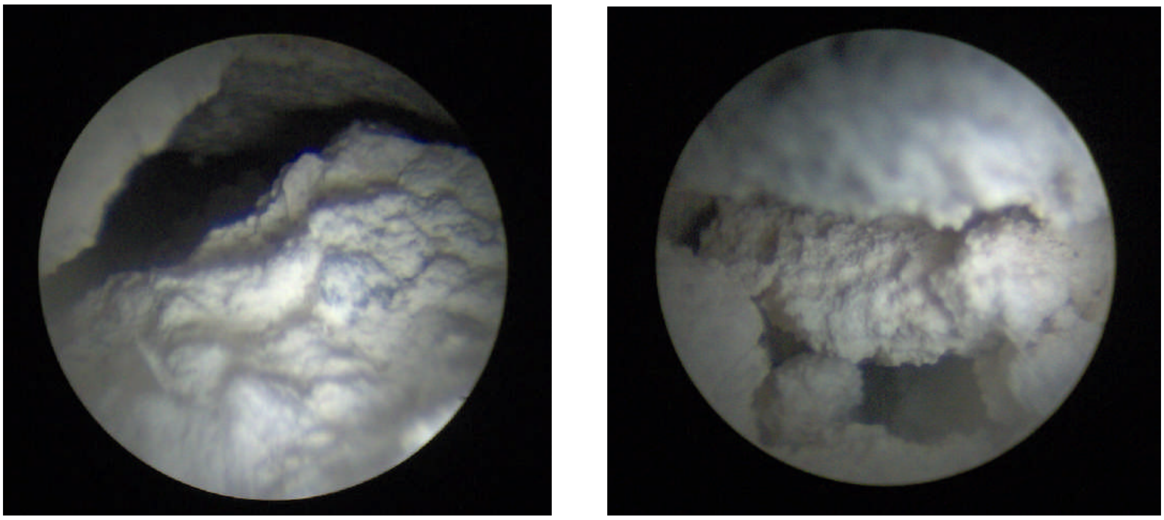


Fig. 6. Pictures acquired during the endoscopy

Monitoring of cracks

Monitoring of cracks has been set up in order to assess possible risks and to understand the mechanical behaviour of the structures before planning the intervention. Aiming at evaluating the differential movement of the Archbishop, the most serious cracks have been monitored for 19 months. The displacements were measured by removable extensometer (Fig. 7) every month.

In the detail, the monitoring has interested 2 fissures located on the ground floor (Fig. 8), 8 fissures on the first floor (Fig. 9) and 4 fissures located on the second floor (Fig. 10) Locations of monitoring devices are summarized in Table 2.

Table 2 Locations of monitoring devices.

Crack	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Position	g. f.	g. f.	1^{st} f.	1^{st} f.	1^{st} f.	1^{st} f.	1^{st} f.	1^{st} f.	2^{nd} f.	2^{nd} f.	2^{nd} f.	2^{nd} f.	1^{st} f.	1^{st} f.

Results and discussion

The trend of cracks displacements is reported in Figures 11-13.

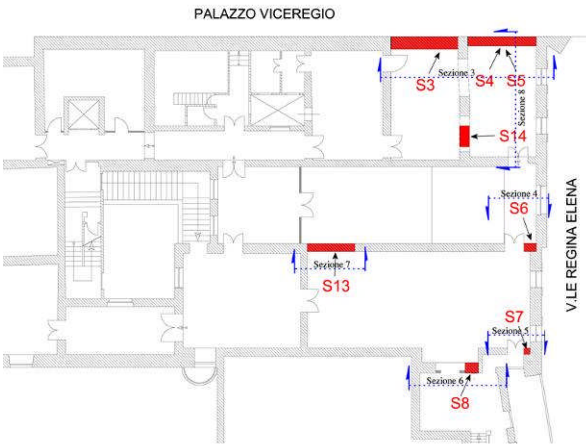
Collected data pointed out the following results:

- displacements of cracks S3, S4, S5, S8, S13 at the 1^{st} floor and S12 at the 2^{nd} floor were quite moderate, and their sinusoidal trend seemed to depend on the temperature changes;
- crack S1 at the ground floor, S6, S7, S14 at the 1^{st} floor and S9, S10 at the 2^{nd} floor showed most important displacements;
- displacements trend of cracks S6, S7 and S14 was sinusoidal with slowly time-increasing amplitude;
- displacements trend of cracks S1, S9 and S10 wasn’t sinusoidal.

Thus, monitoring results highlighted that a slow but steady displacement of the Archbishop’s side where cracks S1, S6, S7, S14, S9, S10 are located was ongoing.

