Technical University of Civil Engineering Bucharest

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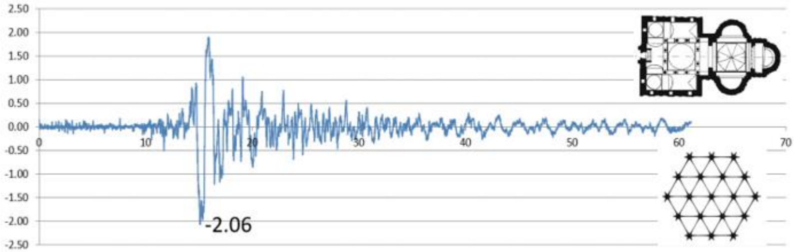
SEISMIC PROTECTION OF THREE-LOBED CHURCHES

Summary PhD THESIS



SCIENTIFIC COORDINATOR
Professor Ramiro Sofronie
UNESCO CHAIR #177, BUCHAREST

Bucharest, 2021

Cuprins

Cap.1 Introduction

The oldest monumental buildings preserved in the Carpato-Danubiano-Pontic space on the territory of Romania are the three-lobed shape churches, the region being well known for its early Christianity. For centuries they were the most representative creations of church and monumental architecture. They have always represented the typical Orthodox churches, since Romanians are the only Latin people of Orthodox religion, while other Latin or Latin peoples of Latin origin are Catholic.

The first three-lobed shape churches are the Holy Trinity Church of the Siret of Moldova, built in 1377, and the Church of Cozia Monastery in Wallachia, built-in 1388. Both churches are preserved and are still in permanent service.

The thesis was written at a time when the environment is strongly aggressive due to population growth for which the UN, in 2004, made an estimate comprising three scenarios, amplifying the Babel syndrome which creates confusion. The subject is approached both from a geometric perspective - configuration in plan and elevation, and from a physical perspective of material - the behavior of historical masonry.

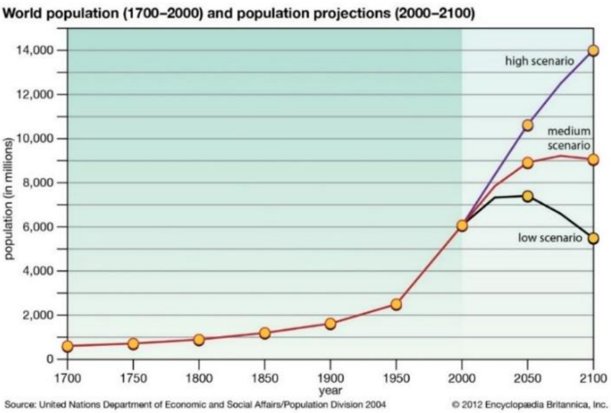


Figure 1.1. Population growth 1700-2000 and population attenuation 2000-2100

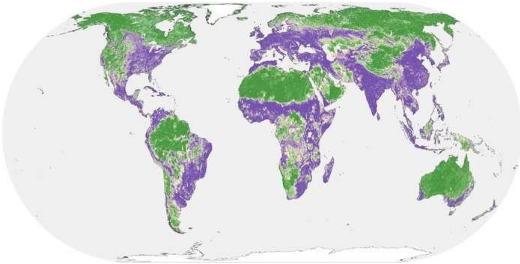


Figure 1.2. Human impact on the environment

Cap.2 Objectives of the thesis

The doctoral thesis has the following objectives:

1. Presentation of the state of knowledge of the trilobate configuration and the masonry used;
2. Criticism of the state of knowledge from the point of view of the codes in force;
3. Description of the subject's conception from the perspective of configuration;
4. Establishing the influence of the trilobate configuration on the seismic resilience of the church;
5. Establishing the influence of the foundation depth on the seismic resilience of the church;
6. Stability of church spires at seismic jerks;
7. Description of the conception of the subject from the perspective of masonry;
8. Numerical analysis of the weaving of historical masonry under gravitational actions;
9. Determination of the behavior of historical and modern masonry in gravitational actions on physical models;
10. Determination of the behavior of historical and modern masonry in gravitational actions on numerical models;
11. Numerical analysis of the behavior of historical masonry under seismic actions;
12. Determination of the performance of historical masonry, armed with polymer grids, on numerical models.

Cap.3 State of knowledge of trilobate configuration and masonry used

The following were studied in this chapter: The Legend of Oedipus, Aesopus Lesson, Master Manole Legend, historical masonry, modern masonry, dislocation theory, tests carried out at INCERC-Iasi, JRC-ISPRA-Italy, ISMES-Italy, earthquake findings, the concept of seismic resilience, the phenomenon of seismic jerking, comparison between historical and modern masonry, the collection of information about earthquakes occurring between 1320 The teachings of the Manole Master explained by Mircea Eliade:

1. Landscaping - removal of rainwater
2. The East-West orientation of the churches
3. Depth of foundations
4. Binding the body of the church, both at the base and on the roof in a closed three-dimensional body
5. Anchoring the towers in the church body and protecting them against lightning with lightning

Cap.4 Criticism of the state of knowledge from the point of view of the codes in force

The chapter criticized the following:

Foundation system – Churches generally have a surface foundation. A defective foundation causes degradation of the walls of the abscinds and transverse arches;

Body - The apses of the naos and altar have also been severely damaged by earthquakes by the deplaning of the curved walls;

Steeples – Instability due to the phenomenon of seismic jerking;

Intervention concepts and practices – Criticism of methods of intervention on historical masonry;

Heritage conservation requirements as recommended by ISCARSAH and the Venice Charter.

