METHODOLOGY FOR REHABILITATION AND SEISMIC STRENGTHENING OF ST. CLEMENT'S CHURCH, ST. PANTELEYMON -PLAOSHNIK – OHRID

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ABSTRACT:

The paper deals with application of an originally developed methodology for rehabilitation and seismic strengthening of St. Clement's Church, Plaoshnik, Ohrid. To renovate the structure based on the original foundation dating back to the IX century, complex multidisciplinary investigations were performed in the field of archaeology, conservation, engineering and construction. Presented in this paper are the investigations related to the design of the structural system based on elaborated architectonic floor plans that are to preserve the authenticity of the structure, performed geotechnical investigations of the site and defined input seismic parameters. A linear-elastic and nonlinear dynamic analysis of the structure was performed. Based on the obtained results, the concept of repair and seismic strengthening of the church was adopted. It consisted of incorporation of horizontal and vertical steel ties in the bearing walls of the structure. This method, which is based on the philosophy of "minimal intervention – maximal protection" has originally been developed at IZIIS, Skopje and it has been experimentally and analytically verified. The techniques of consolidation of the authentic foundation of the structure and the existing walls with original fresco-paintings are also presented.

KEYWORDS: seismic strengthening, rehabilitation, St. Clement's Church, bearing and deformability capacity

1. INTRODUCTION

In the place called Plaoshnik lying between the lake and the monumental ramparts of the Samoilo's fortress dating back some 1100 years ago, St. Clement from Ohrid, the first Slavic episcope erected the church of St. Panteleymon upon an old three-conched sacral structure, preaching the Christian religion and generally performing humanistic activities of invaluable importance for all the Slavic peoples. The Plaoshnik compound is under the protection of the Law on Protection of Cultural Monuments.

In 2001, at the initiative of the established Organizational Board for Restoration of St. Clement's church "St. Panteleymon" in Plaoshnik, Ohrid, there started the realization of the idea for the renovation of the church based on assuming its appearance from the original remains of the church walls without damaging the excavated fresco fragments. The final intention of the Board was to return the remains of St. Clement in the grave chosen by himself, as a token of the great respect toward his outstanding deeds as the founder of the Slavic and Macedonian culture and literacy. At the initiative of the Board established for the restoration of the Plaoshnik compound, a professional body consisting of eminent architects, structural engineers, archaeologists, art historians and conservators was constituted. Their main concern was to find the most appropriate solution for this holy place and hence make their own contribution toward the St. Clement's great humanistic and lofty work.

Based on the defined and adopted appearance of the restored Plaoshnik complex presented in the architectonic documentation elaborated by the Institute for Protection of Cultural Monuments and National Museum - Ohrid, a detailed static and dynamic analysis of the structure was carried out by the Institute of Earthquake Engineering and Engineering Seismology - Skopje, who made the solution determining the structural system of the structure as well as the conditions for foundation and consolidation of the existing church walls, [Gavrilovic et al. 2001, Necevska-Cvetanovska et al. 2001]. Presented in the paper are part of the results from the analyses as well as the characteristic details of repair and consolidation of the existing walls.

2. EXISTING STATE AND DESIGN CRITERIA

The archaeological investigations and excavations of the Plaoshnik - Ohrid locality done in 1942, 1965, 1999 and particularly 2000 enabled complete definition of the phases of construction of the St. Clement's church dating back to the IX-XIV century, i.e., its tearing down in the XVth century when the Sultan Mohammed's Mosque was erected upon its remains.

The St. Clement's church was restored upon the existing foundations from the construction phases dating back to IX to XIV century. The renovation was carried out upon the original remains of the church walls, without damaging the excavated fresco fragments, by previously eliminating the parts of the walls that were added during the conservation of the structure in 1965. During the restoration of the church, traditional materials (stone, brick and lime mortar) were used as construction material, preserving the original walling pattern of each of the different chronological periods of construction of the structure. Figure 1 shows the existing walls onto which the new structure of the church was built.

