QUASI-STATIC TESTS ON WALL ELEMENTS CONSTRUCTED DURING THE RECONSTRUCTION OF ST. ATHANASIUS CHURCH IN LESHOK

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ABSTRACT :

The church of St. Athanasius is situated within the monastic complex of the Holy Virgin in the village of Leshok - Tetovo area. On August 21, 2001, during the armed conflicts in R. Macedonia, this monastic church experienced strong detonation which resulted in its almost complete demolition: a greater part of the church was torn down, while the still existing part was characterized by severe damage. The Main Project on the Reconstruction of the Monastic Church of St. Athanasius has been realized by the Institute of Earthquake Engineering and Engineering Seismology, IZIIS in collaboration with the Republic Institute for Protection of Cultural Monuments and has been financed by the European Agency for Reconstruction. To verify experimentally the design strength characteristics of lime mortar, used as a basis for the elaboration of the structural solution for reconstruction of the church, quasi-static tests on wall elements were carried out in the Dynamic Testing Laboratory of IZIIS in accordance with the previously adopted testing programme and scheme and the corresponding age of the wall elements. The wall elements were constructed in the same way as the original bearing walls of the St. Athanasius church. The paper presents the objective, the procedure and the results from these experimental quasi-static tests.

KEYWORDS: Quasi-static testing, masonry wall elements, lime mortar

1. INTRODUCTION

The church of St. Athanasius in the village of Leshok was formerly part of the complex of the Holy Virgin – Tetovo area which as such was put under the protection of the Law on Protection of Cultural Monuments of Republic of Macedonia, (fig.1).

Figure 1 Monastic complex of the Holy Virgin, Leshok

It was built in the thirties of the 20th century and in the structural sense, it represented a three-conched structure with an elongated narthex on the west side that housed the belfries. The dome and the tambour rested on the massive circular from the inside and polygonal from the outside apses – conches via a system of spherical triangles – pendentives. The tambour was octagonal from the outside and circular from the inside.

On 21.08.2001, in the course of the armed conflicts of 2001, this monastic church was almost ruined to the ground by a strong detonation. The vaulted structure surmounting the gallery was destroyed, while only the timber beams of the floor structure remained with visible deformation of the wood. In the part of the two preserved belfries, there were visible large cracks with a width greater than 2 cm along the height of the bearing walls, in the staircase area, the walls of the tambours and the domes, (fig.2).

Figure 2 St. Athanasius church after detonation

2. RECONSTRUCTION OF ST. ATHANASIUS CHURCH

In July 2003, the reconstruction of the church of St. Athanasius in Leshok began by joint efforts of the European Agency for Reconstruction, the Ministry for Culture of Republic of Macedonia and the Republic Institute for Protection of Cultural Monuments based on the project for reconstruction, repair and strengthening of this church elaborated by the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje (1). Based on all the previous investigations and knowledge gained, the following concept was adopted within the frames of the project for reconstruction, repair and strengthening of the church, (Figs.3, 4):

1. For the damaged existing part of the structure, a concept involving repair and structural strengthening up to the necessary level of seismic safety was adopted because of the objective and justified (architectonic conservatory) complete preservation of this part;
2. For the torn down part of the structure, a concept involving complete reconstruction based on prepared architectonic documentation was adopted including maximum possible use of the selected material (limestone, sandstone, bricks) and lime mortar with designed compressive strength of 1.0 MPa, whereat elements for structural strengthening were anticipated from structural aspect for the purpose of providing the necessary level of seismic safety.
3. Due to the different treatment of these two structural units composing the integral structure, an expansion joint was also anticipated with the project.