Cap.5 Subject design from a configuration perspective

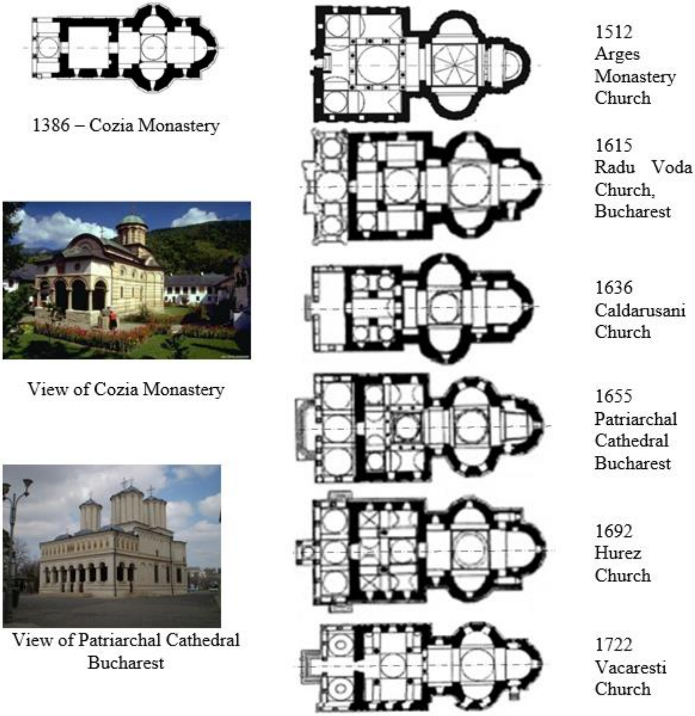
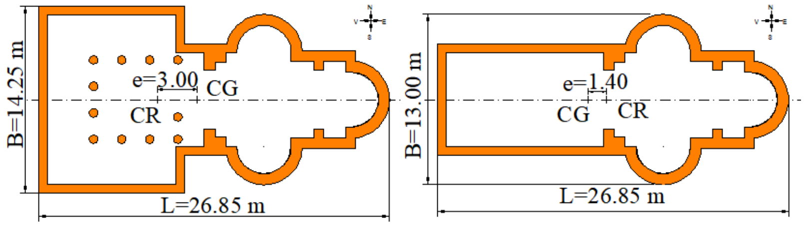


Figure 5.1. Churches of three-lobed shape with overstretched pronaos

5.1 Influence of the trilobate configuration on the seismic resilience of the Arges church

Figure 5.2. Perspective - Arges church



a) Real model b) Reference three-lobed shape

Figure 5.3. Positions of the center of mass and rigidity – Arges church

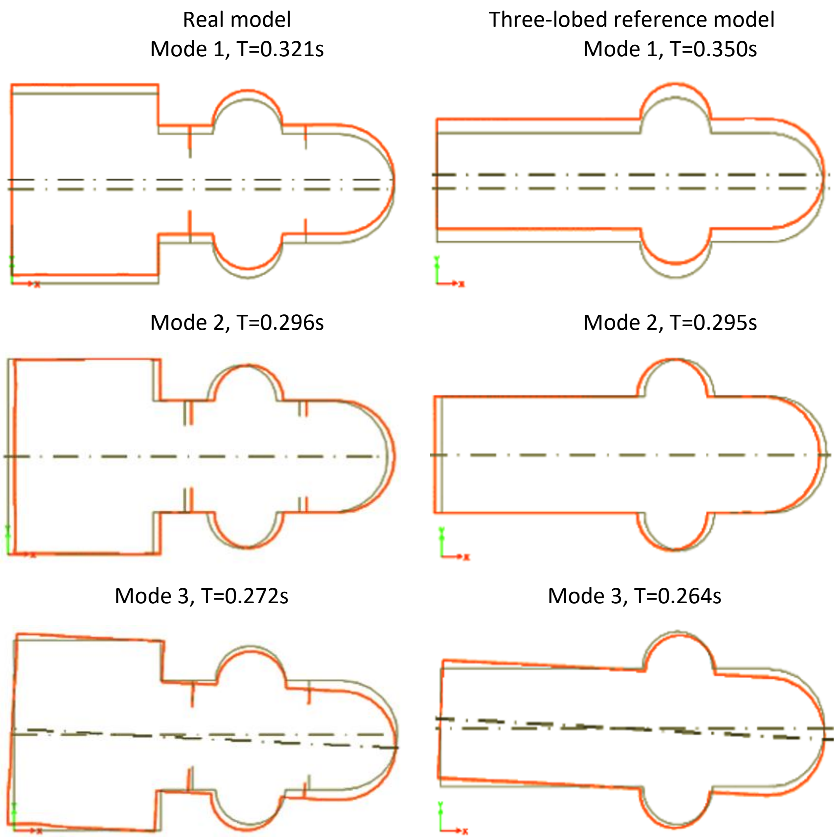


Figure 5.4. Distribution of oscillation modes - Arges church

By conforming the Arges Church to that of Cozia, the position of the CR rotation center, which passes on the axis of symmetry of the structure, on the other side of the cm mass center, is changed. At the same time, the distance from the center of CR rigidity to the walls of the apses has increased substantially, so that the cutting forces are reduced by about 20% in the case of the Arges church compared to that of Cozia. The cutting force is inversely proportional to the distance from the CR center and the extreme points of the plane.