Fig. 7 Removable extensometer

Figure 8 Cracks monitored. Ground floor



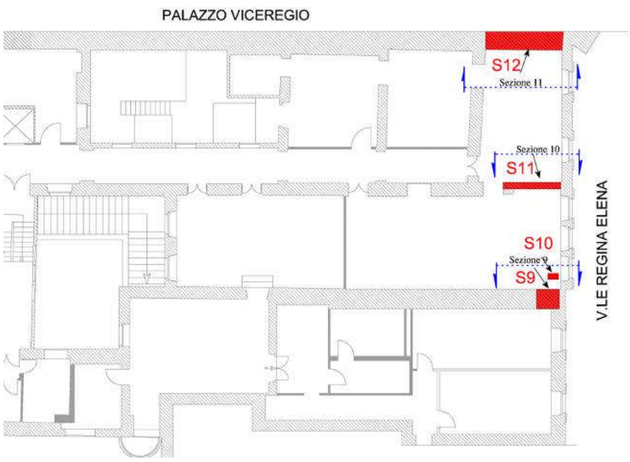


Fig. 9-10 Cracks monitored. First floor (left) - Second floor (right)

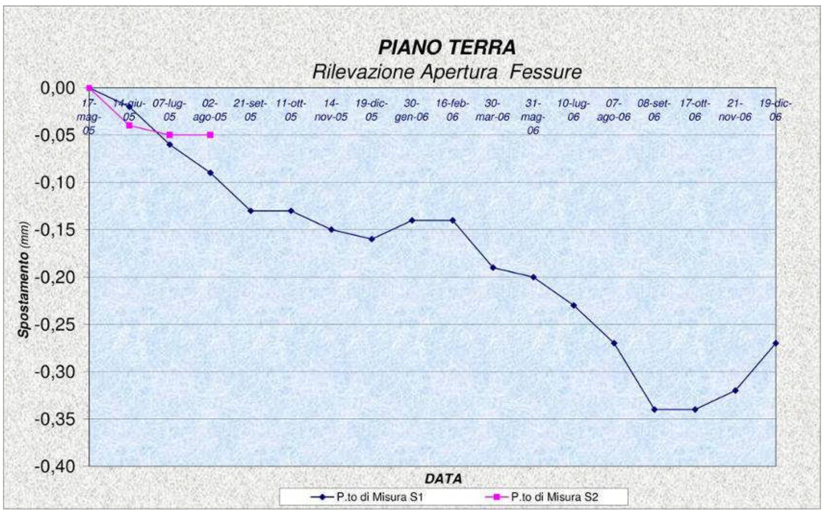


Fig. 11 Crack’s displacements trend. Ground floor.

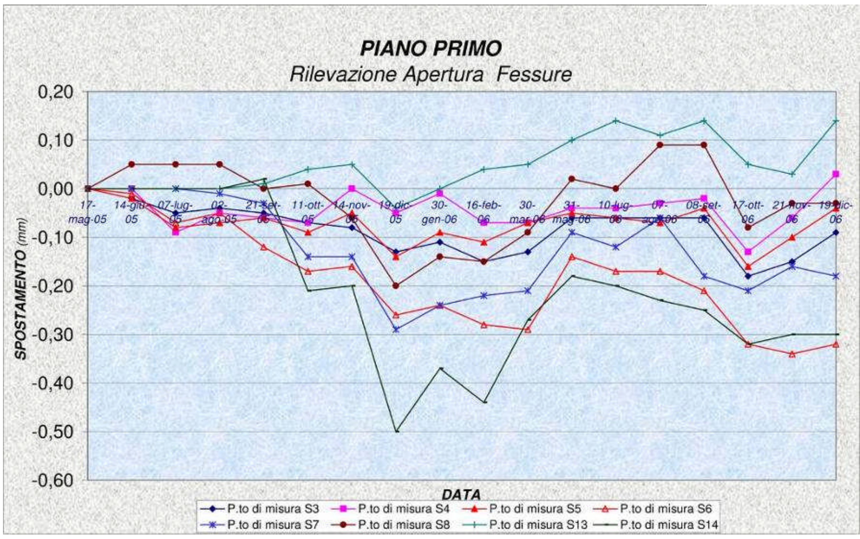


Fig. 12 Crack’s displacements trend. First floor.