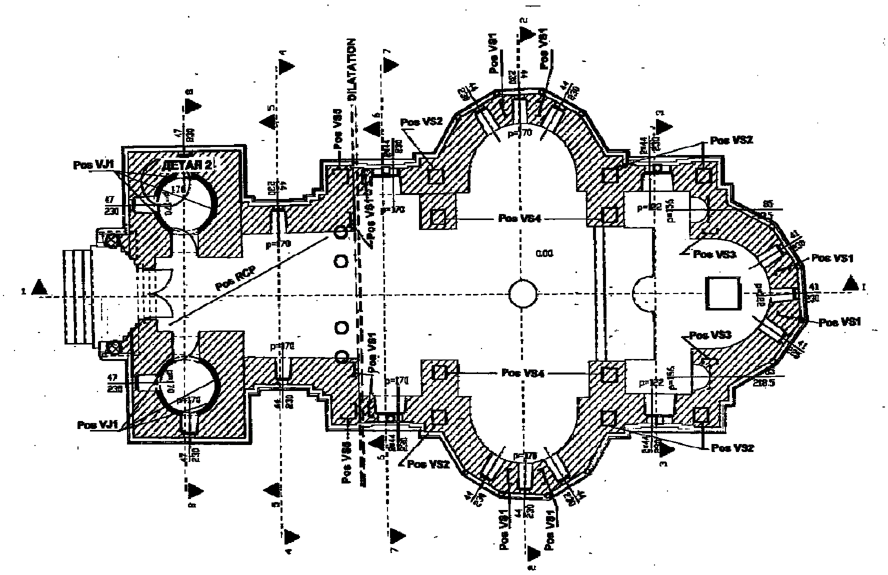


Figure 3 Plan of reconstructed, repaired and strengthened church

Figure 4 St. Athanasius church after reconstruction

The analyses used as a basis for the elaboration of the structural solution of reconstruction of the church were carried out with designed compressive strength of lime mortar of 1.0 MPa and all the remaining characteristics pertaining to that class of mortar in accordance with the Regulations on Technical Norms for Masonry Wall.

In order to achieve the design class of lime mortar, the job mix formula for lime mortar was used in carrying out the reconstruction of the church of St. Athanasius. According to this formula, in addition to the slaked lime and sand with a certain grain size distribution, broken half-baked brick was used as an additive in the corresponding proportion (M: 1:1:1) to achieve the strength characteristics faster. To define the mechanical characteristics of masonry, the bearing capacity and the failure mechanisms, quasi-static tests on the wall elements were necessary to be carried out in addition to the static ones. The advantage of these tests is the possibility of detailed monitoring of certain phenomena, while the only drawback is the absence of dynamic effects.

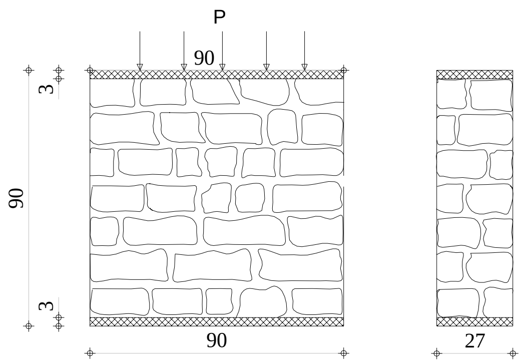
The main objective of the experimental quasi-static tests on the wall elements, which were the subject of these investigations was, in fact, experimental verification of the design strength characteristics of the lime mortar, i.e., checking and confirming the achieved compressive strength of the used lime mortar considering its different age, i.e., defining the ultimate bearing capacity of such constructed walls. For that purpose, in the period October – December 2004 when the first phases of the reconstruction of the church took place, 9 wall elements were constructed in the same way as the bearing walls and under the same weather conditions and were transported to the IZIIS' Dynamic Testing Laboratory.

3. EXPERIMENTAL QUASI-STATIC TESTS ON WALL ELEMENTS W1, W2, W3

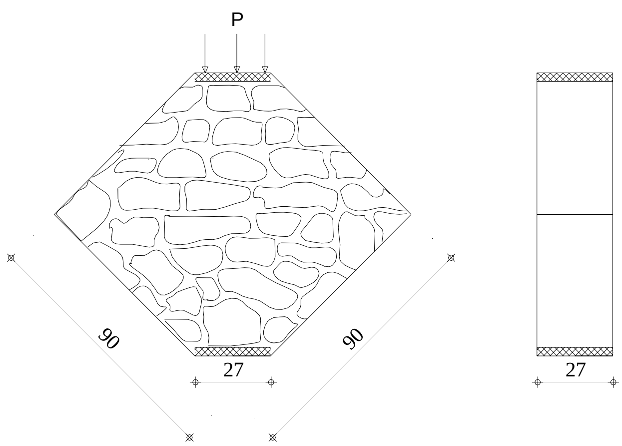
3.1. Characteristics of Wall Elements

All the wall elements are proportioned 90 cm x 90 cm x 27 cm (Fig. 5). In accordance with the adopted programme and scheme of testing, these were classified into three groups as follows:

- 3 wall elements of the W1 type tested under axial pressure by cyclic application of axial force of up to max. 400 kN, cured three months;
- 3 wall elements of W2 type tested under diagonal compression by cyclic application of force of up to 100 kN, cured three months;
- 3 wall element of the W3 type tested under diagonal compression by cyclic application of force of up to max 100kN, cured six months.