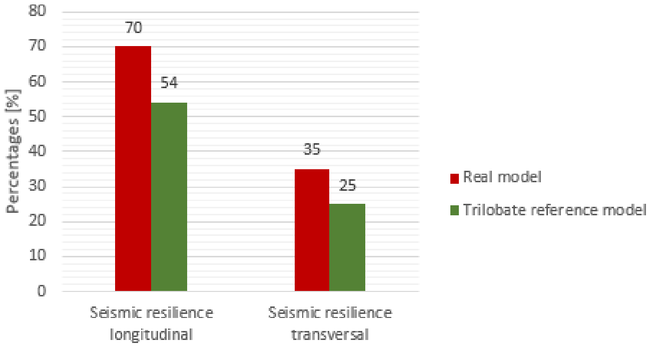


Figure 5.5. Seismic resilience - Arges church

5.2 Influence of foundation depth on seismic resilience

Model 1 – shallow depth of foundation, about 30 cm
Model 2 – medium depth of foundation - depth of frost
Model 3 – depth of foundation greater than the depth of frost

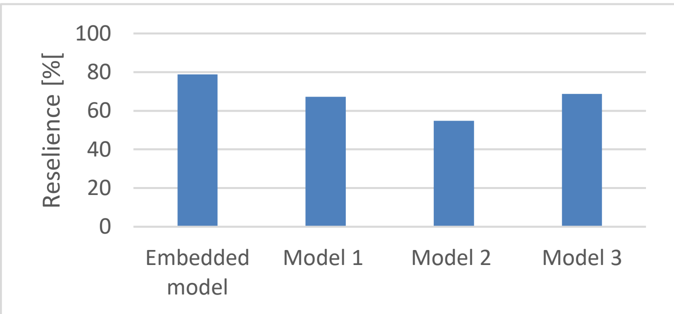


Figure 5.6. Seismic resilience according to the depth of the foundation

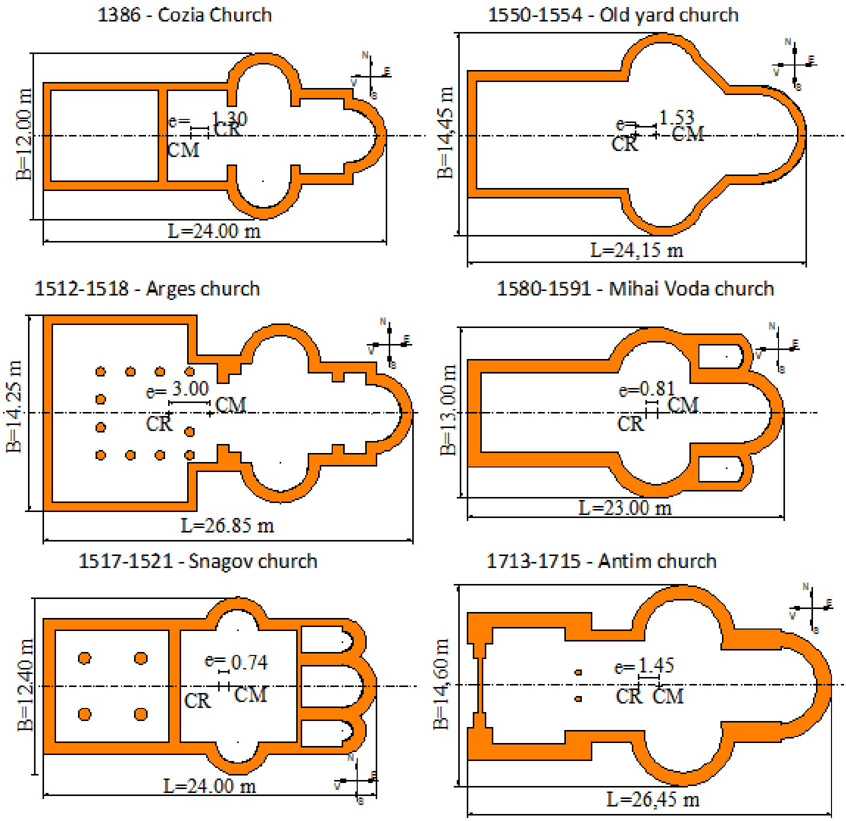


Figure 5.7. Distribution of CR and CG centers for trilobate plans studied

The seismic protection solution discovered during the construction of the Arges church, between 1512 and 1518, inspired by the myth of immolation, consisted in the over widening of the pronaos. Through this remodeling, the center of rotation changed its relative position with the center of gravity and moved from naos to pronaos. Since then, all churches in similar forms have been protected against earthquakes. Each church has reached the level of seismic resistance according to its form. However, the greatest capacity was the Arges church.

