BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LXI (LXV), Fasc. 1, 2015
Secția
CONSTRUCȚII. ARHITECTURĂ

STRUCTURAL AND DAMAGE ASSESSMENT OF AN HISTORICAL MASONRY CHURCH

BY

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Received: March 3, 2015
Accepted for publication: March 17, 2015

Abstract. *In situ* investigations and numerical analysis are being increasingly used in the non-destructive evaluation of masonry historical churches taking into considerations that the diagnostic analysis of ancient buildings supposes important challenges from the point of view of its evaluation under field conditions. This paper describes on a study case, the application of non-destructive testing techniques and numerical application with finite element method, in order to asses the structural and damage state of a typical orthodox church. The results of the study reveals that this investigation tools can be used for providing valuable information regarding the evaluation of the current state of the cultural heritage buildings. Moreover, this knowledge of great significance that can be used in the intervention process, resulted with a minimal effect on the structural component analyzed.

Key words: historical masonry church; *in situ* investigations; structural analysis throught FEM.

1. Introduction

The Church St. George from Harlau was built in 1492, in less than five mounths by Stephen the Great, with a cross shape plan, lateral polygonal apses

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and a tower above the nave. The monument has the following dimensions: 21.50 m – interior length, 24.20 m – exterior length, 8.40 m – width (12.00 m at the apses) and 21.50 m the maximum height of the tower dome.

According to the specific architectural conception of orthodox churches, the structure consists of a well established sequence: narthex, nave and altar.

The church walls are made of stone with lime mortar masonry and the roof (composed of arches, vaults and the tower) is made of brick masonry. The longitudinal walls of the church are, in general, 1.25 m thick and smaller (1.0 m at the apses). The transversal walls of the narthex are 1.38 m and 1.10 m thick. Four buttresses, with in plane dimensions of 0.80 × 1.20 m, are placed at the exterior of the church at the right position to take the thrusts of the transversal arches.

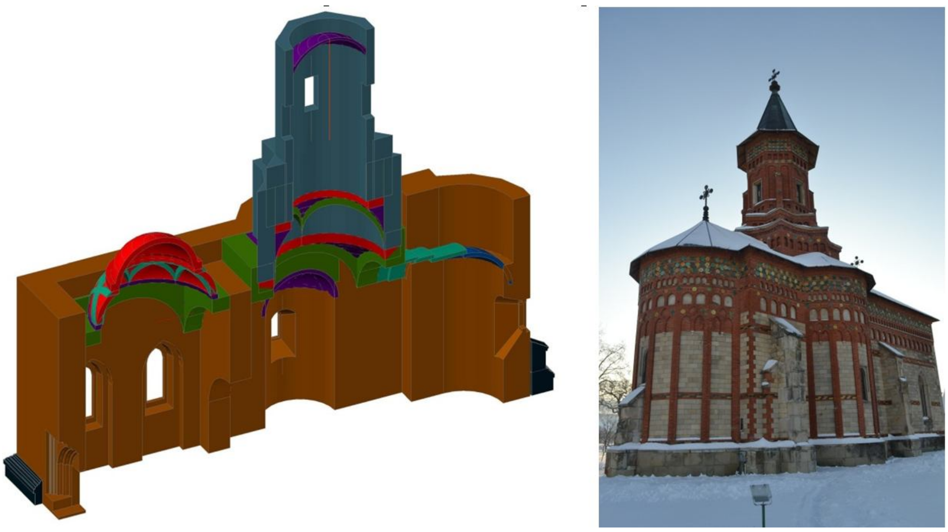


Fig.1 – Sf. Gheorghe Church.

2. *In Situ* Investigations

Non-destructive testing may be useful in identifying defects in the interior of the masonry and in the characterization of structural elements.

Although non-destructive evaluation techniques on cult monuments are relatively advanced, they can be difficult to apply due to several factors: different types of masonry materials, high heterogeneity of the constituent materials, interpretation and harmonize the results from different techniques. Moreover, most non-destructive techniques from different or adjacent research fields require application in a complementary nature and specific calibration. The expert must be able to interpret the results of all applied techniques and use them at least in comparison between different parts of the structural elements of the monument (Soveja & Gosav, 2014).