While building the church structure, two timber bond courses placed at a vertical distance of 1.26m as well as timber ties were used. The sub-base zone between the original and the renewed part was solved by a joint made of lime mortar with a thickness of 5 cm shaded with a certain nuance, while the renovated walls are withdrawn in respect to the original ones for 3 cm in order to make a boundary between the old and the renewed part. Figure 2 show photos of the excavated material.

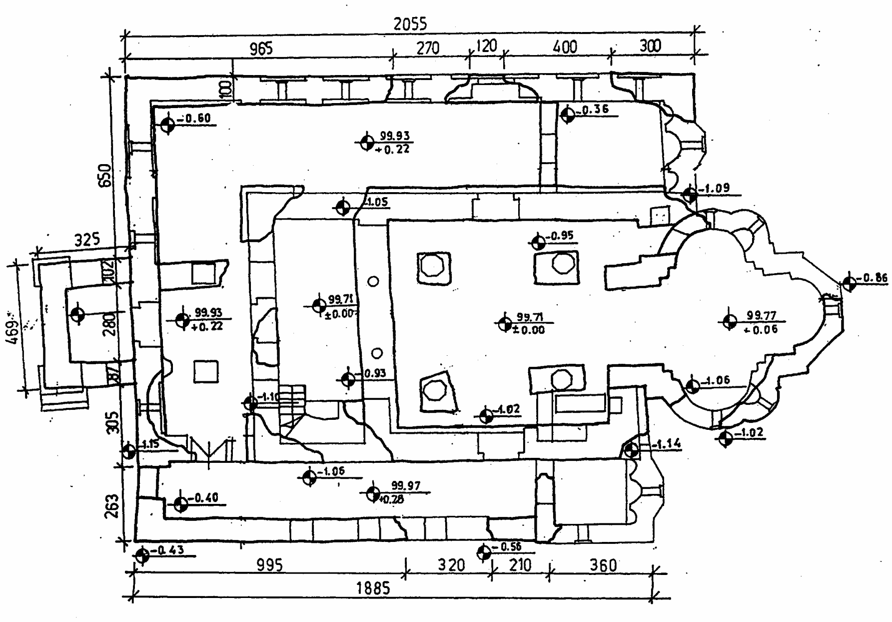

Figure 1. Plan of the existing state of the church of St. Panteleymon

Based on the performed investigations, geotechnical surveys of the site and materials characteristics on the one hand as well as the conservation requirements as to the preservation of the existing elements on the other, the existing system was consolidated by lateral strengthening using RC elements, a finishing belt course of steel ties and masonry and a concrete floor slab, i.e., the newly designed structures started to be constructed at level 0.00m.

The basic design criteria and requirements for the structure were:

- To be built from traditional materials as the original church.
- To meet the criteria for seismic stability and safety under the expected earthquake acceleration of a_{max}=0.36g whereat the total integrity of the structure will be preserved.

Figure 2. Existing state of the church (excavated material - 2001)

3. ANALYSIS OF THE CHURCH

The main structural system of the church consists of massive stone and brick masonry with incorporated steel horizontal and vertical ties. The structure is founded on existing walls for which corresponding consolidation and strengthening was defined.

The structural system of the St. Panteleymon church in the Plaoshnik locality - Ohrid was analyzed in compliance with the present existing national regulations and the proposed European regulations [prEN1998-1: Eurocode 8, 2003]. Two methods were used:

1. Analysis of the bearing and deformability capacity of the structure and its dynamic analysis by consideration of expected actual earthquake effects of maximum intensity of 0.36 g, using the methodology and computer programmes developed at IZIIS, [MAS-ANL3,1998].
2. Static and seismic spectral three-dimensional analysis of the structure by means of the SAP 2000 computer programme, [Wilson and Habibulah, 1998].

