BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 66 (70), Numărul 4, 2020
Secţia
CONSTRUCŢII. ARHITECTURĂ

NUMERICAL MODELING OF MASONRY TESTS

BY

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Received: November 26, 2020
Accepted for publication: December 10, 2020

Abstract. The paper deals with the numerical interpretation of pseudo-dynamic tests carried out on the reaction wall of JRC Ispra, Italy. Four panels of masonry infill at a natural scale were used. Two by two the panels consisted of plain and reinforced masonry, with openings and without ones. The method of reinforcing masonry with polymer grids, patented in 1995, is applied only to masonry with lime mortars and is based on two ideas: 1) The vertical joints of the masonry are geometric irregularities. Consequently, each brick receives six degrees of freedom. That holistic freedom confers to that infills the quality of slight deformations in all directions called *adaptation*. 2) According to the Theory of Dislocations, around each geometric fault stress concentrations occur, causing damages. By their geometric regularity, the polymer grids prevent that inconvenience. All results of the numerical analysis are comparatively presented by considering plain masonry and reinforced one with biaxial and triaxial grids. The paper presents the diagrams for hysteresis, strain energy, plastic dissipation energy, internal energy, and damage dissipation energy. All results are accordingly commented. The paper concludes that by all laboratory tests the idea of reinforcing masonry, based on lime mortars, with polymer grids, was successfully confirmed.

Keywords: Structural-fault; Stress – concentration; Seismic – resilience.

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1. Introduction

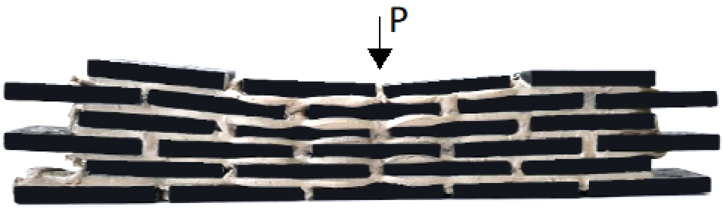
The historic masonry was used in Mesopotamia to build ziggurats. The most representative ziggurat was the Tower of Babel (Fig. 1), erected during the reign of Hammurabi the Great (1792-1750 BC). The historical masonry consists of either dried or baked bricks and lime mortars, manually made in the gravitational field. The verticality of structural elements was obtained with the help of the plumb - bob wire.

Fig. 1 – Hypothetical view of the Babel Tower of 90x90x90m.

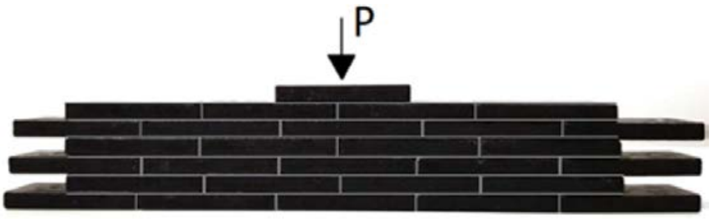
The Great Fire in Chicago, that occurred on the 8th of October, 1871 was the moment of the appearance of modern masonry. On the new Chicago town, situated on a territory where no earthquakes occur, high buildings began to be built, which required stronger masonry. The new concept of masonry structure quickly became popular in all American States. For obtaining bricks with high strength, they were burned at higher temperatures, even over the vitrification point of clay. To increase productivity and reduce weight, the bricks were hollowed out. Also, to increase the strength of masonry, the strength of the lime mortar was increased by the addition of Portland cement.

Fig. 2 – Greek Philosopher Aesopus.

In this way, the original masonry became historical, while the new masonry, was called advanced or modern masonry. The acronym *mascrete* was also suggested as appropriate for advanced masonry. Historical masonry is flexible, like the reed in Aesop's philosophy (Fig. 2), and modern masonry is as rigid as oak (Timoshenko, 1930, 1953; Beles, 1937; L'Hermite, 1953).



a) Flexible masonry panel created by the author with domino pieces



b) Stiff masonry panel created by the author with domino pieces

Fig. 3 – Stiff and flexible panels according to Aesopus' philosophy.

During the 21st century, the World Cultural Heritage of UNESCO has recorded some irrecoverable losses, because the difference between historic masonry and advanced, modern masonry, was not considered or simply ignored (Icomos, 2001; Sofronie, 1982, 1983, 2017, 2019; Eliade, 1943; Sofronie, 2018; Sofronie and Virsta, 2006; Paun, 2003).

Fig. 4 − Tiger's Nest Monastery built in 1692 at 3,120 m height in the Bhutan Kingdom.

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 (Landau and Lifchitz, 1967).

The practical method to annihilate the stress concentration around a structural imperfection is presented below. In 1995, the reinforcement of the historical masonry with polymer grids was patented (Sofronie and Feodorov, 1995; Pascu, 2006).

