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## RETROFIT OF STONE MASONRY BUILDINGS IN GREECE I. DAMAGE PATTERNS AND PREVENTIVE RETROFIT/REPAIR MEASURES

ΒY

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Abstract. This paper concerns the retrofit of seismic retrofit of stone masonry buildings in Greece. Unlike the study of historic buildings, which is in most cases done for masonry buildings since reinforced concrete is not considered historical enough, for benefit-costs studies of seismic retrofit more studies were conducted for reinforced concrete buildings, as these are more common. First seismic retrofit measures for common masonry buildings are presented, using steel and reinforced concrete. The focus lays in division of seismic retrofit measures in singular steps and to organize them in order to make possible the determination of the individual costs of the partial works. The measures are divided into preventive measures are compared to those used in the practice of monumental buildings, considering two buildings in Athens, where concrete and FRP were employed. These buildings belong to a wider stylistic European movement of the 19<sup>th</sup> century Neoclassicism, as foreign architects settled to Greece that time.

Key words: stone; masonry; monuments; retrofit; historic buildings; Greece.

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## 1. Introduction

The majority of population lives and will continue to live in existing buildings. Therefore earthquakes pose a major threat to life and property of people living and working in such buildings, if situated in earthquake prone zones. Most existing buildings, especially the historic ones, were designed before seismic codes were introduced. In this case, in order to protect life and property from seismic risk the retrofit of existing buildings is an aim to be pursued.

The International Seminar on Seismic Risk and Rehabilitation of Stone Masonry Housing was an occasion to come back to an issue present at the begin of the research on economic efficiency of the first author, namely the economic efficiency of retrofit of old masonry buildings (Boştenaru-Dan & Bourlotos, 2008). In Romania, which was the country more extensively studied, stone masonry buildings are scarce, so, given that at the begin research was done supervising the individual study of a Greek researcher this work was done for the Greek stone built stock.

Each building is unique and a building retrofit measure only satisfies its scope when the identity of the construction work remains maintained.

The work is completed by analysing retrofit interventions on two monumental buildings in Athens: the National Library of Greece (Fig. 1) and the National Theatre of Greece (Fig. 2). The first is a neo-classical building designed by Theofil von Hansen and supervised by Ernst Ziller (Schiller), while the second is moving toward eclecticism and is designed and built by Ernst Ziller. Theofil von Hansen was a Danish architect of Classicism mainly active in Vienna (Figs. 3,..., 5). Ernst Ziller was a German architect mainly active in Athens, Greece.

## 2. Damage Patterns at Stone Masonry Buildings in Greece

Since the Antiquity Greece is known for its stone buildings. Stone sculptures from the Antique Greek continue to impress, and the country is rich in stone as construction material.

### 2.1. Damage Pattern of Common Buildings

Earthquake resilient features, seismic deficiencies and earthquake damage patterns are the information gathered in the World Housing Encyclopedia, for example in the report on Greek stone masonry housing by Tassios and Syrmakezis (2004). These ones describe load bearing stone masonry buildings, which are considered for Greek housing. "These buildings are mainly found in historic centres of Greek cities and provinces" (Tassios and Symakezis (*op. cit.*)). The load bearing system consists of unreinforced stone



Fig. 1 – National Library of Greece (Εθνική Βιβλιοθήκη) buildings, Athens, architects Theofil von Hansen (1813-1891) and Ernst Ziller (Ερνέστος Τσίλλερ, 1837-1923), 1888-1903.



Fig. 2 – Preserved part of the National Theatre (Εθνικό Θέατρο) buildings (Schiller phase), Athens, architect Ernst Ziller, 1895-1901.



Fig. 3 – Parliament building (Reichsratsgebäude), Vienna, architect Theofil von Hansen, 1874-1883; photo M. Boştenaru, 2009.



Fig. 4 – Music Association (Musikverein), Vienna, architect Theofil von Hansen, 1867-1870, photo M. Boştenaru, 2009



Fig. 5 – Army museum (Heergeschichtliches Museum) at Arsenal, Vienna, architect Theofil von Hansen, 1856, photo M. Boștenaru, 2009.