3.1. Analysis of Bearing and Deformability Capacity and Dynamics Analysis

The bearing and deformability capacity of the structure are the main initial parameters in defining the behaviour of the structure. The methodology for obtaining the bearing capacity in the form of ultimate shear force (Qu) consists of summing up the elastic-plastic bearing characteristics of each of the bearing walls, where the bearing capacity of each of these is limited to the lower value than that of the bending or shear bearing capacity. This force compared to the equivalent seismic force provides the factor of safety against failure.

In accordance with this procedure and using the computer programme developed at IZIIS – Skopje, [MAS-ANL3, 1998] two variants of the structural system of the church of St. Panteleymon, Plaoshnik – Ohrid were analyzed.

As the first variant, the church structure was tested only with bearing walls in both orthogonal directions,i.e.plain masonry. The total horizontal force at the base of the structure was 30% of the structural weight computed in accordance with the valid regulations for construction of structures in seismic conditions.

The results from the analysis showed that the safety factor at occurrence of the first cracks was less than a unity, (table 3.1), i.e., that the structure did not have sufficient bearing and deformability capacity wherefore it needed strengthening of the principal structural system.

Table 3.1 Bearing and deformability capacity of the structure in longitudinal direction – ***plain masonry***

Storey	**Weight [kN]**	**Qb,code [kN]**	**Qy [kN]**	**Qu [kN]**	**Δy [cm]**	**Δu [cm]**	**Fy**	**Fu**
3	892	611	386	732	0.044	0.19	0.63	1.20
2	5136	3023	1832	2038	0.159	0.18	0.61	0.67
1	12040	5420	3333	4413	0.103	0.16	0.61	0.81

Qy- force at the state of occurrence of the first cracks
Qu- ultimative bearing capacity
Δy- displacement at the state of occurrence of the first cracks
Δu- ultimative displacement
Fy- safety factor at the state of occurrence of the first cracks
Fu- safety factor against failure

Strengthening of the structure was anticipated to be done by incorporation of horizontal and vertical ties. As the second variant, the walls were treated as a confined masonry at three storey levels with included horizontal and vertical ties. The total seismic force at the base was computed in accordance with the valid regulations for construction of structures in seismic conditions and compliant to Eurocode 8. Due to the importance of the structure and the fact that it represents a historic heritage of R. Macedonia, the analysis was carried out by a seismic force of 0.45g.

The results showed that the storey safety factor against failure in both directions is greater than a unity, (tables 3.2 and 3.3), i.e., that the walls had a sufficient bearing and deformability capacity.

Table 3.2 Bearing and deformability capacity of the structure in longitudinal direction– ***confined masonry***

Storey	**Weight [kN]**	**Qb,code [kN]**	**Qy [kN]**	**Qu [kN]**	**Δy [cm]**	**Δu [cm]**	**Fy**	**Fu**
3	892	917	1181	2108	0.13	0.54	1.29	2.30
2	5136	4534	4983	5531	0.43	0.51	1.10	1.22
1	12040	8131	9252	10717	0.28	0.34	1.14	1.32

Table 3.3 Bearing and deformability capacity of the structure in transversal direction– ***confined masonry***

Storey	**Weight [kN]**	**Qb,code [kN]**	**Qy [kN]**	**Qu [kN]**	**Δy [cm]**	**Δu [cm]**	**Fy**	**Fu**
3	892	917	1713	1864	0.22	0.26	1.82	1.98
2	5136	4534	4603	5861	0.49	0.66	1.01	1.29
1	12040	8131	6976	8065	0.41	0.49	0.86	0.99

To obtain the dynamic response of the structure (shear type model), four different types of earthquakes, (El Centro, Parkfild , Ulcinj (Albatros) and Petrovac (Oliva)) with maximum input acceleration of 0.36g have been applied.

The selected results in the form of required displacements versus capacity displacements are given in the figures 3 and 4. The results showed that, under acceleration of 0.36, the structure behaves in the elastic range.