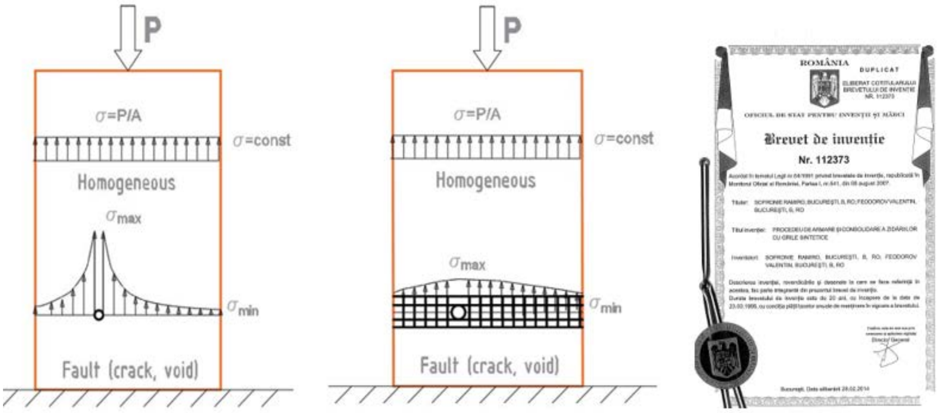


Fig. 5 − Annihilation of stress concentration with polymer grids.

The idea started from the remark that all vertical joints, appear as geometrical faults, according to the theory of dislocation issued by Landau in 1967 (Fig. 5). Covering imperfections with resistant grids leads to reduced stress concentrators. Regarding the anchoring mechanism, there are two systems. One, based on shear forces, which was applied by Joseph Monier in 1867, and the other based on tension forces, obtained by anchoring steel reinforcement in granular soil, used by Henri Vidal in 1962. The same system is now applied to synthetic reinforcement (Vidal, 1966).

Because in contact with the lime, the metal grids rusts, these are not suitable for reinforcing of the historical masonry. Also, the carbon fibers are not recommended for reinforcement because they veil. The most convenient reinforcement proved to be the polymer grids with solid joints. They should fulfill three conditions: 1) High tensile strength, 2) Durability, and 3) Safe anchoring in the mortar. It is also important that the horizontal joints of masonry be deepened about 2 cm for a good anchoring of the reinforced mortar. Usually, the thickness of the mortar should assume a minimum of 18 mm, and not more than 25 mm. To show the difference between the two materials, physical models were tested in European Engineering Laboratories, with EU financial support.

2. Physical Models

In the European Laboratory for Structural Assessment of the European Commission in Ispra, Italy, pseudo-dynamic tests were carried out inside of the Euroquake project. The dimensions of the panel were 460x260mm and the thickness of 250 mm. For masonry, hollowed bricks with dimensions of 250x190x120 mm with 42% voids and mortar M3 was used. The compressive strength of bricks and that corresponding to plain masonry were already available: 13.3 MPa normal and 3.3 MPa parallel to the bed joints for bricks and 7.3 MPa normal and 2.4 MPa parallel to the bed joints for masonry with 120 mm thick running bond. For reinforcing the masonry polymer grids with a strength of 30 kN/m were chosen (Sofronie, 2005, 2001).

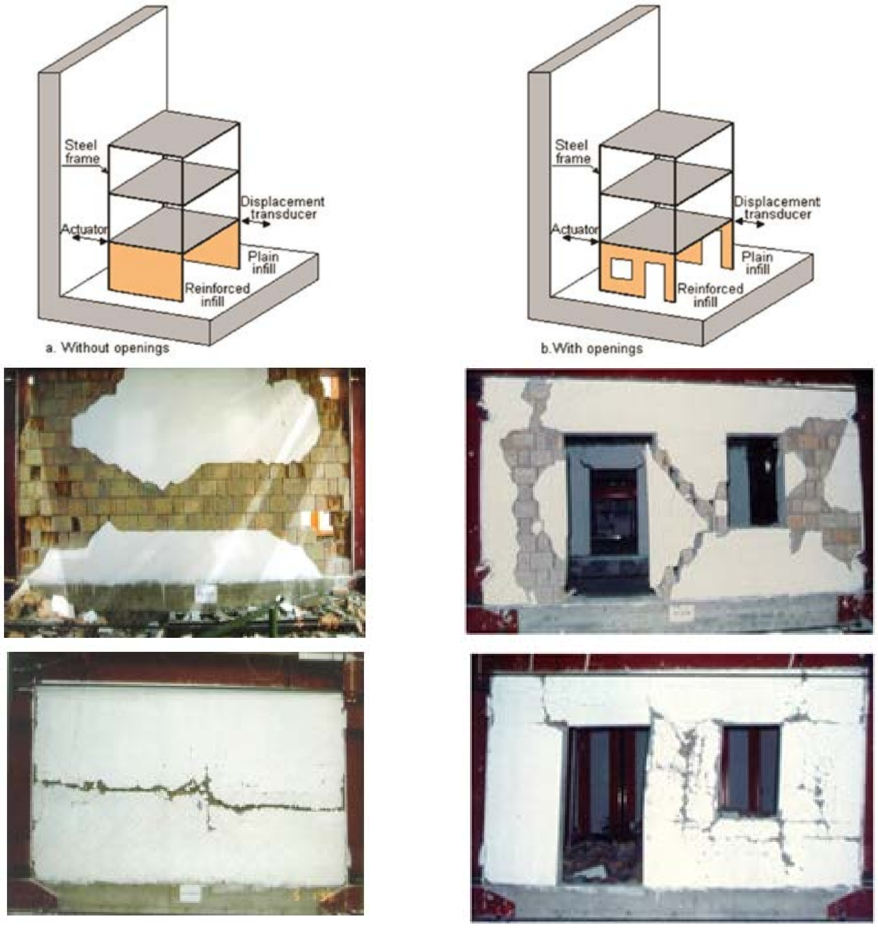
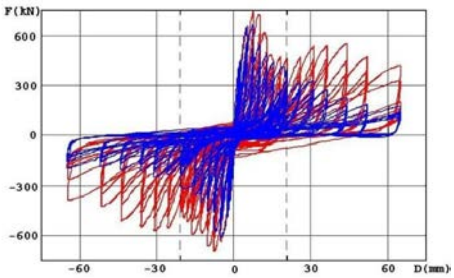