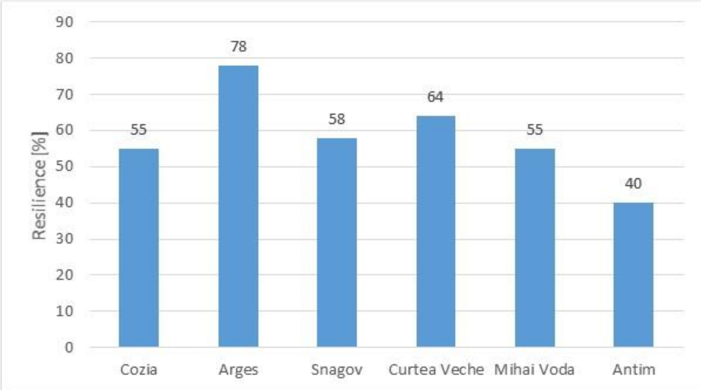


Figure 5.8. Seismic resilience of the trilobed plans studied

5.3 Stability of church spires at seismic jerks

Figure 5.9. Perspective - National Orthodox Cathedral

Table 5.1. Geometric properties

L	B	H	H_c	H_f	D_t	H_t
125.40	54.60	112.50	49.90	23.5	25.0	62.6.00

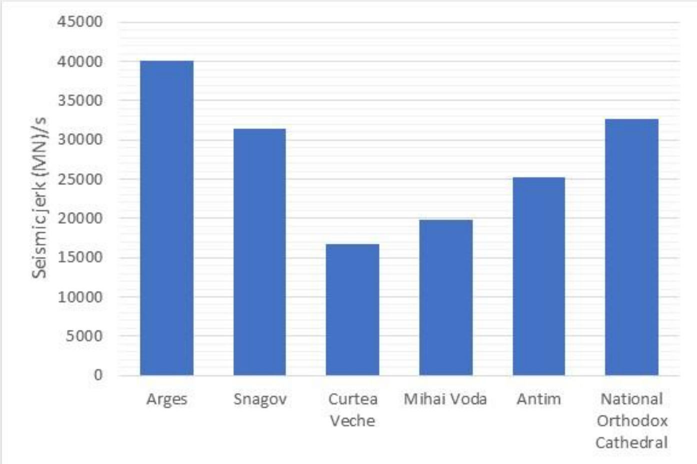


Figure 5.10. Seismic jerk for trilobate plans studied

The dimensions of the spires must be carefully chosen to have sufficient capacity to take up the force corresponding to the seismic impulse

Cap.6 Design of the subject from the perspective of masonry

Stone constructions began to be created from the very period of megalithic culture. Individual pieces of rock were collected and superimposed manually, one by one. They were kept in gravitational balance only by dry friction. Egyptian pyramids, for example, were erected by this procedure.

Figure 6.1. Great Pyramid of Giza, Egypt

After a while, in regions rich in clay soils, masonry was invented. The original brickwork consists of solid bricks, either dried or ripe, with pure lime mortars. It is handmade using gravitational force, using the "full-by-purpose" principle. The horizontality of the joints is controlled by the water level. Due to the ductility of lime mortars, historical masonry has the quality *of adaptation.* This spontaneous phenomenon consists of the formation of small plastic deformations at constant volume. As a consequence of the "full per-sense" effect, the vault effect appears, which consists of the decomposition of a vertical force after the horizontal directions.

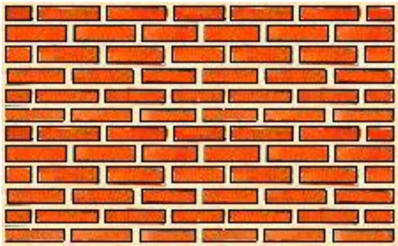


Figure 6.2. Historical masonry

The original brickwork cannot be reinforced with steel bars, as the steel rusts in contact with the lime mortar. Lime mortar is not polluting. The first masonry buildings in history were built in Mesopotamia in the form of ziggurats. The Tower of Babel was one of the most representative buildings.

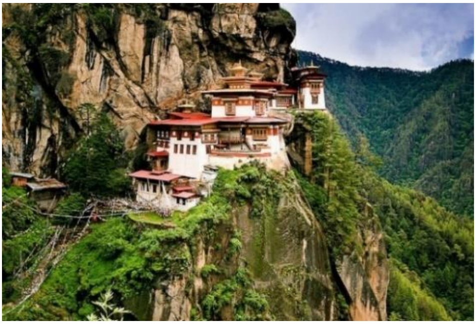
Figure 6.3. The Shinar Plan and the reconstruction of the Model of the Babel Tower

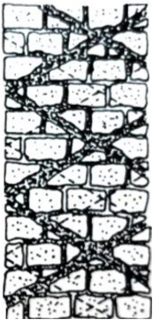
The great Chicago fire, which took place on October 8, 1871, was the time of the emergence of modern masonry. To rebuild the city, located on a territory where there are no earthquakes, tall buildings began to be built, requiring stronger masonry. The new concept of masonry structure quickly became popular in all U.S.A.

Figure 6.4. Catherine O'Leary – The Great Fire of Chicago - Oct 8, 1871

The modern brickwork is also called Mascrete. The word mascrete is an acronym of the English words **mas**onry and con**crete**. It consists of ceramic bricks with gaps and cement mortars. This masonry is fragile, very sensitive to earthquakes, and differentiated settlements. Thanks to SIO2 of the cement composition, modern masonry is polluting.

In the 21st century, UNESCO World Cultural Heritage has suffered some irretrievable losses, as the difference between historic and modern masonry has not been taken into account, or has been ignored. The Tiger's Nest Monastery has been strengthened by the use of cement-based mortars, thus ignoring ICOMOS recommendations. Another consolidation technique, which Professor Leonhardt Fritz called a "monstrous" one, consisted in the consolidation of monuments by metal inserts in masonry.





a) Tiger's Nest Monastery in the Kingdom of Bhutan b) Metallic inserts

Figure 6.5. Controversial consolidation solution

6.1 Numerical analysis of the historical masonry weaving under gravitational actions

To determine the influence of the weaving of masonry on a solid brick masonry panel 6x12x24 cm were considered comparative 3 cases, as follows:

- Case 1: predefined vertical purpose;
- Case 2: vertical joint located one quarter and three quarters respectively from the end of the brick;
- Case 3: vertical joint located halfway through a brick.