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masonry walls out of rubble stone with lime mortar, with timber floors and roof. The seismic performance of such buildings is generally poor, and they were damaged during the 1999 Athens earthquake (EERI, 1999). Such damages were

a) partial collapse of walls;

- b) collapse of corners;
- c) separation of the two walls converging at a corner;
- d) extensive cracking.

According to Tassios and Syrmakezis (*op. cit.*), vertical and horizontal reinforced concrete confining elements significantly improve the behaviour.

The retrofit measures analysed in this paper are directed to the improvement of the seismic behaviour or to the reparation of damage as it was in the Athens 1999 earthquake. The proposed measures will be described together with the costs determination in the  $\S3.3$ .

## 2.2. Damage Pattern and Retrofit of Monumental Buildings

The two cases of monumental buildings presented in this paper were retrofitted also without innovative measures, such as metal and concrete, even with the constraints of short intervention time and reversible light method as required by monuments. Reparation measures included injection of the cracks as it will be described in the following chapter.

### a) The National Library of Greece

In case of the National Library of Greece (Fig. 1) the buildings are built from Unreinforced Masonry (URM) constructed externally with smoothened marble megastones combined with marble kions while the floors are composed of steel beams filled with brick vaults in between. The buildings had three different type of damage (Penelis & Penelis, 2001)

(I) Time related.

(II) Damage from the 1981 earthquake which had not been repaired.

(III) Damage from the 1999 earthquake.

In all three wings the type (I) damage consisted mainly of water leakage and oxidation of the steel beams, while the damages of types (II) and (III) are different for each wing.

More specifically the two side wings presented inclined cracks at the edges of the transverse walls typical of independent out of plane behavior of these walls due to the lack of diaphragm constraint at the floor and roof levels. Furthermore horizontal cracks were presented at the foot of the piers of the longitudinal walls due to in plane flexure. The spandrels of the longitudinal walls suffered small vertical cracks indicative of tensile stresses. One of the side wings had an additional R/C mezzanine level, which during the 1999 earthquake pounded on the URM back transverse wall and caused significant damages. The main wing had significantly less damages that can mainly be

attributed to its higher rigidity and robustness (longitudinal walls) and the intermediate transverse walls that prevented independent out of plane behavior.

As has been aforementioned the intervention mainly concentrated on the side wings except for type I damages (time dependent) which also existed in the main wing. Furthermore all the intervention has been directed towards being light and reversible. So, in that context, for the two side wings, the structural restoration consisted in the implementation of a perimetrical, internal zone consisting of beams on the roof level, in order to restore the diaphragm constraint, either using concrete with stainless steel as reinforcement or uniformly stainless steel profile in order to avoid future corrosion. Furthermore four titanium stitches per corner per wall were suggested in order to secure the uniform behaviour of the longitudinal and transverse walls (Fig. 6). The cracks on URM were filled with enema with specially selected composition in order to



Fig. 6 - Titanium stitches of corners at the National Library of Greece.

conform chemically, mechanically and aesthetically with the existing mortar using the sophisticated laboratory tests that had been performed and the existing database at the Reinforced Concrete Lab of AUTH. Finally the mezzanine level was demolished and reconstructed with a composite steel-lightweight concrete structure providing a suitable seismic joint with the surrounding URM walls, to avoid pounding damage in the future.

# b) The National Theatre of Greece

The National Theatre of Greece building, located near Omonia square in Central Athens consists of two phases, the monumental part of initial building which commenced construction in 1891 and completed in 1901 by the architect Schiller (Ziller) and the addition of a Reinforce Concrete Annex following the architectural design of the initial Building.

The structural system of the main building of the National Theatre of Greece consists of URM Stone walls and piers for vertical elements. The floors, with the exception of the stalls area and the balcony, are constructed of steel beams filled with brick vaults in between. The balcony has steel beams embedded in the masonry walls which act as cantilevers. The roof is a steel structure with trusses and girders typical for the period of late 19<sup>th</sup> century.

- The building had the following type of damage:
- (I) Time related.
- (II) Damage in the perimeter walls from the balcony cantilever.
- (III) Damage from the 1999 earthquake.