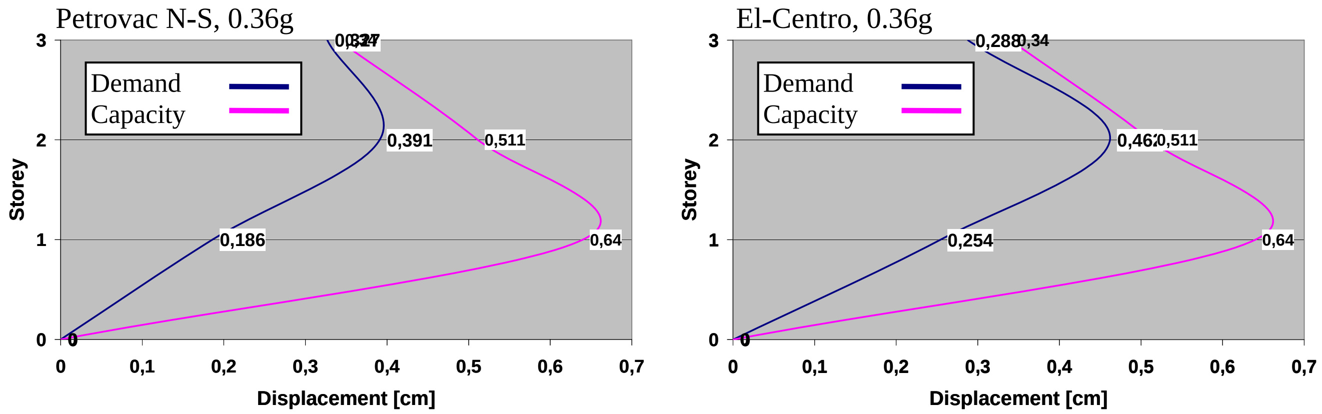

Figure 3. Selected results from dynamic analysis in longitudinal direction

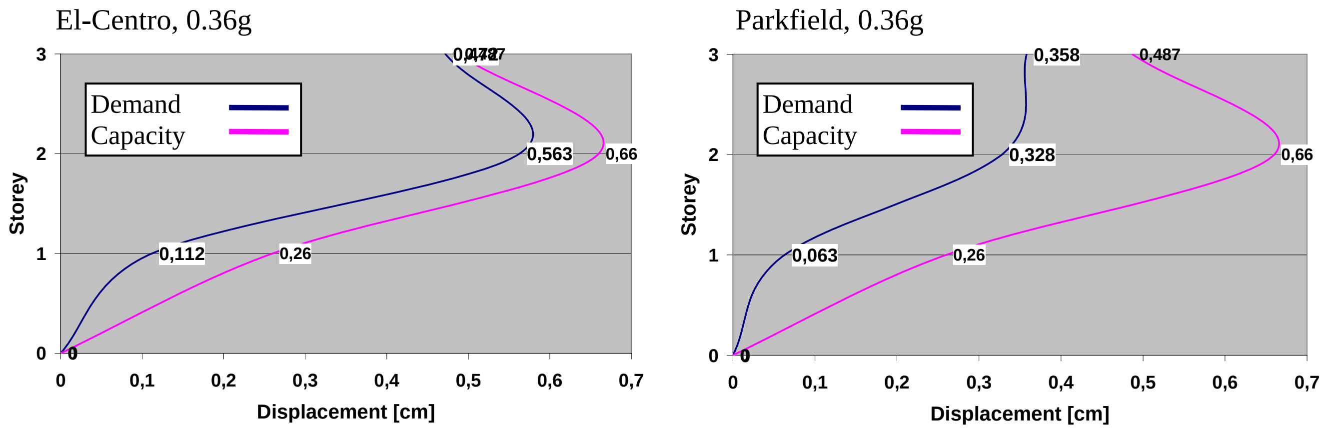

Figure 4. Selected results from dynamic analysis in transversal direction

3.2. Analysis of the Structure by Use of the Finite Element Method

Based on the defined structural system a static and seismic analysis of the structure was carried out by use of the finite element method, applying the SAP 2000 computer software, [Wilson and Habibulah, 1998]. The bearing massive walls of the church was modeled by a three dimensional finite element with eight nodes of the SOLID type, i.e., by a total of 4083 elements. The steel vertical and horizontal ties were modeled by 3D-FRAME i.e, 3D-TRUSS elements, i.e., by a total of 1061 elements. The domes of the church bell tower, the centre and the altar were modeled by 265 SHELL elements, (figure 5).

For such modeled structure, a static analysis has been performed for the effect of the dead weight and equivalent seismic forces computes according to the regulations.

Dynamic analysis of the structure was carried out for a previously defined design acceleration spectra, in compliance with Eurocode 8.