2.1. Moisture Detection

Moisture detection in the walls structure was performed with the portable hygrometer, type LT MS-7003, based on resistance principle and measurement capability between 0,…,100%. By perforating the masonry surface with metal pins, the machine allows the evaluation of moisture in any point on the examined masonry surface.

After visual investigation of the walls affected by humidity, as a study area, the interior of the north longitudinal wall was chosen. The examined surface was divided by a grid so that the measuremenets are carried out in points at approximately equal distances of 1.0 m, at four diferent heights (+0.25 m, +0.75m, +1.25 m, +1.75 m).

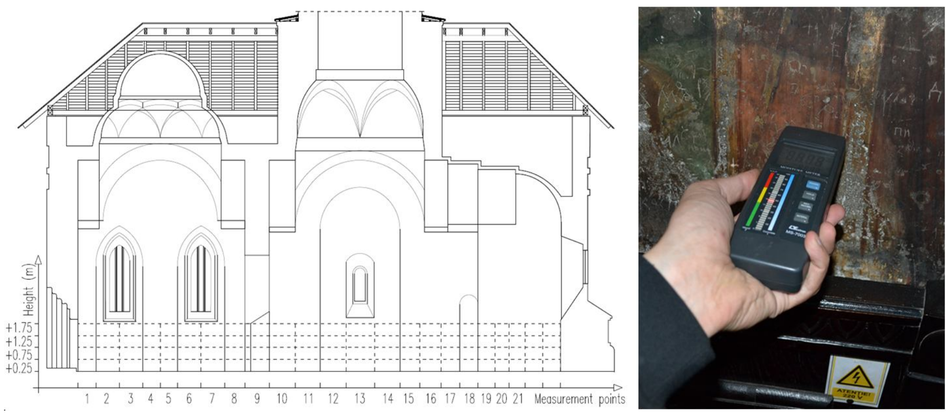


Fig. 2 – The division of the study area with a grid and humidity measurements.

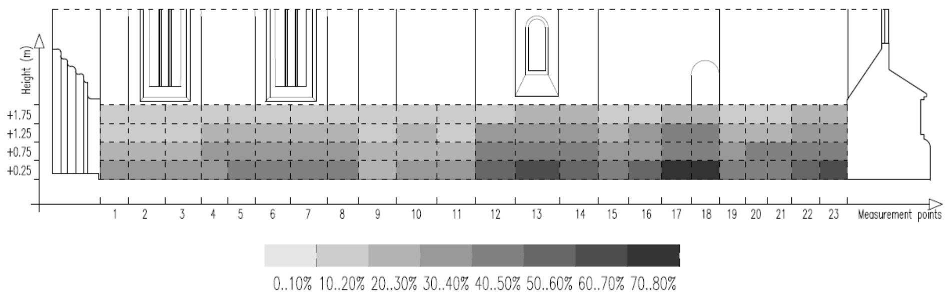


Fig. 3 – Humidity cromatic map at the interior of the northen longitudinal wall.

For an easy visual identification of the humidity level, on the grid initial establish, a cromatic map corresponding with the humidity values is plotted in Fig. 3. Also, the variation of the humidity at the test points, different for each height indicated, where plotted in a graph of the longitudinal moisture profile (Fig. 4).

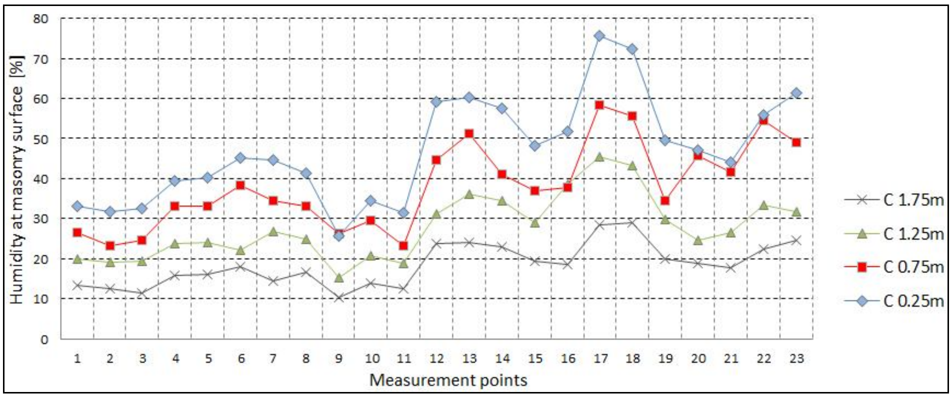


Fig. 4 – Longitudinal moisture profile at four indicated heights.

