Reinforcing original masonry with polymer grids

C M Irimia¹ and R Sofronie²

¹ Technical University of Civil Engineering, Bucharest, Romania
² UNESCO Chair #177, Bucharest, Romania

Correspondence: irimia_mihai_cristian@yahoo.com

Abstract. The paper deals with enhancing the strength of original masonry with polymer grids by preserving its basic physical properties of strength, stiffness, and potential energy. The behavior of the original masonry is carefully analyzed. The adopted solution for seismic protection of masonry was based on Landau’s Theory of dislocation. The basic idea of the patented method of reinforcing original masonry was related to the vertical joints of the original masonry. The suitable reinforcement for the original masonry should have high strength and long durability. The paper is suggesting some applications of reinforcing the original masonry. The tests on physical models confirm the practical value of the proposed method of reinforcing the original masonry. The numerical models extend the field of application regarding the polymer grids as suitable reinforcements.

1. Introduction

According to the first written documents, between 1471 and 1846, on the Carpatho-Danubian-Pontic territory over 60 strong earthquakes were occurred. Fortunately, just a few were strong enough as those in 1620, 1738, and 1802. During the twentieth century, earthquakes were recorded in 1903, 1912, and 1938, but the strongest occurred on the 10th of November 1940, and on the 4th of March 1977.

The oldest monumental buildings preserved in the Carpatho-Danubian-Pontic area are three-lobed churches. For centuries they were the most representative creations of ecclesiastic and monumental architecture. Erected with stone and brick masonry these Eastern Churches of Balkan-Byzantine style were always evidence of the level of technical knowledge and artistic refinement reached during their epoch. They also reflect the foreign influence on the autochthonous art of building. In the former Wallachian capital of Curtea de Arges, Prince Neagoe Basarab (1512-1521) founded the church of Arges Monastery. This church was consecrated on the 15th of August 1517 and became immediately famous due to its outstanding architecture (Figure 1). According to the Legend of Master Manole, the ten members of the team started carefully to work. However, after a while the walls they erected during the day tumbled down during the night. Mysterious failures recurred until they decided to immolate Master Manole’s wife. Only thus the walls were stopped to fall, and the church could be finished, lasting for centuries. Mircea Eliade, as a historian of religions, explains that such a legend is typical for the Balkan region. Although some versions are spread far away, towards India and Scandinavia e.g., only here in Romania, one finds its richest philosophical content. The Legend has disclosed that practically the three-lobed plan was reshaped by enlarging the pronaos. Thus, the two intrinsic centers CG and CR changed their relative positions, protecting the church against earthquakes. The reference plan has the length L=26.85m, the width B=13.00m, and the aspect ratio...
B/L = 0.484, while the enlarged plan B=14.25m and B/L=0.530. The enlargement of 13.5% was devoted to the immolation of Ana, Manole’s wife. (Figure 2 and Figure 3) [1,2,3]

**Figure 1.** The Church of Arges Monastery

**Figure 2.** Reference three-lobed plan

**Figure 3.** Three-lobed plan enlarged

2. **The behavior of original masonry under seismic actions.**
As concerns the damages caused by earthquakes first should be mentioned the steeple, due to seismic jerk, also called „the snap of the whip”. As a rule, the masonry columns of the steeples were horizontally sheared at their bottom and top. As concerns the three-round walls of the naos and altar, they display vertical cracks when there are no window openings, and cracks at 45° degrees when there are some window openings. The diagnosis of seismic damages is established with the specific methods of Strength of Materials, while the therapy must be performed taking into consideration the ICOMOS-Iscarsah Recommendations. Original masonry and reinforced concrete are incompatible. Masonry components are made by the fire, while the reinforced concrete contains water. The two basic Aristotelic elements are antagonistic. [4, 5, 6, 7, 8, 9]

3. **Theory of dislocation**
In 1962 Professor Lev Landau was awarded the Nobel Prize for his Theory of dislocation. It is presented in Chapter IV of his book *Théorie de l’élasticité* published five years later, in 1967. The practical method to annihilate the stress concentration around a structural imperfection is presented below. (Figure 4) [10, 11]