Fig.  $7 - 2^{nd}$  basement interventions, National Theatre of Greece.

From the analysis results as well as the observed crack patterns which confirmed the analysis results, it was decided that an intervention would be <u>26</u>

performed aiming at the structural and seismic upgrading of the existing preserved part of the theatre. The interventions in general include two-side shotcrete jackets at selected interior piers, one side shotcrete jackets at exterior



piers, strengthening of spandrels – lintels with FRP laminates and stitching of selected corners with inox anchors to reduce the out-of-plane flexure of URM walls. Typical intervention plans are shown in Figs. 7 and 8. It should be noted

that in the upper floor, exterior piers having frescos in their interior face were strengthened not with shortcrete but with grout injections, with grout material that is mechanically consistent with the existing materials and chemical composition not harmful to the frescos.

### **3. Retrofit Measures**

### **3.1. Retrofit Methods in Case of Retrofit of Common Buildings**

As early as 1988 the National Technical University of Athens edited a book on measures to be taken to retrofit masonry buildings (NTUA). The measures described there were taken as a basis for the costs calculation in the individual study of Bourlotos (2001). In the light of the earthquake of 1999 in Athens these measures should be reconsidered. For the measures the steps given in GSOSB (2000) were used. The measures described use traditional methods, with steel and reinforced concrete. New materials such as FRP were not considered.

## a) Retrofit measures in case of pre-damaged buildings

As mentioned in §2.1, typical damages for stone masonry buildings in Greece are

a) extensive cracking;

b) buckling of masonry walls (at corners or in field).

The extensive cracking considered occurs in X shape in the field of masonry walls (Fig. 9 *a*), for example between two openings. There are two kinds of cracks: deep cracks or small rifts. Fig. 9 summarizes the measures. In a first step the plaster is removed (Fig. 9 *b*), the crack is enlarged to several centimeters with hammer and chipper and cleaned with air under pressure, then the rubble rests are removed. If the cracks are large, there is an additional step (Fig. 9 *c*) with injections all 30 cm. The crack and, if necessary, the injections, are filled with cement or reparation mortar and the plaster is re-established (Fig. 9 *d*).

While load bearing stone masonry is the more common one and can be found, for example, in Greece, also infill stone masonry is occurring in historic buildings, for example in Portuguese "Pombalino" buildings (Cardoso *et al.*, 2004).

Masonry walls can be buckled on one side or on both (Fig. 10). If only one side is affected, the other side acts as framework for filling in with cement and repairing the wall.



Fig. 9 – Rifts in not load bearing masonry walls. Step (c) is not necessary at small rifts (from Boştenaru & Bourlotos, 2008).



Fig. 10 – Rehabilitation of buckled masonry walls (in the second case one side of the wall acts as framework) (from Boştenaru & Bourlotos, 2008).

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In both cases the loads are caught with a support (ex. Fig. 11) and lead into the load bearing foundation. Then the old wall or part of wall is demolished and a new wall is built. Finally the wall is loaded again (the support is unmounted).



Fig. 11 – Unloading of the wall in order to add confinement (from Boştenaru & Bourlotos, 2008).

### b) Retrofit measures as preventive measures

One of the frequent damages of stone masonry buildings in Greece affects corners (collapse of corners, separation of two walls converging at a corner). The first retrofit measure is envisaging the retrofit measures in case of lack of confinement of the corner. Intervention on corners can be also a reparation measure.



Fig. 12 – Confinement of masonry corners with a column (from Boştenaru & Bourlotos, 2008).

As in the previous case the loads from the roof and the floors are caught with a scaffold construction (Fig. 11). It is bolted in two directions on the inner side of the wall. The corner masonry is demolished on a length of ca. 2 m and disposed (Fig. 12 *a*). The corner is reinforced with a column: forming, concreting and stripping of the corner column (Fig. 12 *b*). In the zone of the column reinforced masonry is created (Fig. 12 *c*).

For horizontal reinforcement a ring beam can be created.



Fig. 13 - Confinement of door frames (from Boştenaru & Bourlotos, 2008).