The vertical component of the design acceleration was taken as 2/3 of the horizontal component. The following was obtained as a result of the 3D analysis of the church structure by use of the SAP2000 computer programme:

- forces in the horizontal and vertical steel ties due to vertical loads and seismic loads represented through a design acceleration spectrum;
- stresses and deformability states in the SOLID elements, by which the structural elements- walls were modeled, under vertical loads and design acceleration spectra,(figure 6).
- stresses and deformability states in the SHELL elements (by which arches and domes were modeled) under vertical loads and design acceleration spectra, (figure 6).

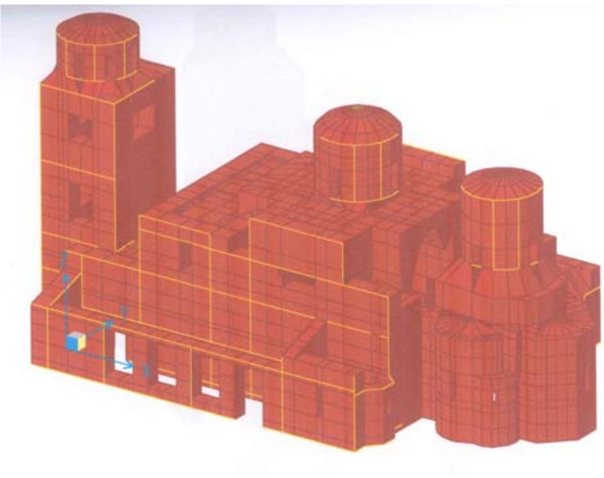

Figure 5. 3D- view of the model of the structure

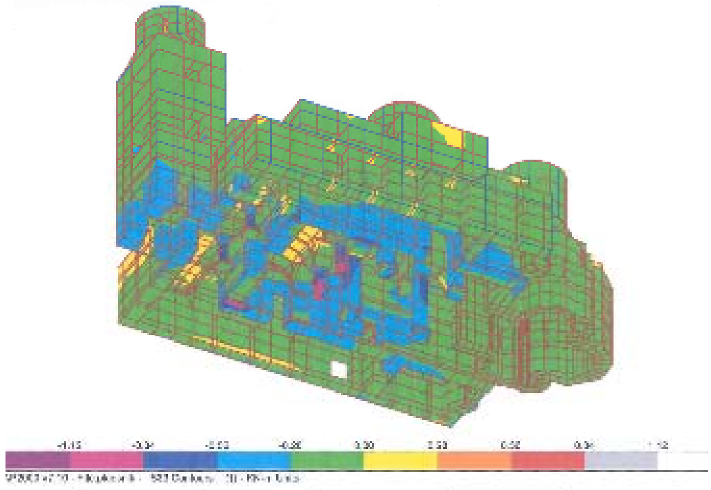

Figure 6. Distribution of stresses due to vertical load

4. ADOPTED STRUCTURAL SYSTEM

Based on the performed ample analyses, the structural system of the church, the proportions of the horizontal and the vertical steel ties were defined and a solution for the foundation of the structure was elaborated.