The conclusions obtained from data interpretation are as following:

a) the highest values of mouisture at the masonry surface was identified at the altar niche, where the wather needed at specific rituals was not carefully drained; the accentuation of the moisture values had been read at all four heights;

b) high values were revealed in the walls of the nave and altar apse, wich increased with the curvature of the apse, probably due to greater exposure to weathering action;

c) the lowest humidity values have been reported at the intersection with the transversal wall (10.3% at the measuring point 9);

d) in the current areas of the longitudinal walls, the average humidity values where mediated at 39.5% at +0.25 m height decreasing to 17.5% at 1.75 m height;

e) the maximum values of moisture, of 76.8% were recorded at +0.25 m height near the altar veil.

2.2. Infrared Thermography

In investigation of these types of structures, where the restoration and conservation solutions can cause irreversible degradation to the building integrity, infrared thermography is a useful tool. Masonry, and especially historic masonry, has a very inhomogeneous structure, containing several different materials (brick, stone, mortar, plaster, wood, metal, etc.) with different thermal properties. Thus, thermography is, in general, well-suited for the detection of plaster and tile delaminations, for the investigation of cracks, for the location of detached parts behind the plaster, for the characterization of the masonry structure behind plaster, for the location of empty joints, and for the detection of excessive moisture (Soveja & Gosav, 2014; Plesu *et al.*, 2012; Binda *et al.*, 2011).

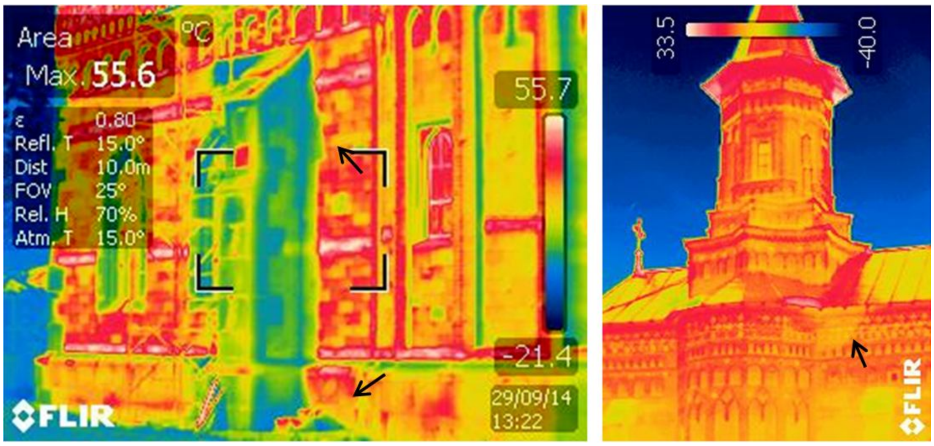


Fig. 5 – Infrared thermography at the north wall of the nave.

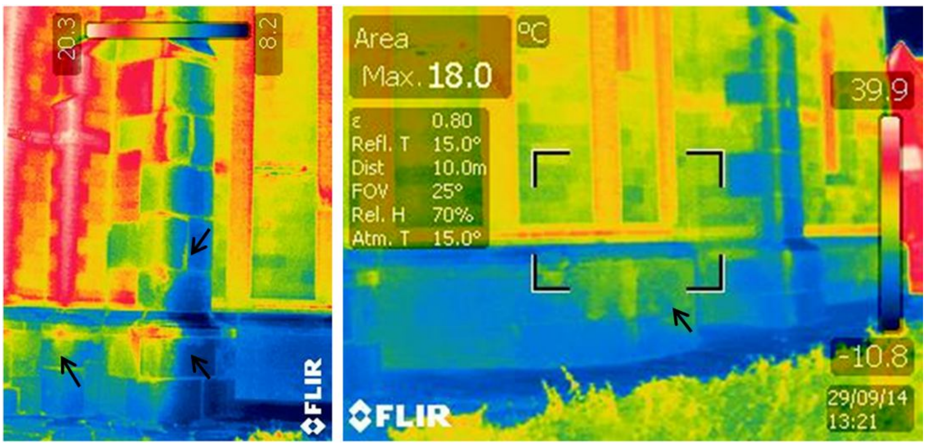


Fig. 6 – Infrared thermography at the base of the longitudinal north wall.