Wall element W1



Wall element W2 and W3

Figure 5 Wall elements of the type W1, W2 and W3

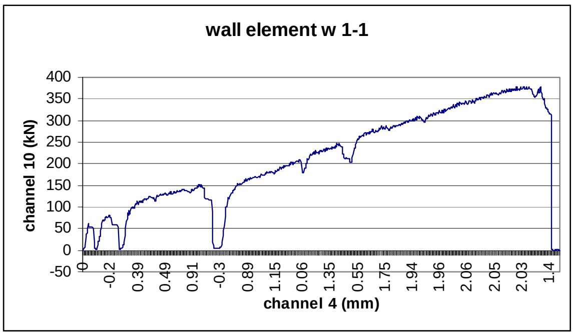
3.2. Instrumentation of Wall Elements

The instrumentation of the wall elements was done by use of corresponding types of instruments in accordance with the programme and the objectives of the tests. The behaviour of the wall was monitored throughout the tests via (in this case) the 10-channel data acquisition system of which 5 channels were used to measure displacements (LVDT-s), 4 channels were used to measure strains (SG) and one channel was used to measure the size of the applied force. In that way, an information on the behaviour of the elements was obtained through the relative displacements at characteristic points as were also the deformations of the wall mass, i.e., experimental values of strength characteristics were obtained. The subsequent chapters show the individual instrumentation schemes for each of the tested wall elements.

3.3. Quasi-static Tests on Elements under Axial Pressure

A total of three elements were tested under axial pressure by cyclic application of axial force of up to 400 kN (W1-1, W1-2, W1-3). With the instrumentation of the elements, in addition to the total force, the total displacement of the actuator in the direction of application of force and other quantities of concern as was the shortening of the element, (channels 1-4), the deformations of the element width (channel 5), the opening of cracks in the face of the wall element (channels 6, 7 and 9) and the lateral deformation – the swelling of the element (channel 8) were recorded. The difference between testing of W 1-1 and the remaining W 1-2 and W 1-3 consisted in different application of axial pressure. The first element was subjected to cyclic loading and unloading, while the second and the third were subjected to monotonous increase of the force amplitude up to total failure of the elements. The characteristic failure mechanisms and force-displacement diagrams were obtained for all the tested channels, (fig.6).

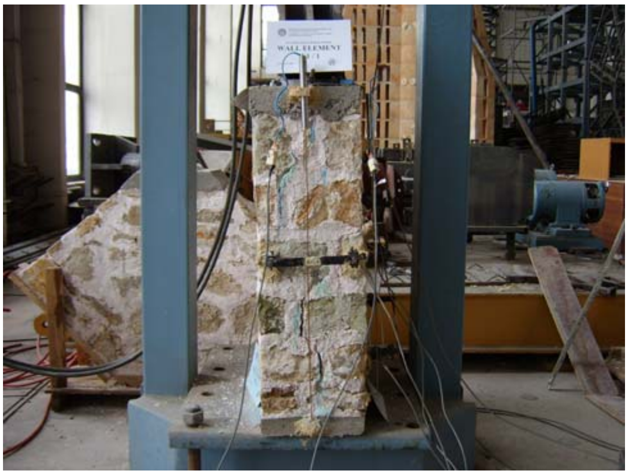
Disposition of the element W1-1



Force-displacement relationship

Figure 6 Testing of wall element W1-1

The characteristic of all the wall elements exposed to axial load was the occurrence of a crack along the middle of the wall thickness which ended with falling off material and complete separation of both wall faces, (fig.7). In the three tested elements, the first crack occurred under vertical stress of σ_o = 370 – 440 kPa. More important results from these tests are presented in Table 3.1.