Sometimes the lintels consist of stone arches, wood or metal joists. These do not always correspond to the sizes and surfaces of the wall openings. This is also a seismic deficiency. The steps in taking the measure are described on the example of a door opening (Fig. 13). First the old door and the door frame are demolished and disposed. If there is a lintel, this is also demolished and disposed. Then the masonry adjacent to the door opening is demolished and disposed on a 15 cm width (Fig. 13 a). The reinforcement of the reinforced concrete frame is anchored in the floor slab. Other reinforcement works are done, then the reinforced concrete door frame: formed, concreted, stripped (Fig. 13 b). Finally the new door is introduced (Fig. 13 c). The confinement of window frames is similar (Fig. 14).



Fig. 14 - Confinement of window frames (from Boştenaru & Bourlotos, 2008).



Fig. 15 – Shotcreting of masonry walls. (from Boştenaru & Bourlotos, 2008).

Another measure to protect masonry walls is the shotcreting of the wall (Fig. 15). First the plaster is removed, then the mortar, up to 1 cm deep with a steel brush. The wall is cleaned with water. It is shotcreted in a thickness of 4...8 cm. Alternatively a cast in place jacketing of 10 cm thickness can be done.

The reinforcement has a diameter of 8/25. The new wall has to be anchored in the existing masonry wall. The shotcreting can be done only on one side of the wall if the façade has to be kept or if place reasons speak for this.

### 4. Discussion

Stone masonry housing can be found also in other parts of the world. In the World Housing Encyclopedia (http://www.world-housing.net/) documented are examples from Algeria, India, Iran, Italy, Nepal, Pakistan, Portugal, Slovenia and Switzerland, and of course Greece. Most of them are historic, heritage buildings. Stone masonry is not only a material for common housing, but also for monumental buildings. In this case, apart of the structural safety also the maintenance of the aesthetic qualities stays in foreground. Sometimes also the original material of heritage buildings must be preserved, and the intervention must be reversible.

Traditional intervention methods were simulated as being performing well for monumental structures out of stone masonry (Penelis & Penelis, 2001).

Simulations are also useful in order to asses the efficiency of interventions, which is useful for the decrease in seismic vulnerability associated with the intervention.

## 5. Conclusions

Stone masonry is a fragile material when subjected to seismic loads, but at the same time it is a traditional material for which a number of retrofit methods exist. While in Romania not so frequent, in Greece stone masonry buildings can be found both in traditional construction and in monumental buildings, with contribution of foreign architects, such as the one presented in this work. Especially for the case of monumental buildings more sensitive retrofit methods than the traditional ones have to be developed, in order to preserve the characteristics determining their value.

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## CONSOLIDAREA CLĂDIRILOR DIN ZIDĂRIE DE PIATRĂ ÎN GRECIA I. Modele de avarii și măsuri de consolidare preventivă/de reparație

#### (Rezumat)

Se determină costurile consolidării seismice a clădirilor din zidărie de piatră din Grecia. Spre deosebire de studiul clădirilor istorice, care se referă în cele mai multe cazuri la clădiri din zidărie, betonul armat nefiind considerat suficient de istoric, pentru studii de beneficiu–cost ale consolidării seismice au fost făcute studii mai numeroase privind clădirile din beton armat, care sunt mai răspândite. Întâi sunt prezentate măsuri de consolidare pentru clădiri din zidărie de piatră fără valoare deosebită, utilizând oțel și beton armat. Accentul cade pe divizarea măsurilor de consolidare seismică în pași singulari pentru a face posibilă determinarea costurilor individuale ale lucrărilor parțiale. Măsurile sunt clasificate în măsuri preventive asupra unor clădiri neavariate și măsuri de reparație după cutremur. Măsurile sunt comparate cu cele utilizate în practica clădirilor monumentale, considerând două clădiri din Atena, unde au fost utilizate beton și FRP. Aceste clădiri aparțin unei mișcări mai largi stilistice europene a neoclasicismului secolului XIX, întrucât arhitecți străini au imigrat în Grecia în acea perioadă.