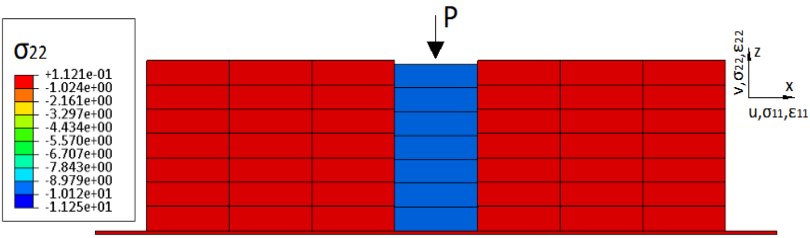


Figure 6.6. Normal unit compression efforts σ_{22} [MPa] - case 1

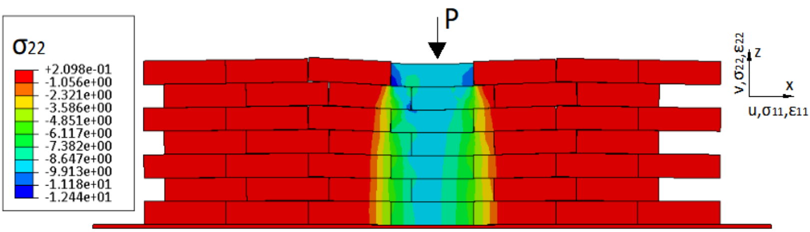


Figure 6.7. Normal unit compression efforts σ_{22} [MPa] - case 2

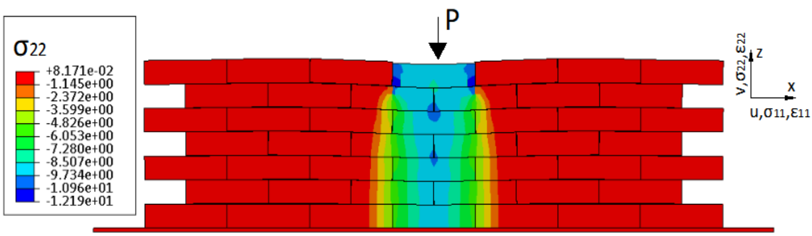


Figure 6.8. Normal unit compression efforts σ_{22} [MPa] - case 3

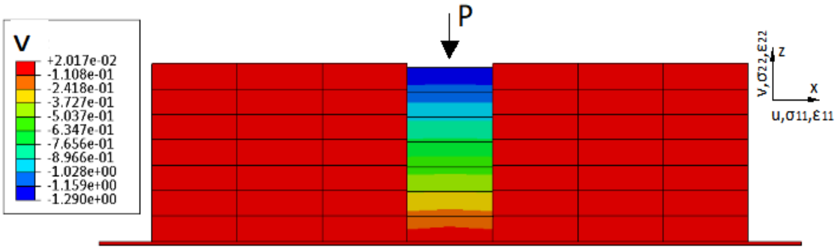


Figure 6.9. Distribution of movements v [mm] – case 1

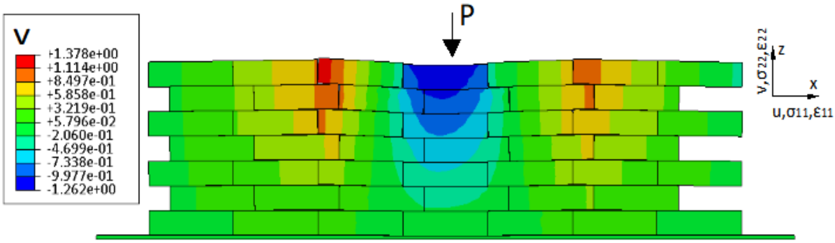


Figure 6.10. Distribution of movements v [mm] – case 2

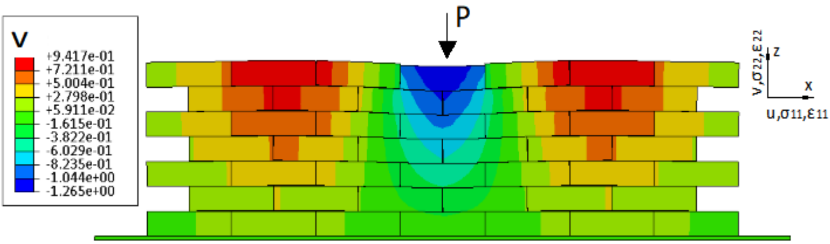


Figure 6.11. Distribution of movements v [mm] – case 3

In the case of masonry, vertical spaces between bricks are interpreted as structural defects. This is why it alternates from one layer to another in the system of shaving the joints. By shifting the vertical joints, an almost uniform distribution of voltages occurs. When in masonry the solid bricks are placed off, the maximum voltage levels reached remain below certain acceptable values.

In conclusion, the use of the full principle by the point leads to a uniformity of efforts around vertical joints.

6.2 The behavior of historical and modern masonry in gravitational actions on physical models

In this study, two small-scale physical models were made from dominoes, as follows:

1. Rigid and non-deformable panel – modern masonry
2. Flexible panel – historic masonry

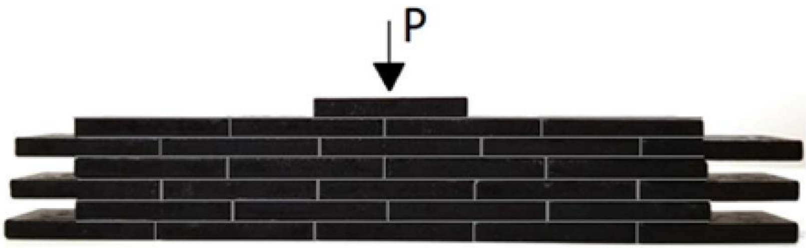


Figure 6.12. Deformed shape of the rigid and non-deformable small-scale panel

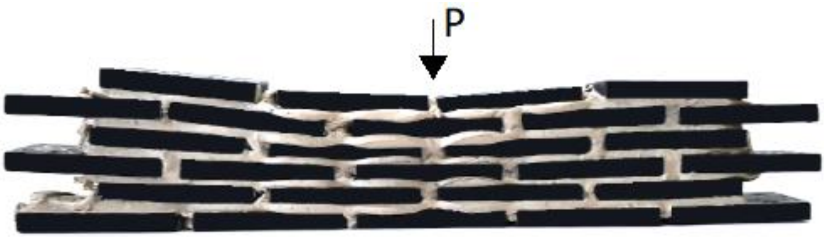


Figure 6.13. Deformed shape of the flexible panel

In conclusion, the use of lime mortar allows small movements, which leads to the protection of bricks, while when using cement mortar movements are not allowed, and efforts are concentrated at the level of bricks, which will suffer degradation.