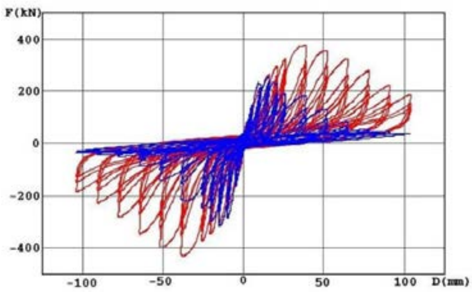
Fig. 6 − Panel with openings and without openings, reinforced with polymer grids and plain masonry, after pseudo-dynamic tests.

The cracking state is directly influenced by the two openings, the cracks being initiated at their corners. The reinforced masonry panel did not collapse, while the plain masonry panel partially collapsed. The pre-collapse state of the plain masonry and the final layer of the reinforced masonry after testing are presented comparatively in Fig. 6. The areas near the windows showed a panel behavior, where thin and dense cracks developed, inclined at 45 degrees. The area between the door and the edge of the panel had a column behavior, with thin and dense cracks, oriented vertically.

Fig. 7*a* and Fig. 7*b* show a comparison between the behavior of plain masonry panels and reinforced masonry with polymer grids, expressed in the relationship between force-displacement. Polymer grids had the desired effect and led to reduced degradation and increased panel capacities. At the end of the program, both reinforced panels had substantial strength reserves of about 200% compared to plain masonry.



a) Panels at full scale without openings.



b) Panels at full scale with openings.

Fig. 7 − Hysteresis diagrams after the pseudo-dynamic tests.

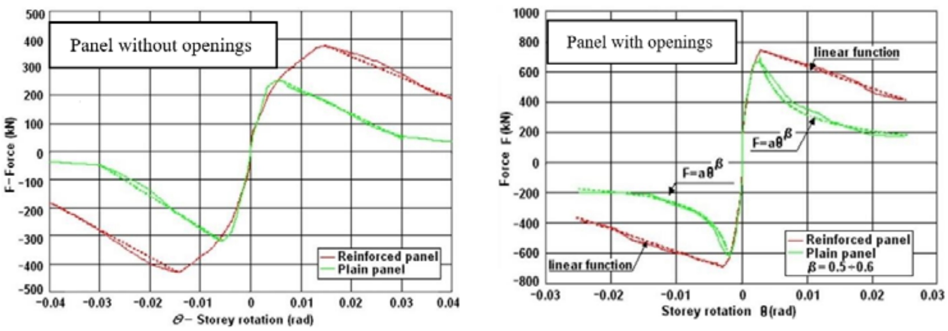


Fig. 8 – Envelope curves for two masonry panels, with and without openings, after pseudo-dynamic tests.

In the Fig. 8, where the behavior of simple and reinforced panels was superimposed, the benefits brought by the use of polymer grids are presented from a quantitative point of view. The reinforced masonry behaved very well and safely in the post-elastic field. Even at the end of the program, both panels of reinforced masonry remained standing, with reserves of resistance. However, the main benefit of polymer grids reinforcement is to strength the partial or even complete collapse of the panels, meaning the elimination of the main cause of human and material losses.

3. Numerical Modeling

To determine the influence of reinforcing for the history masonry with polymer grids, three numerical models were created for a masonry panel. The dimensions and properties of the model are similar to the panel model tested in the Euroquake project (Fig. 10). For reinforcement, were used biaxial grids - the strength of 30 kN/m and triaxial grids - strength of 130 kN/m.

According Lourenco's classification (Fig. 9), modeling strategies fall into three categories: detailed micro-modeling, simplified micro-modeling, and macro-modeling (Lourenço *et al*., 1995).

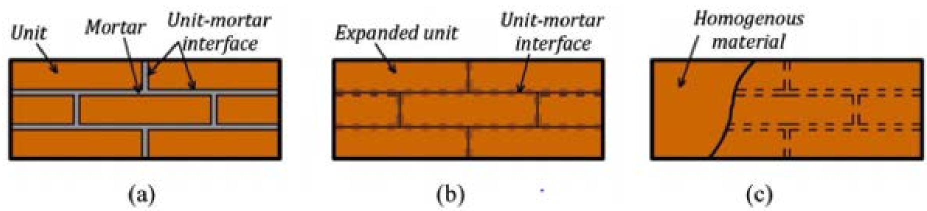


Fig. 9 − Different FE modeling strategies for masonry.