Wall element W1-1

Wall element W1-2

Figure 7 Characteristic failure mechanism

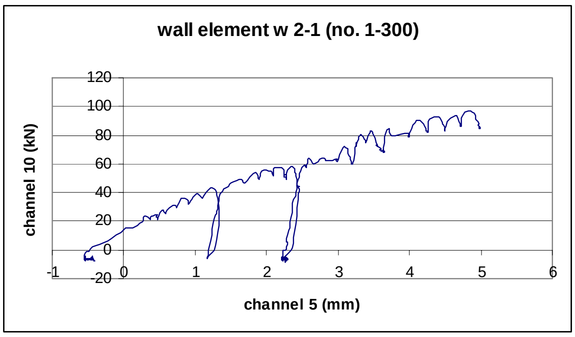
Table 3.1 More important results from tests of elements pertaining to type W1

Wall element	Date of testing	Age of element (months)	Cross-section A (m^2)	Maximal force P_{max} (kN)	Compressive strength $\sigma_c = P_{max}/A$ (kPa)
W1-1	28.03.2005	4	0.243	372	1530
W1-2	31.03.2005	4	0.243	355	1460
W1-3	1.04.2005	4	0.243	292	1200

3.4. Quasi-static Tests on Elements Under Diagonal Pressure

A total of 4 elements were tested under diagonal pressure by cyclic application of force of up to max 100 kN as follows: two elements of type W2 (W2-1, W2-2) and two elements of type W3 (W3-1, W3-2). Wall elements W2-3 and W3-3 could not be tested since cracks and even failure of the wall mass were observed during their curing which would have caused obtaining of invalid results from the testing of such elements.

Disposition of the element W2-1



Force-displacement relationship

Figure 8 Testing of wall element W2-1

With the instrumentation of the elements, in addition to the total force, the total displacement of the actuator in the direction of application of the force as well as other quantities of interest as were the shortening, i.e., the elongation of both diagonals of the element, respectively and opening of cracks at places where these are expected were recorded, (fig.8).

During the experimental testing of these elements, the force was applied monotonously under an angle of 45° in respect to the longitudinal joints of the wall until its failure. Development of diagonal cracks and shortening (elongation) of the diagonals was very characteristic, (fig. 9). A more important result from these tests was, in fact, the obtaining of the tensile strength of mortar (Table 3.2) which was computed on the basis of the maximum applied force that tears down the element by using the following expressions:

- compressive and shear stresses - $\sigma_0 = \tau_u = P_{max} \cos 45^o / A$
- tensile strength - $f_t = - \sigma_0/2 + (\sigma_o^2/4 + \tau_u^2)^{0.5}$

Wall element W2-1 Wall element W2-2

Figure 9 Characteristic failure mechanism

Table 3.2 More important results from tests of elements pertaining to type W2 and W3

Wall element	Date of testing	Age of element (months)	Cross-section A (m^2)	Maximal force P_{max} (kN)	Tensile strength f_t (kPa)
W2-1	07.04.2005	~ 4	0.344	98	127
W2-2	08.04.2005	~ 4	0.344	31	40
W3-1	26.05.2005	~ 6	0.344	92	120
W3-2	28.05.2005	~ 6	0.344	52	68

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the performed and presented experimental quasi-static tests on wall elements performed in the same way as the bearing walls of the church of St. Athanasius in Leshok during its reconstruction, the following is concluded:

1. The agreed programme of quasi-static tests has thoroughly been realized and the necessary results have been obtained.
2. The experimentally obtained results on the compressive strength f_c of the built-in lime mortar prepared according to a special job mix formula range within 1.20 MPa to 1.53 MPa (Table 3.1) with which it can be confirmed that the design compressive strength of 1.0 MPa has been achieved by its considerable

increase.

3. The experimentally obtained values of tensile strength f_t of the built-in lime mortar prepared by a special job mix formula ranges within 0.04 MPa to 0.127 MPa (Table 3.2) which is in compliance with the regulations and the recommendations on the tensile strength/compressive strength ratio of masonry, i.e., $f_t = (0.03 – 0.08) f_c$.
4. The results obtained point out that the values of the characteristics of the lime mortar given in the technical regulations on masonry walls are within the lower initial limit of the bearing capacity range. It can be considered that the ultimate strength of bearing capacity of the walls constructed in lime mortar with the anticipated masonry structure and mortar is considerably greater. While defining the seismic stability under a probabilistic earthquake, special importance will be given to the age of the bearing structure. To draw a conclusion, i.e., confirm this assertion, it is necessary to perform many-faceted and a great number of tests on wall elements constructed of ordinary masonry in lime mortar and thus provide material for the preparation of the new national regulations in the process of adaptation and acceptance of the European Standards.

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