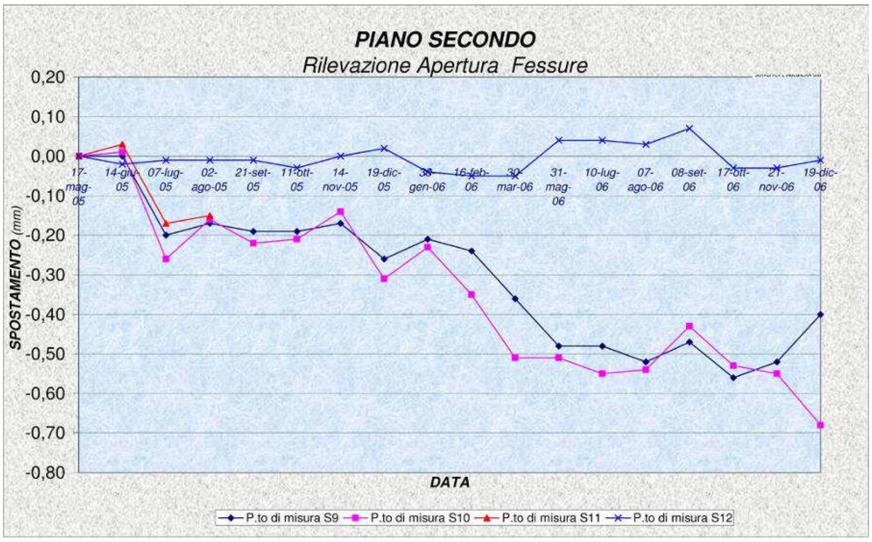


Fig. 13 Crack’s displacements trend. Second floor.

THE RESTORATION PROJECT

The restoration involved the setting-up of the new floors, the staircase and the lift (Fig. 14-15).

The design of the new floors had originally provided for a composite steel-concrete structure made of double T-shaped steel beams with a overlying concrete cast, keeping up a interposed precast joists and hollow tiles mix. Given the difficulty of handling the materials caused by the hard operating conditions (old town centre), the contractor proposed to replace the designed floors with a different system providing the same static performance and better performance in terms of installing and safety working (Fig. 19-20). The system provided the use of a corrugated steel sheet 1.2mm thick resting on the double T-shaped steel beams extrados instead of the precast joists and hollow tiles mix floor; a concrete layer overlaid the structure (Fig. 16-21-22).

Fig. 14 Ground floor and first floor plans (Type A HEA beams – Type B HEB beams).

Fig. 15 Second floor and roof floor plans (Type A HEA beams – Type B HEB beams).

The new adopted system led to the following advantages, achieved without growing costs:

- increasing in the floor's thickness and inertia, thus enhancing its performance in terms of strength as well as rigidity;

- quickness in installation works, because the corrugated steel sheet laid over the structure provided the form for the subsequent concrete cast, thus allowing to avoid the use of scaffolding and formworks
- safety increasing, because the floor could be built without scaffold resting on the lower floors, therefore avoiding collapse's risks.

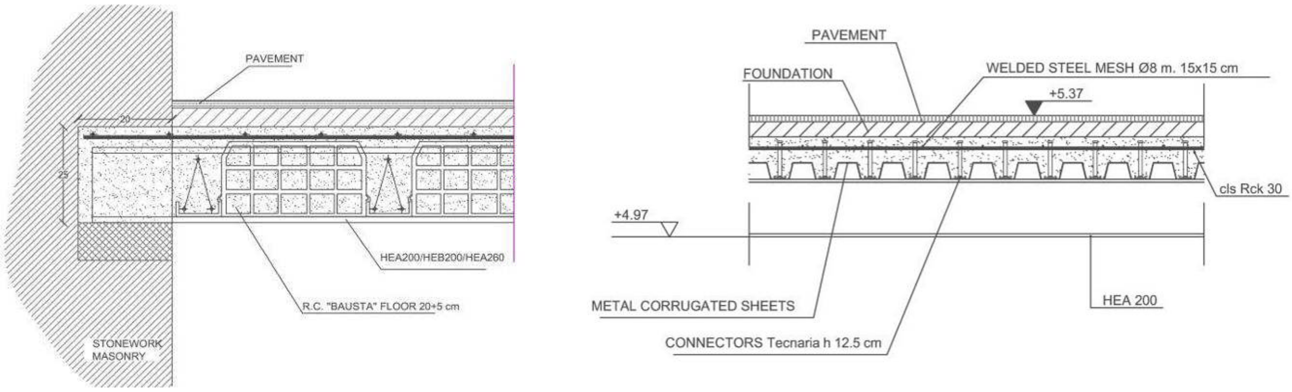


Fig. 16 Composite steel-concrete structure: original design (left) ad solution applied (right).

In order to guarantee the static unity of the load-bearing steel structure and the overlying concrete cast, it has been used a new system that consists of cold fastening the connectors using special nails. The connector consists of a headed stud inserted in a suitably shaped and stiffened base plate. Two cold-fastening nails, made of highly resistant material, passing through the plate, ensure the rigid fastening of the connector to the steel beam. The nails are punched in the means of a powder-actuated tool (Tecnaria 2008).