**Figure 4.** Annihilation of stress concentration

**Figure 5.** Patent Office

4. **Patenting concept of reinforcing the original masonry with polymer grids**
The basic idea of patenting (Figure 5) was the remark that all vertical joints of original masonry, that are being total or even partial free of mortars, appear as geometric faults. Always, around them, stress concentrations occur. By applying over the vertical surface of the wall a resistant grid, the stress concentration is annihilated (Figure 4). As concerns the working mechanism of reinforcing materials, there are two systems. One, based on shear forces obtained in steel bars by the vice effect, which was applied in 1867 by Joseph Monier. Another, based on tensile forces obtained by anchoring the metallic...
reinforcement in granular soil was used in 1962 by Henri Vidal for soil structures. Now, by the same anchoring mechanism, it is applied to synthetic reinforcement for reinforcing original masonry. The adherence of concrete to steel reinforcement was elucidated only 71 years later. Then Mihail Hangan, in his doctoral thesis, supervised by Nicolae Vasilescu-Karpen, succeeded a scientific explanation, that is still valid in the present time. (Figure 4) [11]

4.1. Suitable reinforcements for original masonry
Metallic grids are not appropriate. They might be either rusting or are too expensive. Neither the fibbers. The most convenient reinforcement proved to be the polymer grids. They should fulfill three conditions: 1) High tensile strength, 2) Durability, and 3) Safe anchoring in the plaster. It is also important that the horizontal joints of masonry be deepened about 2 cm for a good anchoring of the reinforced plaster. Usually, the thickness of the plaster should assume a minimum of 18 mm, and not more than 25 mm.

Suggested practical applications. (Figure 6)

5. Physical modeling

5.1. Full-scale 1D models of beams and columns →Iasi
The program was designed according to the existing facilities at INCERC Laboratory in Iasi, an AMSLER400 press together with mechanical and electric transducers. Since hollowed bricks behaved rather badly to earthquakes and vertically perforated bricks are poorly calibrated solid clay bricks of 240x120x60, with typical strength 7.5MPa, have been chosen. Two kinds of standard mixtures were used: M25Z with cement-lime-sand rate 1:1:12 for mortar and M25T with cement-sand rate 2.3:12 for plaster. For reinforcing the masonry polymer grids with a strength of 40 kN/m and peak strain of 11%. With the aid of the above-mentioned construction materials, wall panels were prepared with dimensions 875x240x874. The results are presented as shown in σ - ε diagrams. (Figure 7) [12]

Figure 6. Construction details

Figure 7. Wall panels submitted to diagonal tension
5.2. **Full-scale 2D models of walls tested on the resistance wall→JRC Ispra, Italy**

During the Euroquake project, pseudo-dynamic tests were carried out in the European Laboratory for Structural Assessment of the European Commission in Ispra, Varese, Italy. The dimensions of the wall panels were 460x260mm. For masonry, vertically perforated bricks with dimensions of 250x190x120 mm and 42% voids were used. The class of mortar was M3. For reinforcing the masonry, polymer grids with a strength of 30 kN/m were chosen. The reinforcement was first inserted in the bed joints at distances of 600mm. (Figure 8)

![Figure 8. ELSA reaction wall in Ispra](image)

The panel of reinforced masonry was covered on both sides with very small inclined cracks, caused by the principal stresses and therefore inclined at 45 degrees. However, very few pieces of plaster detached and fell off. While in the panel of plain masonry many bricks crashed, and some were even expelled, the other panel remained integer. It was proven again that hollowed and perforated bricks are not suitable for structural members submitted to seismic loading. Synthetic reinforcement compensates for the lack of brick ductility by acting mainly after the limited state of cracking. This behavior is typical for the approach and the technique of passive reinforcing and polymer grids proved to be an appropriate choice for this purpose. (Figure 9) [12]

5.3. **Full-scale 3D models of buildings tested on the shaking tables→ENEL Seriate, Italy**