4.1. Structural System

The principal structural system of the church consists of massive masonry, stone and brick with incorporated steel horizontal and vertical ties. The steel ties are manufactured of stiff steel tube-like, square profiles externally protected against corrosion by epoxide resins and quartzite sand and filled with cement mortar inside. The ties of the external walls are proportioned 50.50.3, while those of the inner walls are proportioned 60.60.4. The placement and the distance among steel ties can be seen on the plan of the structure, (fig. 7). It should particularly be pointed out that insertion of steel ties in masonry is necessary from the aspect of seismic stability, i.e., enabling its ductility. From conservation aspects, the same elements are present in the old architecture but are replaced by new materials - steel. Their simultaneous behaviour with the behaviour of masonry was additionally explored and represents a new methodology in the monumental architecture and construction.

Special attention was paid to the stability of the vaults and incorporation of the steel ties for bearing tension forces, as well as for preservation of the integrity of the structure.

- Stone and brick masonry was constructed using lime mortar of selected characteristics defined through static and dynamic analysis.
- The existing walls below the level of the floors were systematically injected with a cement emulsion. The injection of the walls over the floor level that contain remains of fresco-paintings was done by use of emulsions that are not based on cement.
- During the injection of the foundation walls, the problem of elimination of humidity was solved.

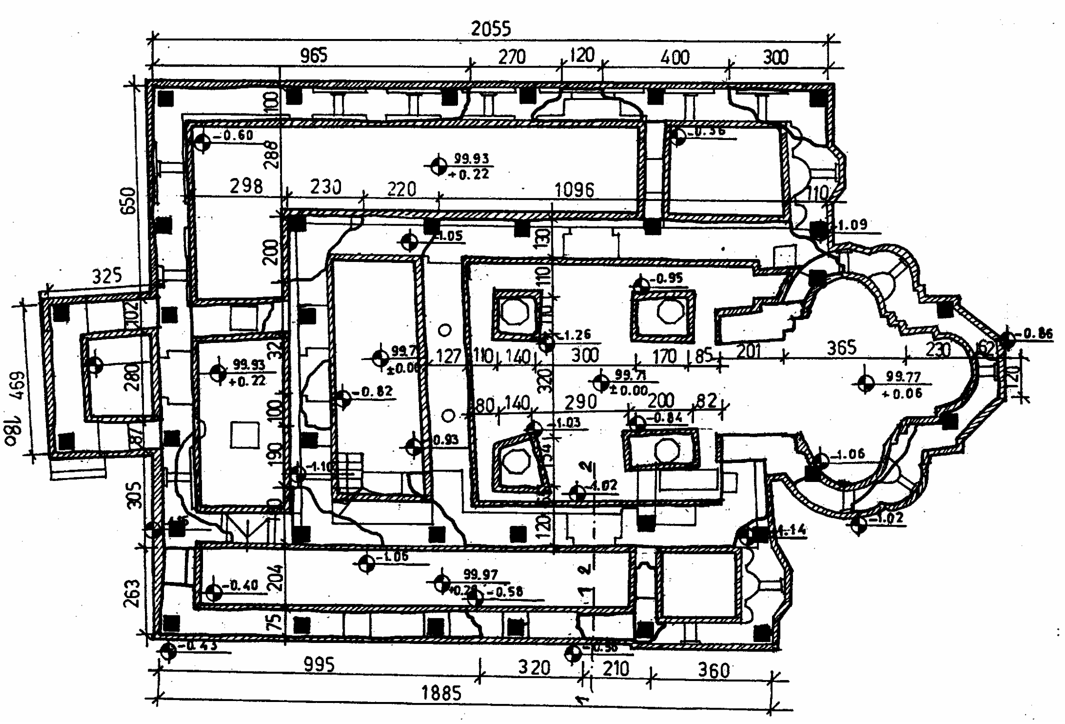

Figure 7. Plan of the structure at the level +0.22m

4.2. Technical Description of the Rebuild Foundation Structure