Micro-modeling involves separate modeling of bricks, mortar, and brick-mortar interface, being used to analyse the structural behavior of small parts of masonry. In this case, macro-modeling is used due to the reduced computational effort, the masonry being considered a continuous material. The type of analysis used is push-over. To track the progressive degradation, each panel was pushed, in two cycles, up to drift between 0.2 - 2.5%.

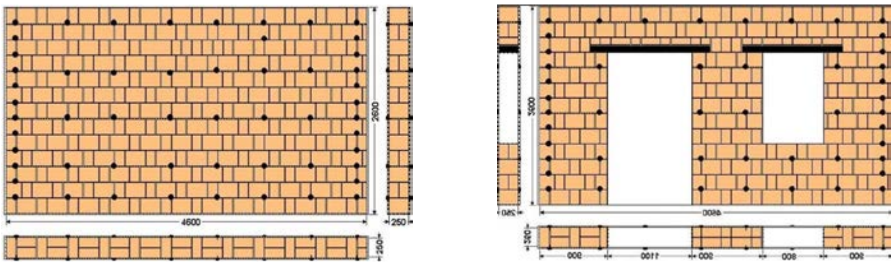


Fig. 10 − Panel without and with openings before reinforcing with polymer grids.

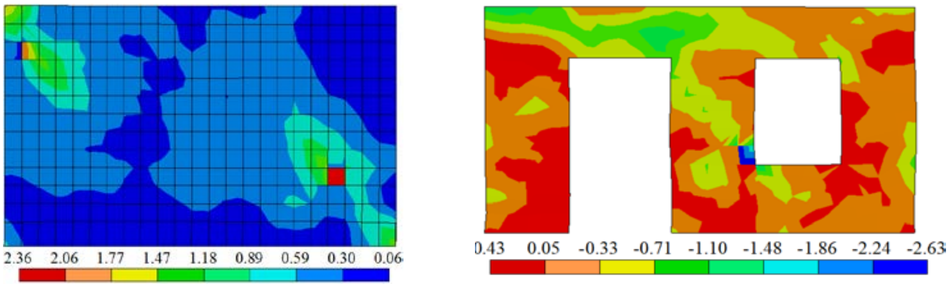


Fig. 11 − Maximum stress plain masonry of panel without and with openings.

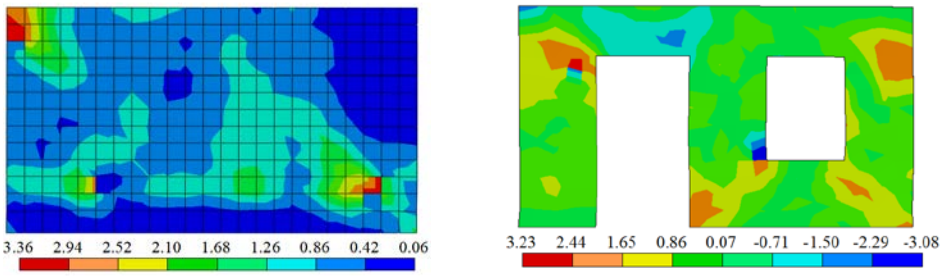


Fig. 12 − Maximum stress panel without and with openings before reinforcing with biaxial polymer grids.

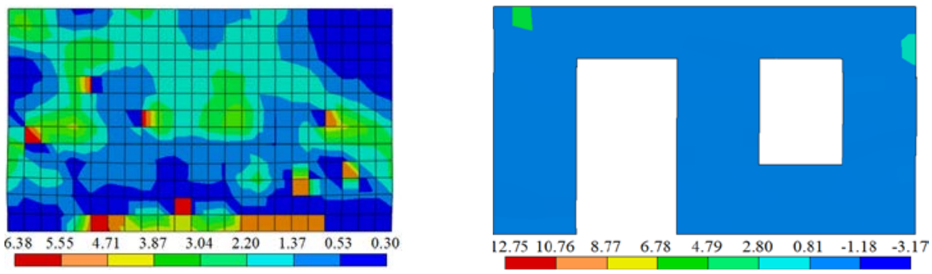


Fig. 13 − Maximum stress panel without and with openings before reinforcing with triaxial polymer grids.

In both cases, by introducing biaxial and triaxial grids the state of efforts to change substantially compared to the model with plain masonry. From Fig. 11 to Fig. 13 it can be observed that by introducing the grids a uniformization of the efforts happened, being reduced the concentrations of efforts, but also an increase of load-bearing capacities of the panel, due to the resistance of the grids and the confinement of the masonry panel.

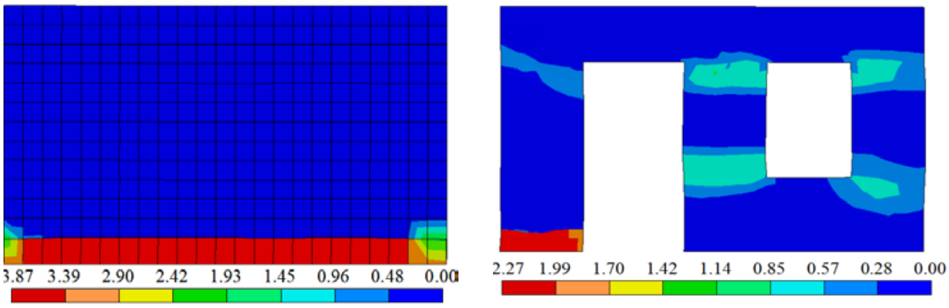


Fig. 14 − Maximum plastic strain plain masonry of panel without and with openings.