The original model had one axis of symmetry and was provided with five openings with circular archways. At its top, the model was closed with a wooden floor. For masonry, there have been used solid bricks with dimensions 230x105x60 and mortar lime-cement M1. The model of the first generation was tested to Vrancea '77 tectonic earthquake by using two DOF, the translation on the principal directions. When the limit state of cracking occurred, the test stopped. (Figure 10)

![Figure 10. First masonry model installed on shaking table](image)

![Figure 11. Second masonry model installed on shaking table](image)

![Figure 12. The exterior of the confined model after the testing program](image)

The first model was confined with the same reinforcement with polymer grids with a strength of 40 kN/m and plaster with the same lime-cement mortar M1. The testing program simulated a typical earthquake that is felt in Bucharest once every 300 years. (Figure 11)
The seismic response of the model was excellent for the high intensities of input. Naturally, due to the large lifting forces, most cracks have been horizontal. The only inclined cracks, but not at 45°, started from the corners of the windows openings. (Figure 12) [12]

6. Numerical modeling
To determine the influence of reinforcing for the history masonry with polymer grids, using the finite element method, two models were created for a masonry wall. The dimensions of the first model are 1470x770mm, with horizontal joints, thickness: 10 mm. The dimensions of the second model are 1470x985mm, with horizontal joints, thickness: 30 mm. The brick used was solid brick with compressive strength of 13 MPa and M3 mortar according to CR6. For reinforcement with polymer grids, we used biaxial grids with a strength of 40 kN/m and triaxial grids with a strength of 130 kN/m. The type of analysis used is push-over. To track the progressive degradation, each wall was pushed with an amplitude in two cycles, corresponding to a drift of 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.7, and 2.0%. The results are shown in Figure 13 to Figure 20.

a) Unreinforced masonry wall

b) Reinforced masonry wall with biaxial grids

c) Reinforced masonry wall with triaxial grids

Figure 13. Hysteresis diagrams reinforced with biaxial grids and unreinforced for the first model

Figure 14. Hysteresis diagrams reinforced with triaxial grids and unreinforced for the first model

Figure 15. Plastic deformation masonry wall for the first model
Figure 16. Time history of dissipative energy for the first model

For the first model, masonry confined played an important role in dissipating induced energy. As Figure 16 shows, in the case of the masonry confined with biaxial grids, the dissipative energy is approximately twice bigger as in the case of the unconfined masonry. Confined masonry with triaxial grids leads to an increase in dissipative energy, which registers even five-time higher values than in the case of unconfined masonry.

For both models the behavior of the unreinforced masonry wall is classic: until the peak force is reached, the behavior is slightly nonlinear, but with the degradation of the cyclic force, especially between the first and second cycles. The top is followed by a phase of rapid degradation due to the corners panel crushing and the extensive cracking of some bricks in the central area of the wall. (Figure 13, Figure 15 b, Figure 18, Figure 20 b)

For the reinforced models with the biaxial grid, until the maximum resistance is reached, the answer is almost the same as for the simple masonry wall: the initial cycles are identical, only the maximum resistance is slightly higher and has been reached at a higher displacement.

For the reinforced models with triaxial grids, the maximum resistance is much higher and has been reached at higher displacement. During this phase, the same types of cracks appear, but they are very thin and distributed over a large area. (Figure 14, Figure 15 c, Figure 19, Figure 20 c)

Figure 17. Time history of dissipative energy for the second model

For the first model, confined masonry played an important role in dissipating induced energy. As Figure 17 shows, in the case of the masonry confined with biaxial grids, the dissipative energy is approximately twice bigger as in the case of the unconfined masonry. Confined masonry with triaxial
grids leads to an increase in dissipative energy, which registers even five-time higher values than in the case of unconfined masonry.