6.3 The behavior of historical and modern masonry in gravitational actions on numerical models

To determine the influence of geometric characteristics on the behavior of masonry, masonry panels with different sizes of bricks were created in the Abaqus program: 6x12x24 cm, 4x8x16 cm, 7x14x28 cm.

For each brick were chosen 4 types of mortar, as follows: Cement mortar – thickness of 1 cm, Lime mortar – thickness of 1 cm, Lime mortar – thickness of 2 cm, Lime mortar – thickness of 3 cm;

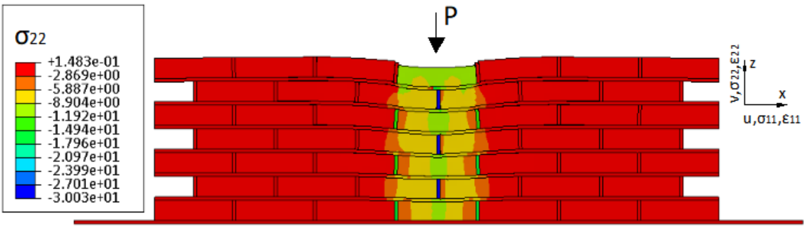


Figure 6.14. Normal unit efforts σ_{22} [MPa] – modern masonry

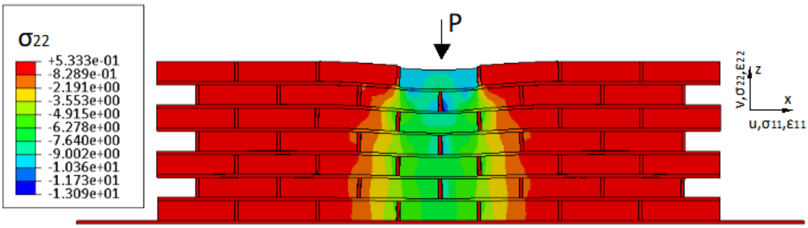


Figure 6.15. Normal unit efforts σ_{22} [MPa] – historical masonry end 1 cm

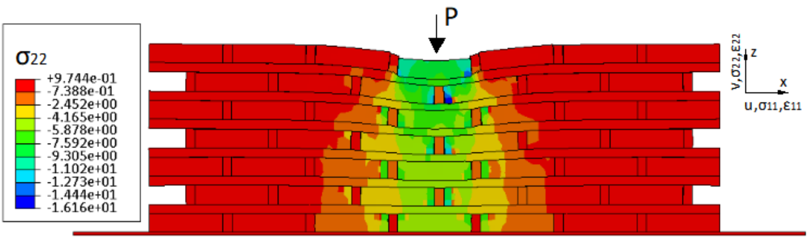


Figure 6.16. Normal unit efforts σ_{22} [MPa] – historical masonry end 3 cm

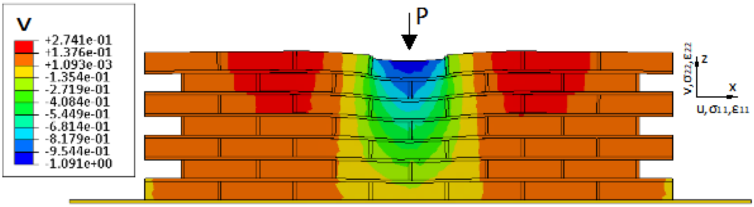


Figure 6.17. Distribution of movements v [mm] – modern masonry

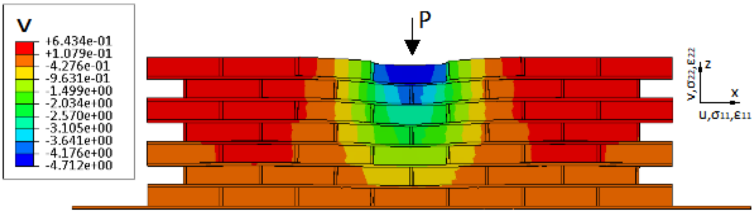


Figure 6.18 Distribution of movements v [mm] – historical masonry 1 cm

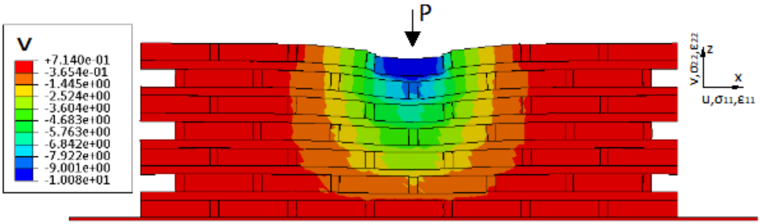


Figure 6.19 Distribution of movements v [mm] – historical masonry 3 cm

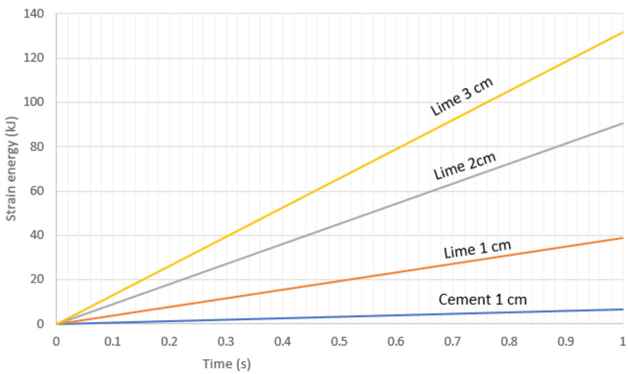


Figure 6.20. Deformation energy - 6x12x24 brick panel

Cap.7 Numerical analysis of the behavior of historical masonry under seismic actions