This kind of connector offers a number of advantages:

- same mechanical characteristics and ductility as the welded headed studs;
- reduced dimensions of the connector (easily positioned on most profiled metal decking shape) ;
- reduced deformation values for limited loads and high deformation values for high loads (ductile behaviour) ;
- the head prevents the detachment of the slab due to dynamic stress or excessive deformation
- optimum behaviour under cyclic loads;
- the fastening operation is not affected by the surface treatment of the connected parts (painted or coated) nor by the presence of the metal deck that lies between the base plate and the beam: these elements, on the contrary, combine to ensure structural unity;
- climatic conditions do not affect results (humidity or low temperatures);
- skilled workers not necessary. The fastening system is safe, reliable, fast and ensures precise high-quality fastening;
- the work can be carried out on site without requiring costly or cumbersome equipment. The operator is fast and mobile;
- the success of the fastening operation can be verified through a simple visual check;
- the galvanized surfaces do not release poisonous fumes.

Along the joints between perpendicular walls, for the entire wall's height, and in correspondence of the floors, tie bars have been inserted in order to upwind the building and prevent additional failures and lesions (Fig. 18).

A particularly scenic floor suspended with stainless steel cables has been carried out in order to expose to view the beautiful palace's wall bordering the Cathedral (Fig. 23-24).

Fig. 17- First phase of steel beams set-up. Fig. 18 Inserted tie bars.

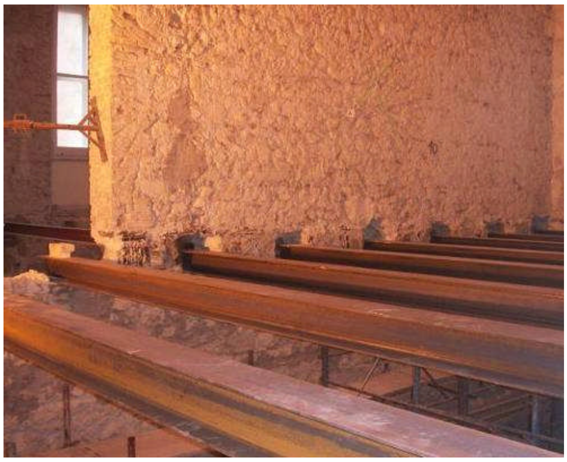
 

Fig. 19-20 Difficulties of steel beams set-up.

Fig. 21-22 Corrugated steel sheet set-up: connectors (left) - Inserted tie bars (right).

Fig. 23-24 The suspension floor in front of the Cathedral.

CONCLUSIONS
In this paper a case study involving assessment, investigations and upgrading of an ancient masonry building has been presented. The building is the historical Archbishop's palace of Cagliari, built between XIII and XVII centuries. Building ageing, in addition to the lack of periodic maintenance, had led to a loss of structural performance; this had caused the huge degradation of floor elements, whose preservation were therefore not achievable.

The final restoration work has been preceded by an extensive campaign of non- destructive investigations, that enabled the set-up of the necessary interventions. The difficulties of the new structures setting up has led to apply advanced novel solutions.

ACKNOWLEDGEMENTS
Authors wish to thank Mr. Bruno Buccellato of Buccellato s.r.l. and Mr. Roberto Porrà of TECNICA Prove s.r.l. for their contribution in the in-situ experimental work. Special thanks for the collaboration go to Mr. Antonio Grussu and Mr. Lino Mancosu of Andreoni s.r.l. (contractor).

REFERENCES
- Binda, L., Saisi, A. and Tiraboschi, C., 'Cattedrale di Noto. Le indagini soniche per la diagnosi di strutture murarie danneggiate e riparate', *L'edilizia e l'industrializzazione* **anno XIV** (9-10) (2000) 8-41.
- Cianfrone, F., 'Indagini Microsismiche ed Ultrasoniche', *Proceedings of the Conference Sperimentazione su Strutture; Attualità e Affidabilità delle Metodologie di Indagine*, Venezia, 1993.
- Concu, G., 'Controlli non distruttivi sulle murature in pietra: validazione di una metodologia sonica', *Proceedings of the 10th AIPnD National Conference* , Ravenna, 2003.
- Concu G., De Nicolo B., Mistretta F. 'Comparative evaluation of two non-destructive acoustic techniques applied in limestone masonry diagnosis', *Proceedings of the 33rd International Conference and Exhibition Defectoscopy 2003*, Ostrava, Czech Republic, 2003.
- Concu, G., De Nicolo, B., Mistretta, F. and Valdes, M., 'NDT Ultrasonic method for ancient stone masonry diagnosis in Cagliari (Italy)', *Proceedings of Structural Faults and Repair 2003*, London, 2003.
- Concu G., De Nicolo B. 'Sonic Tomography in ancient limestone masonry diagnosis and characterisation', *Proceedings of the 8th International Conference on Non-Destructive Testing and Microanalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage*, Lecce, 2005.
- Concu G., Valdés M. 'Applicazione di metodi sonici nel monitoraggio delle murature in pietra della Cattedrale di Cagliari', *Proceedings of the 11th AIPnD National Conference*, Milano, 2005.
- Tecnaria s.p.a. www.tecnaria.com