The tests were carried out with the FLIR B250 infrared camera with thermal sensitivity 70 mK for 30°C, with the spectral range 7.5,…,13 μm and image frequency between 9 and 30 Hz. The accuracy of measurement is ±2°C for a measurement field between –20°C and +120°C. These were useful in revealing the structural system by identifying areas built in different periods with different materials, rebuilt areas and damage investigation (cracks, moisture deterioration, etc.).

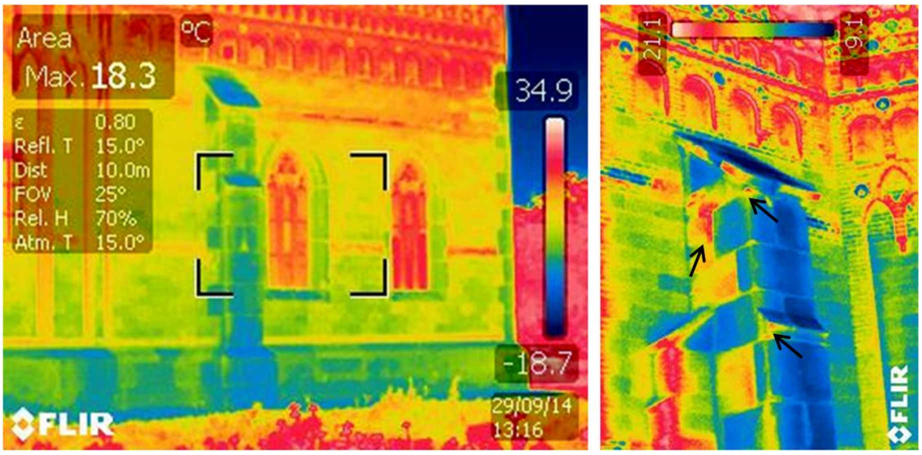


Fig. 7 – Infrared thermography at the south wall of the narthex.

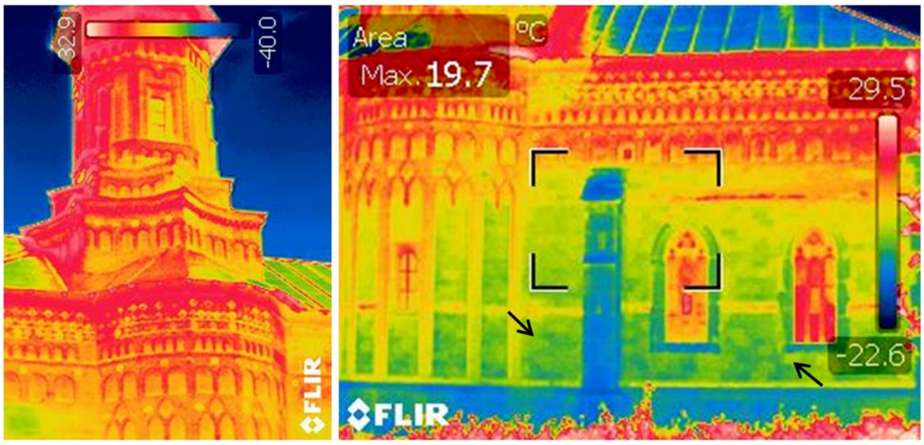


Fig. 8 – Infrared thermography at the tower and north wall.

Analyzing the thermographic maps it can be observed that the changing of the colour proportional with the drop of the surface temperature indicates the presense of high umidity in the masonry walls. Areas where this pfenomenon is generally visible were identified at the base of the walls (Fig. 7), at the altar niche (Fig. 6) and at the narthex (Fig. 8). This was also confirmed by measurements with a portable hygrometer.