The strengthening and the consolidation of the existing foundation walls down to level 0.00 (to the slab) consisted of the following: beside the existing walls, from the inner and the outer side, a reinforced concrete belt course is formed. It is pulled under the existing wall within a length of ≈ 50 cm and, at height, it runs along the existing wall with a thickness of 20 cm towards the floor slab. The reinforced concrete belt course is appropriately reinforced and connected to the reinforced concrete slab with a thickness of 20 cm. The characteristic detail of reinforcement of the existing foundation is given in Figure 8.

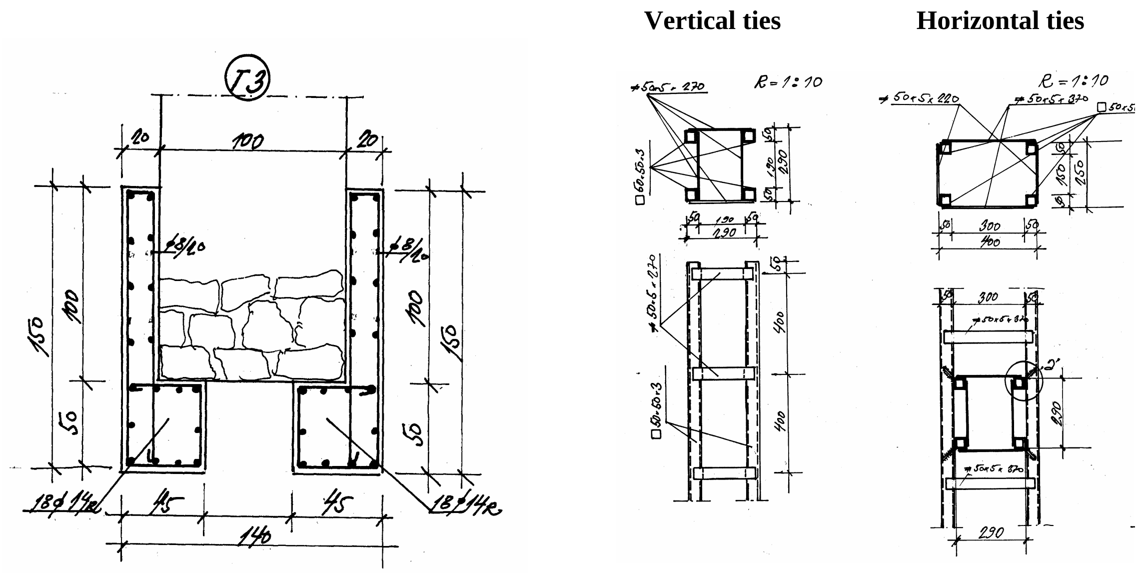

Figure 8. Detail of the foundation and of the horizontal and vertical steel ties

The slab below the floor is made of reinforced concrete with additives to make it watertight. As to the mortar, the injection masses, the insulation and the protection against corrosion, a project was elaborated by A.D. "ADING" - Skopje.

The rebuilding of the church of St. Panteleymon was finished in 2002, (fig. 9).

Figure 9. Present view of the rebuild church of St. Panteleymon

5. CONCLUSION

The structural system of "St. Panteleymon" church in Plaoshnik - Ohrid consisting of bearing walls strengthened by horizontal and vertical ties has a sufficient bearing and deformability capacity. During the expected design earthquake level, the structure is expected to behave elastically, while the maximum expected earthquake is anticipated to induce cracks in the nonstructural elements of the structure. It is generally concluded that the structure satisfies all the prescribed requirements and criteria for design of such type of structures, also satisfying, at the same time, the conservation aspects and requirements pertaining to construction heritage.

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