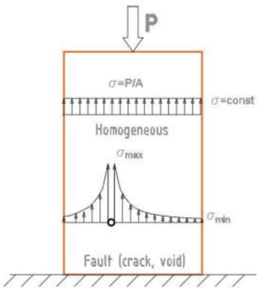


Figure 7.1. Normal stress

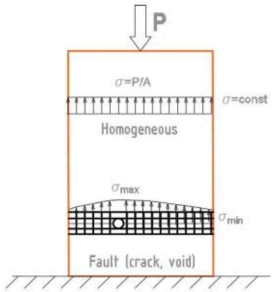


Figure 7.2. Grid over imperfection

Figure 7.3. Patent office

In 1995, by patenting OSIM No. 112373 B1, it was proposed to use polymer grids with integrated knots in masonry work. The idea started from the observation that all vertical joints represent geometric imperfections, according to the dislocation theory issued by Prof. Landau in 1967. Due to regular geometry and tensile strength, the grids can take over the masonry efforts and then evenly redistribute them to neighboring cross-sections, thus removing the danger of dislocations.

7.1 Pseudo-dynamic tests 2D, JRC - Ispra, Italy

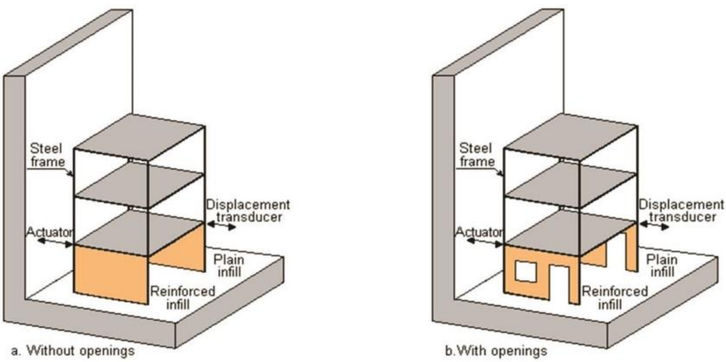


Figure 7.4. Arrangement of panels on the test wall, Ispra, Italy

a) Plain masonry b) Reinforced masonry

Figure 7.5. Goalless masonry panel after pseudo-dynamic test

a) Plain masonry b) Reinforced masonry

Figure 7.6. Empty masonry panel after pseudo-dynamic test

Figure 7.7. Degradation of bricks with gaps

Figure 7.8. Grid Degradation

Analyzing the figures above, it is noted that in the case of the use of hollow bricks, they have suffered degradation, which implies their careful use in seismic zones.

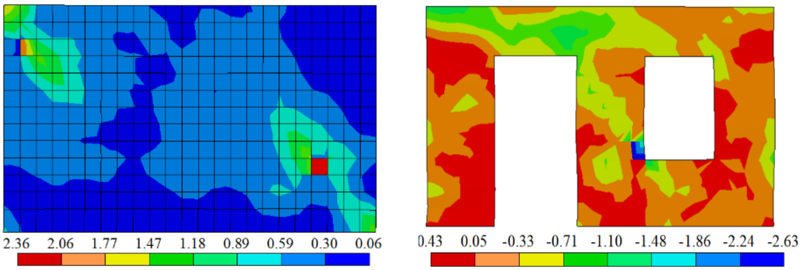


Figure 7.9. Maximum stress for plain masonry

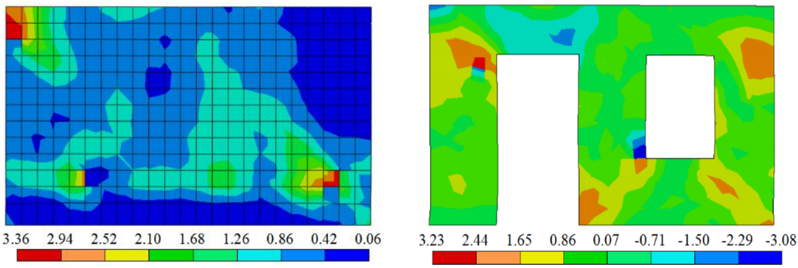


Figure 7.10. Maximum stress for reinforced masonry panel with biaxial grids

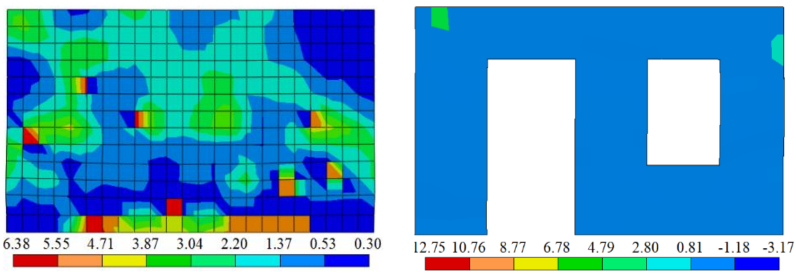


Figure 7.11. Maximum stress for reinforced masonry panel with triaxial grids

In both cases, by introducing biaxial and triaxial grids, the state of effort has changed substantially compared to the simple masonry model, producing uniform efforts, but also an increase in the load-bearing capacities of the panel, due to the strength of the grids and the confine of the masonry panel.