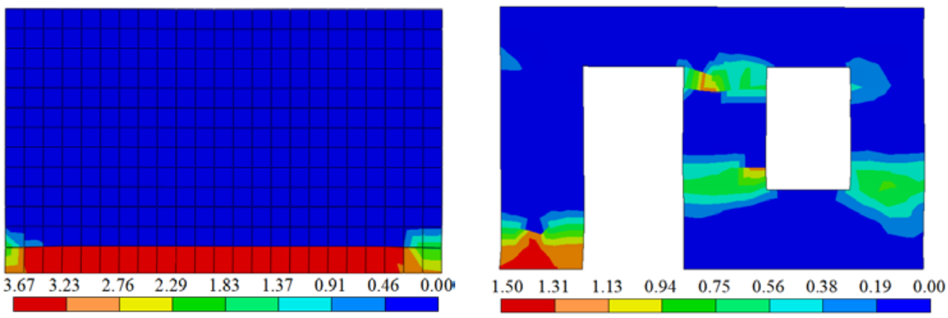


Fig. 15 − Maximum plastic strain panel without and with openings before reinforcing with biaxial polymer grids.

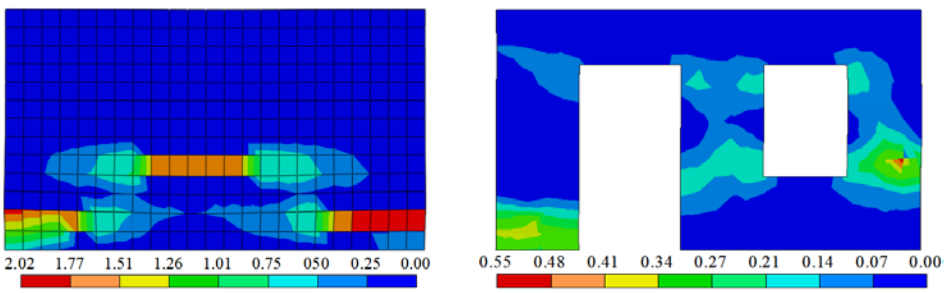


Fig. 16 − Maximum plastic strain panel without and with openings before reinforcing with triaxial polymer grids.

From the point of view of the plastic deformations that appeared, the results are similar to the results in the case of the efforts. By introducing polymer grids, the ability to adapt the historical masonry, which is the deformation of the mortar under constant volume, is not prevented (Fig. 14 to Fig. 16).

The behavior of the plain masonry panel is classic: until the peak force is reached, the behavior is slightly nonlinear, but with the degradation of cyclic force especially between the first and second cycle. The top is followed by a phase of rapid degradation due to the crushing of the corners of the panel and the extensive cracking of some bricks in the central area.

For masonry panel reinforced with biaxial grids, until the maximum resistance is reached, the answer is almost the same as for the plain masonry panel: the initial cycles are identical, only maximum resistance is slightly higher and has been reached at a higher displacement. During this phase, the same types of cracks appear, but they are very thin and distributed over a large area. After reaching maximum strength, the panel can reach the load-bearing capacity over several cycles (Fig. 17).

For masonry panel reinforced with triaxial grid, the maximum resistance is much higher and has been reached at a higher displacement. During this phase, the same types of cracks appear, but they are very thin and distributed over a large area (Fig. 18).

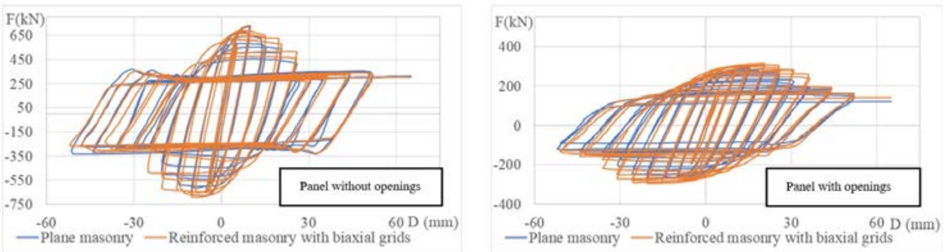


Fig. 17 − Hysteresis diagrams of the two panels at full scale, without and with openings reinforced with biaxial grids and plain masonry.

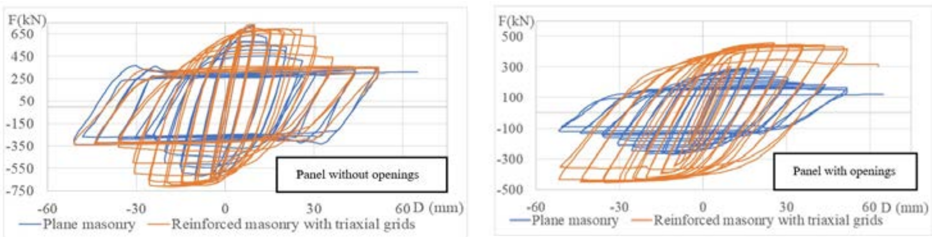


Fig. 18 − Hysteresis diagrams of the two panels at full scale, without and with openings reinforced with triaxial grids and plain masonry.