Figure 18. Hysteresis diagrams reinforced with biaxial grids and unreinforced for the second model

Figure 19. Hysteresis diagrams reinforced with triaxial grids and unreinforced for the second model

Figure 20. Plastic deformation masonry wall for the second model

7. Conclusion
Original masonry used to buildings of Cultural Heritage, many of them protected by UNESCO, is weak to seismic actions. After careful research, it was discovered that vertical joints of the original masonry, even filled up or not with lime mortars, under directly applied actions appear as geometric imperfections. That allows applying Landau’s Theory of Dislocations, awarded in 1962 with Noble. Data regarding the behavior of original masonry under seismic actions were achieved during a complex research program, extended over a decade, and supported by the European Union. The method of reinforcing original masonry with polymer grids was patented 25 years ago, in 1995, in Bucharest. It essentially differs from the former two well-known methods of reinforcing: that of concrete, due to Joseph Monier in 1867, in Paris, and that of granular soil, due to Henri Vidal in 1962, in London. The polymer grids are used as reinforcements for the original masonry, consisting of solid bricks and lime mortars, due to their three qualities: 1) high tensile strength, 2) geometric regularity, and 3) durability by good conservation in lime
mortars. In numerical modeling it has been shown that once applied, into horizontal joints or over the surface of masonry, the grids are taking over the stresses concentrated around structural imperfections discharging them. The bearing capacity of structural members increases substantially in this way. From the very beginning, the idea of reinforcing the original masonry with polymer grids was well received by professionals. The method reflects both the high progress of technology regarding synthetic materials and the advanced level reached by the science of construction materials. The method was first mentioned in Eurocode 8 and then explicitly included in Romanian National Codes P100-1/ 2013 and CR6-2013. Practical applications that followed confirmed the method’s performances. By reinforcing, original masonry conserves its essential quality of adaptation and also proves that it is gravitationally alive. Physical modeling has emphasized the qualities of the original masonry, but also its limits. Numerical modeling of original masonry reinforced with polymer grids was developed in the frame of a doctoral thesis. Its objective was to validate the results obtained by physical modeling and to generalize them for practical applications in design and also further research. It was shown that this innovative method is in full concordance with the Chart of Venice in 1964 and ICOMOS-Iscarsah Recommendations in 2001. The original masonry, reinforced with polymer grids reaches comfortable levels of seismic resilience and thus, good perspectives are opened in seismic protection of all current buildings, including the cultural heritage protected by UNESCO.

Acknowledgments
The unconditional support of the UNESCO Chair #177 in Bucharest, Romania, for writing and submitting this paper is gratefully acknowledged. Respectful thanks are also due to the Doctoral School of the Technical University of Civil Engineering, particularly to Professor Ilinca Nastase, for allowing the continuity of doctoral studies.

References
[1] Irimia M 2020 Original masonry versus advanced masonry The 3rd Conference of the UT CB Doctoral School Technical University of Civil Engineering Bucharest (Preprint)
[2] Eliade M 1943 Comentarii la Legenda Mesterului Manole (Bucharest: Publicom)
[3] Paun S 2003 Romania. La valeur de l’architecture autochtone (Bucharest: Per Omnes Artes)
[4] Beleş A 1936-1937 La notion de sécousse et son rôle dans le dynamique (Bucharest: The Bulletin of the Polytechnic Society)
[5] Sofronie R 1982 The Behaviour of Eastern Churches in Earthquake 7th European Conference on Earthquake Engineering
[6] Sofronie R 1983 Post-seismic Strengthening of Churches IABSE Symposium Venezia
[7] Sofronie R 2017 On the seismic jerk Journal of Geological Resource and Engineer vol 4 pp 147-152
[8] Sofronie R 2019 On the seismic resilience Journal of Geological Resource and Engineer pp 132-139
[9] Icomos Iscarsah 2001 Recommendation for the analysis, conservation and structural restoration of architectural heritage (Paris: UNESCO House)
[10] Landau L and Lifchitz F 1967 Théorie de L’Elasticité (Moscow: Édition Mir)
[11] Sofronie R and Feodorov V 1995 Method of antiseismic reinforcement of masonry works (Bucharest: Romanian Patent Office, OSIM, RO 112373B1)
[12] Sofronie R 2005 Application of reinforcing techniques with polymer grids for masonry buildings vol 5 (Portugal: CASCADE)