The capillary rise of water on the height of the walls, untill the upper part of the nave windows, can be observed on the thermographic map plotted in

Fig. 8. At the intersection between the longitudinal north wall and the nave buttress, the variation of the surface temperature could indicate a vertical crack (Fig. 5).

Areas with damaged masonry were identified at the upper part of the north apse (Fig. 5), at the base of the north altar buttress (Fig. 6) and at the south nave buttress (Fig. 7).

2.3. Crack Survey and the Spatial Damage Mechanism

The structure of “Sf. Gheorghe” Church in Hârlău is affected in longitudinal direction by a fracture, which, at the towers level, follows the boundary of their plan. This fracture is accompanied by vertical cracks in the wall between the narthex and nave, in the transversal arcs and in the altar apse (Fig. 9). In transversal direction, from all the windows parapets and arcs, vertical fractures in walls and in the domes pendants have been observed (Soveja & Budescu, 2014).

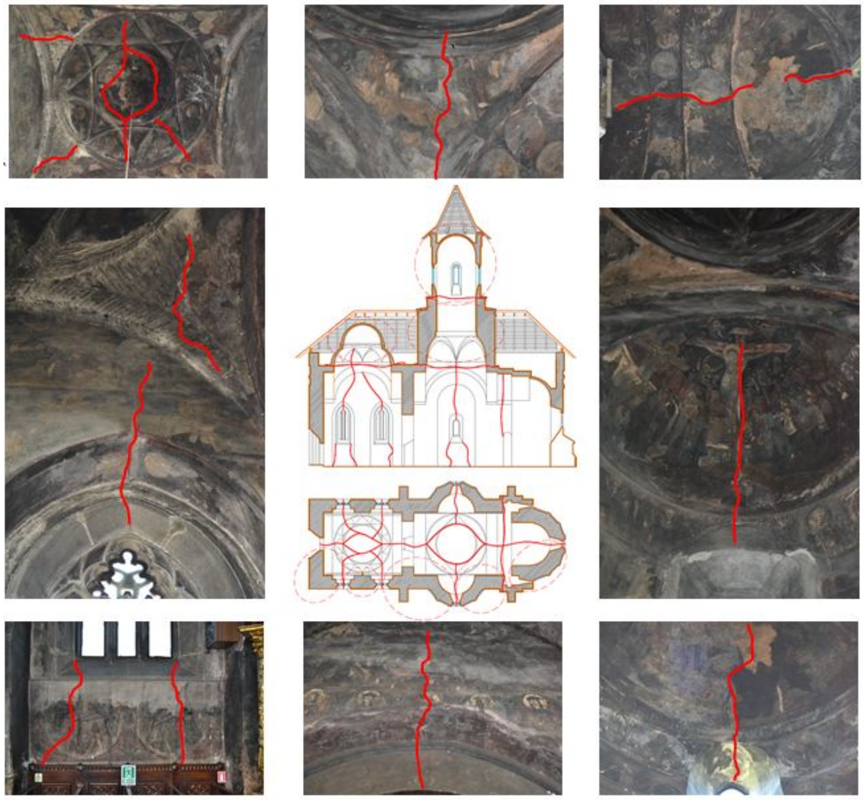


Fig. 9 – Damage mechanism for “Sf. Gheorghe” Church based on in situ investigations (Soveja & Budescu, 2014).

Two main processes were highlited: a longitudinal fracture that separates the main body in two symmetrical halves and transversal fractures systematically arranged in vulnerable areas.