The configuration of the curve shown in Fig. 17 and Fig. 18 is directly influenced by the asymmetric disposition of the openings. Until the maximum resistance is reached, the behavior of the plain masonry is nonlinear, cracks appearing near the corners at both openings.

In the central area, the cracks appear in the double diagonal. After reaching the maximum force, a phase of rapid degradation of the resistance capacity follows.

For the reinforced models with the biaxial grid, until the maximum resistance is reached, the answer is almost the same as for the plain masonry panel: 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.

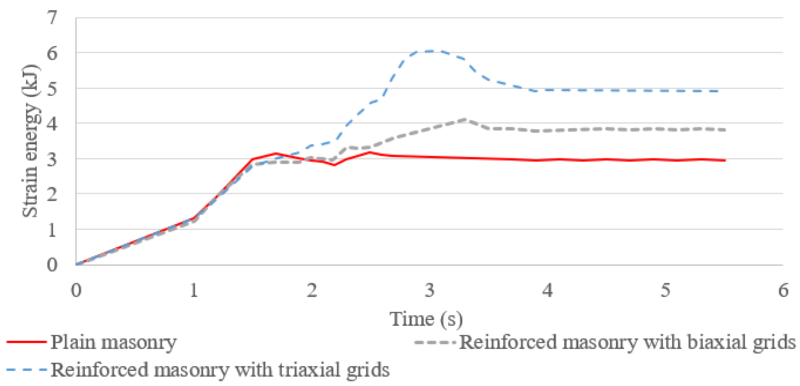


Fig. 19 − Strain energy for the panel without openings.

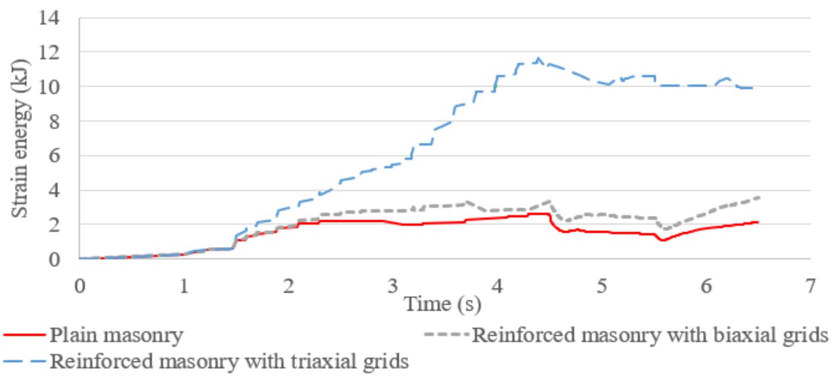


Fig. 20 − Strain energy for the panel with openings.

From Fig. 19 and Fig. 20 it can be observed that until the entry into the nonlinear domain there are variations of the strain energy. After entering the nonlinear domain, one notice that the effect of reinforcing with biaxial and triaxial grids leads to the increase of the strain energy.

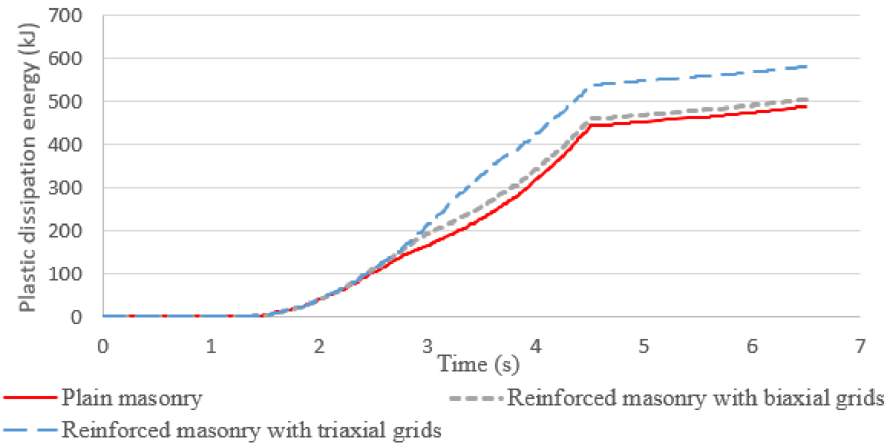


Fig. 21 – Plastic dissipation energy for the panel without openings.

Fig. 21 shows that for the panel reinforced with biaxial grids the dissipated energy by plastic deformations is about 10% higher than the energy dissipated in the case of the plain masonry panel. In the case of the paanel reinforced with triaxial grids, the dissipated energy is approximately 45% higher.