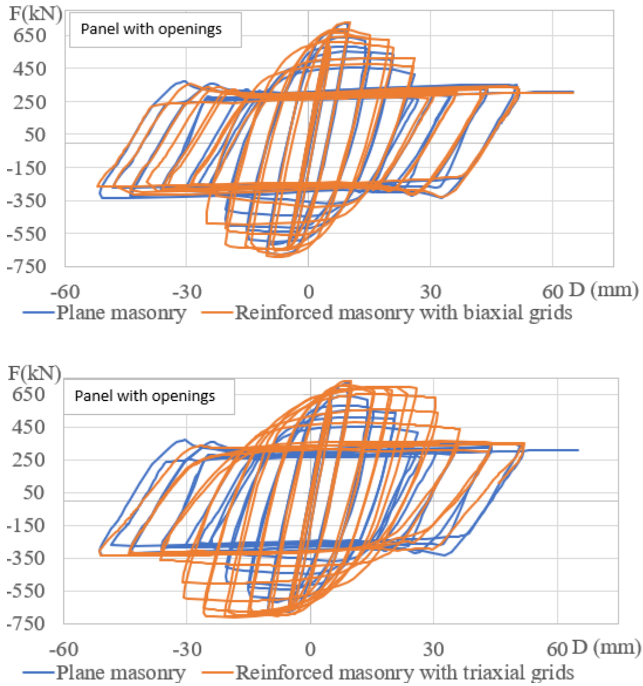


Figure 7.12. Hysteresis diagrams for the panel without openings

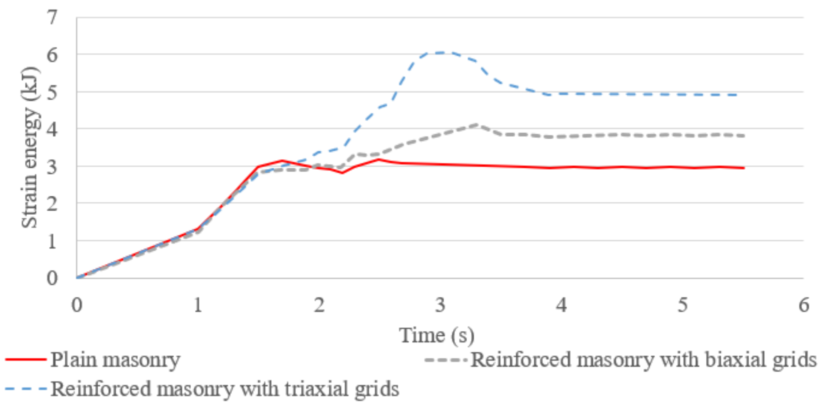


Figure 7.13. Deformation energy for the panel without openings

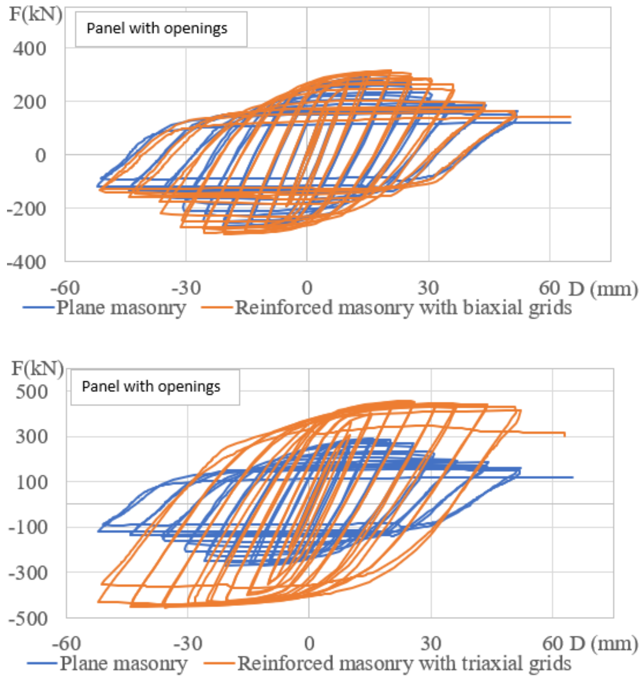


Figure 7.14. Hysteresis diagrams for the panel without openings

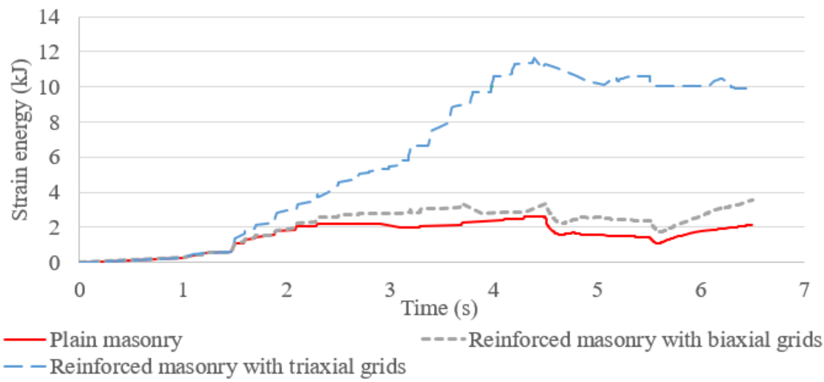


Figure 7.15. Deformation energy for panel with openings

Cap.8 Conclusion

The objectives of the doctoral thesis have been met.

Cap.9 Personal contributions

The doctoral thesis is 220 pages long and is structured as follows:

- 45% - elaboration of the current state of knowledge;
- 55% - Case studies and numerical analyses carried out.

References

The reference includes 109 sources.

Content of the thesis