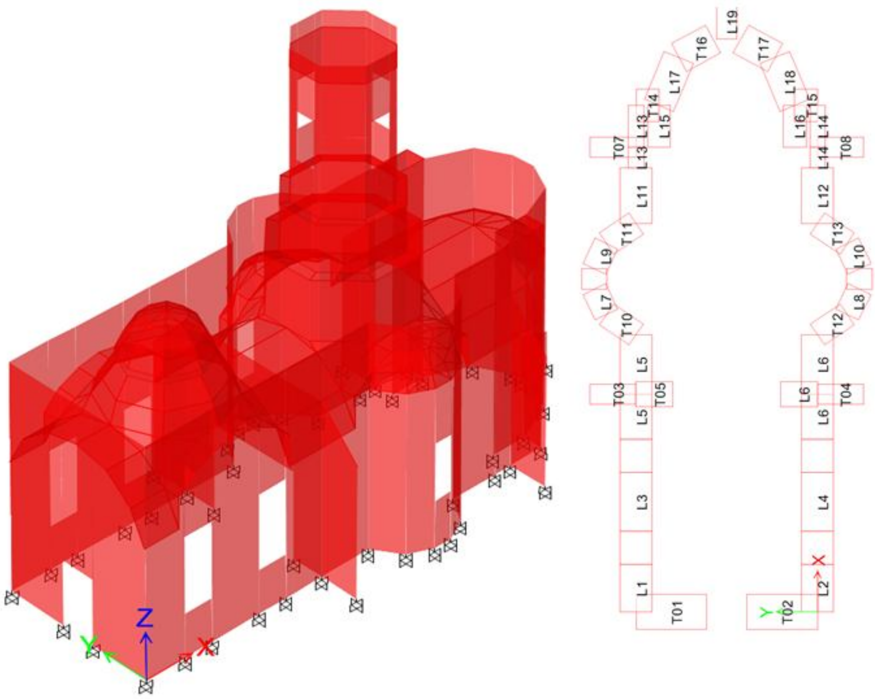
These two types of processes, graphically exemplified in Fig. 9, lead to the separation of the church structure into 13 independent quasi-rigid blocks, each being in its own static equilibrium.

The number of the separation blocks reflects the vulnerability of the church structures.

3. Structural Investigations with Numerical Analysis

In general, unreinforced masonry structures are characterized by complexe structural system because of the architectural forms which correspond to the structure and the massive walls bonded with arches and vaults.

The structural safety evaluation, especial to seismic action, is made by the identification of the areas with stress concentration. Thus a realistic modelling of the structural system is required.



a *b*

Fig. 10 – *a* – Three dimensional model using shell elements and *b* – walls numbering in linear static analysis.

The model used to simulate the church structural behavior was built in Etabs program using 11,400 shell elements with the maximum dimension of 500 mm (Fig. 10 *a*).

In Etabs program, a shell is a three or four-node area object used to model membrane and plate-bending behavior. Shell objects are useful for simulating floor, wall, 3-D curved surfaces and components within structural members.

3.1. Modal Analysis

In case of an orthodox church structure, for an extended comprehension of the vulnerability, special attention should be paid to its towers, considering their number and structural sensibilities.

Each tower can be analyzed according to its cross-sectional shape, number of sides, embrasure area percentage, changes in the thickness of the walls, height (which determines the points of application of the seismic forces) and weight (the main factor in the evaluation of the overturning moments).

In most of the common cases, the general vulnerability of an old church increases significantly with the number of towers and their structural deficiencies (Crişan, 2010).