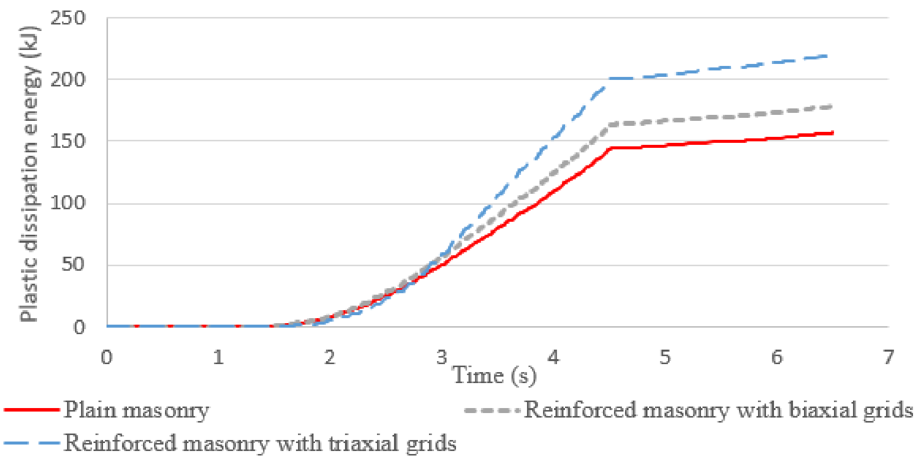


Fig. 22 − Plastic dissipation energy for the panel with openings.

Fig. 22 shows that for the panel reinforced with biaxial and triaxial grids, the dissipated energy by plastic deformations is approximately equal to the dissipated energy in the case of the plain masonry panel. In the case of the panel reinforced with triaxial grids, the dissipated energy is about 30% higher.

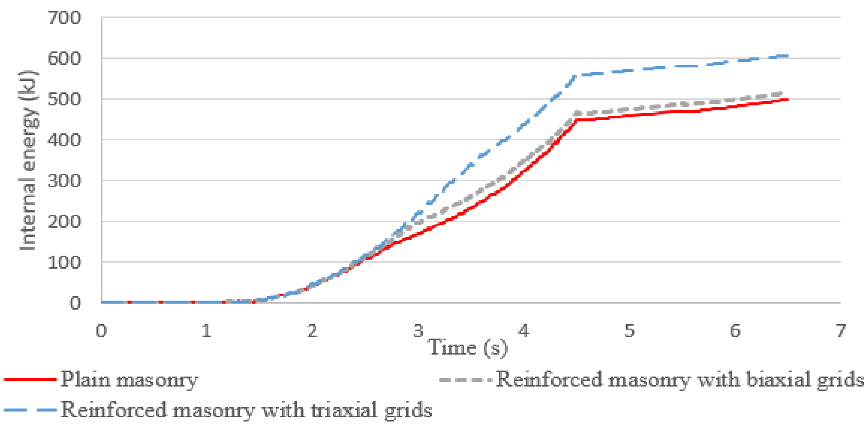


Fig. 23 – Internal energy for the panel without openings.

From Fig. 23 it can be observed that in the case of the panel reinforced with biaxial grids the induced energy has a value about 10% higher than in the case of plain masonry. For the panel reinforced with triaxial grids, the induced energy is 45% higher than in the case of the plain masonry.

For both panels with openings and without openings, the reinforced with polymer grids leads to less degradation compared to plain masonry.

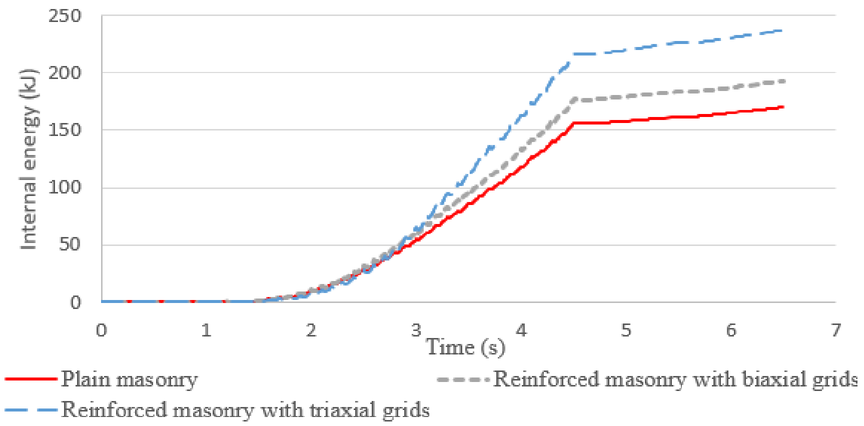


Fig. 24 – Internal energy for the panel with openings.

Taking into account that the internal energy is equal to the induced energy, from the Fig. 24 it can be observed that in the case of the panel reinforced with biaxial grilles the induced energy has a value of about 5%

higher than in the case of the plain masonry panel. For the panel reinforced with triaxial grids, the induced energy is 31% higher than in the case of the plain masonry panel.

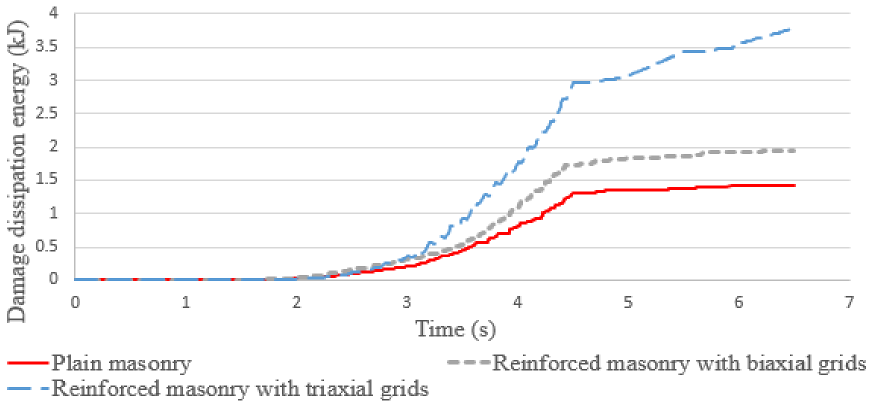


Fig. 25 − Damage dissipation energy for the panel without openings.

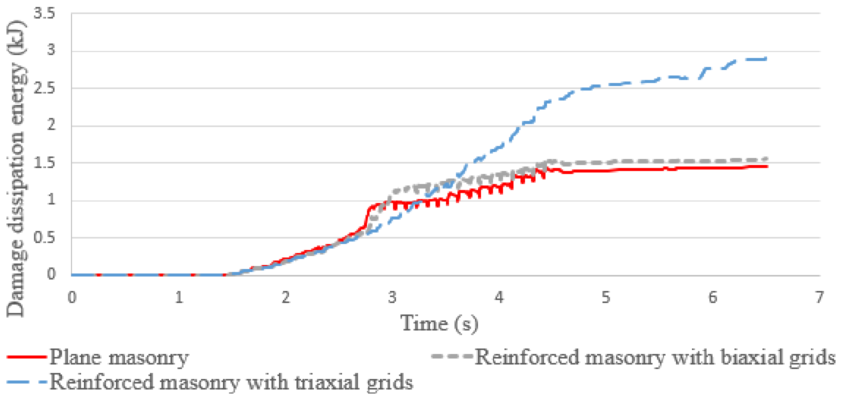


Fig. 26 − Damage dissipation energy for the panel with openings.

From Fig. 25 and 26, it can be observed that up to a point there is no variation between dissipated energy, which means that they are in the elastic domain. After exceeding this point, the dissipated energy increases for panels reinforced with biaxial and triaxial grids.

4. Conclusion

Numerical modeling of testing results has replaced the incapacity of analytical methods to define the fields of application for masonry structural members, based on pure lime mortars and reinforced with polymer grids of high density and strength. The tests were carried out at the special request of UNESCO Chair #177 in Bucharest and financially supported by the Research Programs of the European Union after successfully participating in public competitions. The numerical modeling of the testing results confirms that the use of polymer grids with solid joints as reinforcement is an inspired idea of practical interest. The reinforcing concept is based on the Theory of Dislocations developed by Prof. Landau and was awarded Nobel in 1962. It is interesting to remark that the initial geometric imperfections of masonry are successfully corrected through the geometric perfection of polymer grids. Practically, the paper presents diagrams that numerically confirm that the triaxial grids are more efficient than the biaxial ones. The method patented in 1995 is easy and reliable to be applied and provides durability for about 120 years. It is also worth noting that the method of reinforcing with polymer grids is reversible as requested by ISCARSAH Recommendations in 2001. Indeed, that means after a while of service the old polymer grids can be simply replaced with new ones. Finally, the proposed method is already used for a long time in Romania. It is indeed very useful in enhancing the seismic resilience of masonry structural members.

Acknowledgments. The author is expressing his respectful thanks to the distinguished Professor Ion Giurma, Ph.D., for his kind support to submit this paper to the Scientific Bulletin of the University "Gheorghe Asachi" in Iași. The unconditional support of UNESCO Chair #177 in Bucharest for carrying out his doctoral thesis, supervised by Emeritus Professor Ramiro Sofronie, *Ph.D., D.H.C.*, and for helping to preparing this original paper is also gratefully acknowledged.

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MODELAREA NUMERICĂ A TESTELOR PE ZIDĂRIE

(Rezumat)

Articolul tratează interpretarea numerică a testelor pseudo-dinamice efectuate pe peretele de reacțiune al JRC Ispra, Italia. Au fost utilizate patru panouri structurale de zidărie la scară naturală. Două câte două, panourile erau formate din zidărie simplă și armată, cu deschideri pentru uși și ferestre și fără deschideri. Metoda de armare a zidăriei cu grile polimerice, brevetată în 1995, se aplică numai zidăriei cu mortar pe bază de var curat, fără sau cu puțin ciment și se bazează pe două idei: 1) Rosturile verticale ale zidăriei sunt imperfecțiuni geometrice. În consecință, fiecare cărămidă posedă șase grade de libertate. Această libertate holistică conferă zidăriei calitatatea unei deformării de ansamblu în toate direcțiile, numită adaptare. Conform Teoriei Dislocației, în jurul fiecărei imperfecțiuni geometrice apar concentrări locale de eforturi unitare, provocând avarii. Prin regularitatea lor geometrică, grilele polimerice, previn acest inconvenient. Toate rezultatele analizei numerice sunt prezentate comparativ luând în considerare zidăria simplă și armată cu grile biaxiale și triaxiale. Lucrarea prezintă diagramele pentru histerezis, energie de deformare și energie disipată. În domeniul plastic, energia internă și, în final, energia disipată prin deteriorare. Articolul conchide că prin modelarea numerică a testelor de laborator, idea armării zidăriei pe bază de mortar de var cu grile polimerice a fost confirmată cu succes.