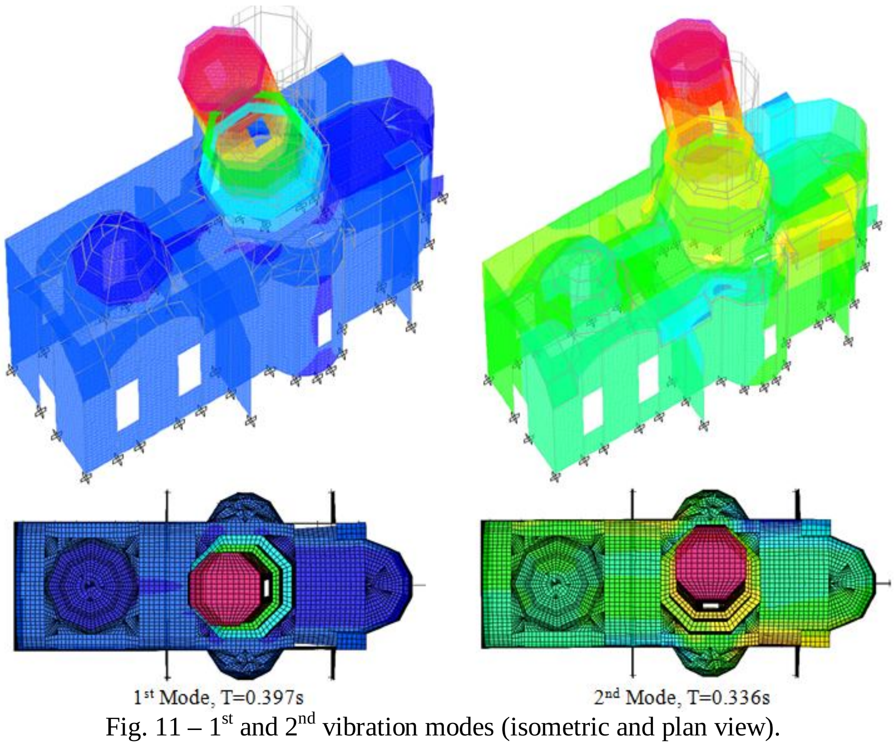


Fig. 11 – 1st and 2nd vibration modes (isometric and plan view).

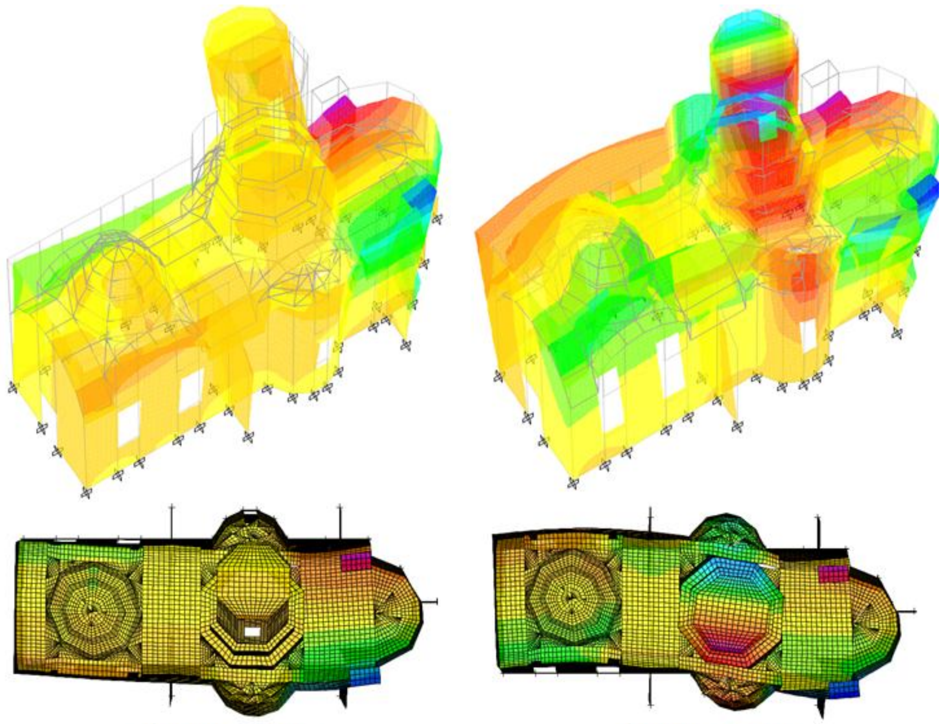


Fig. 12 – 3rd and 4th vibration modes (isometric and plan view).

Analysing the structural behavior of the church towers in case of response oscillations during seismic actions (Figs. 11 and 12), it results that this appendix tends to produce distortions of the response parameters due to high dynamic amplifications. Under this circumstances, the church towers are prone to severe damages and even collapse.

3.2. Linear Static Analysis

Before performing linear static analysis, in order to analyze and compare the shear strength and shear demand in each wall, the macroelements were identified and labeled with letter L for longitudinal walls and with letter *T* for transversal walls (Fig. 10 *b*).

Comparing the shear strength with the shear force demand for each wall due to seismic action, in both longitudinal and transversal direction, it can be observed in Figs.12 and 13 that the most vulnerable points of the structure in case of seismic action are: the longitudinal walls of the nave apses (*L*7,...,*L*10), the transversal walls (with niches) of the altar (*T*14, *T*15), the narthex butresess (*T*3, *T*4) and the altar apse walls (*T*16, *T*17).

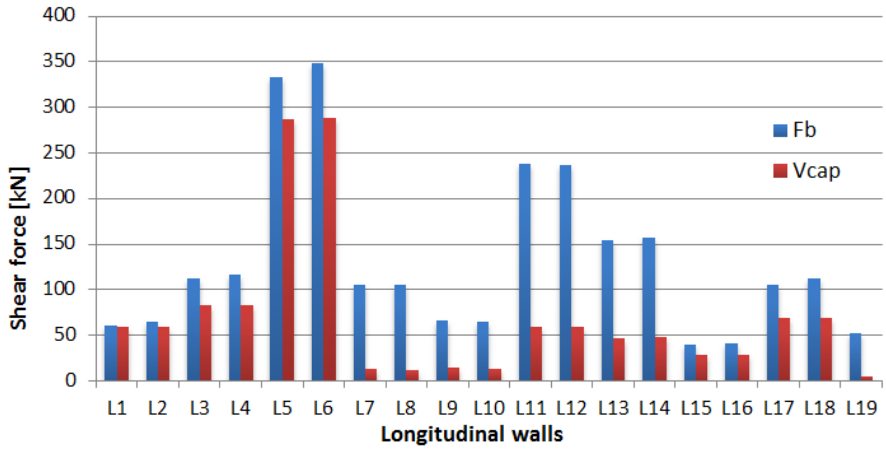


Fig. 12 – Shear strength vs shear force demand for each wall due to seismic action in longitudinal direction.

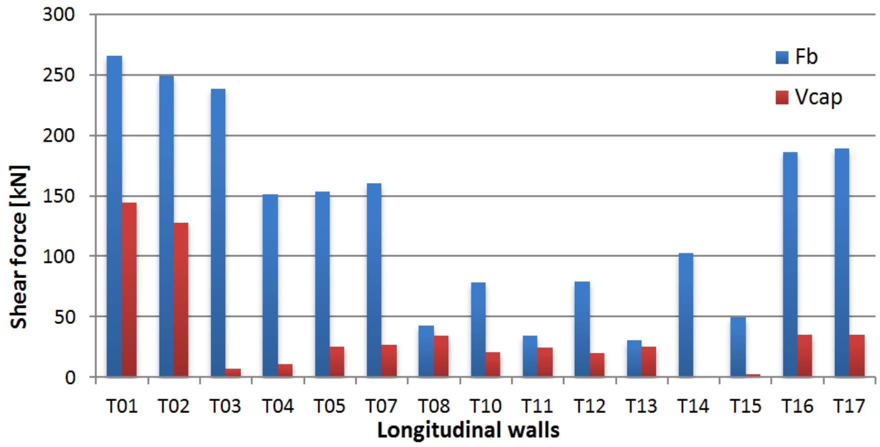


Fig. 13 – Shear strength vs shear force demand for each wall due to seismic action in transversal direction.

4. Conclusions

Investigation works on a historic masonry church are described in this paper. The following conclusions can be drawn from the study:

a) using a portable hygrometer, the level of humidity in the masonry walls has been detected giving useful information regardin the damages causes;

b) in the diagnosis of historic masonry churches infrared thermography can be used as a rapid testing method for identification of masonry texture, hidden elements (gaps, closed spaces, windows, niches), the crack patterns, masonry heterogeneity and distribution of moisture in its interior;

c) based on modal and linear static analysis using FEM, features regarding the structural response of the church ant the vulnerability points of the structure can results; therefore, usefull information regarding a proper intervention solution can easily be obtained.

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EVALUAREA STRUCTURALĂ ŞI LUCRĂRILE DE INTERVENȚII PROPUSE LA UN TURN VECHI DIN ZIDĂRIE

(Rezumat)

Investigațiile *in situ* şi analizele numerice sunt utilizate pe o scară din ce în ce mai largă la evaluarea clădirilor istorice din zidărie, având în vedere caracterul acestora de unicat. Acest studiu descrie, pe un studiu de caz, aplicarea unor tehnici nedistructive de evaluare *in situ* şi modelări cu metoda elementului finit cu scopul de a evalua starea de degradare şi vulnerabilitățile structurale a unei biserici ortodoxe cu o tipologie constructivă des întâlnită pe teritoriul țării. Rezultatele arată că metodele de investigație folosite pot fi unelte utile în evaluarea stării de degradare a patrimoniului construit şi în elaborarea unor soluții de reabilitare potrivite.