Original masonry *versus* advanced masonry

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Abstract. The paper deals with a comparative analysis between original and advanced masonry. Both are of high practical interest in buildings and monuments. Particularly, in seismic areas, where they are submitted to the strong actions of earthquakes, the Latin principle *Primum non nocere* should be applied. That principle was considered by the Venice Chart in 1964. Later it was resumed by ICOMOS-Iscarsah Recommendations in 2001. The paper presents first some historical data for each type of masonry. The original masonry has a long history when it was well checked by time. On the contrary, the history of advanced masonry is very short. Among the basic proprieties of the original masonry is the ductility of the lime mortar. Its mechanical strengths are lower than that of bricks. In these conditions, the original masonry exhibits the phenomenon of self-defending by adaptation. It is not the case of the advanced masonry which remains stiff. By physical modeling, the main proprieties of original and advanced masonry were proved. Then, by numerical modeling, the testing results were generalized and prepared for further use in design and research. From the comparative analysis results that each of the two types of masonry has specific fields of application.

1. Introduction

Stone constructions were created even since the megalithic culture. Individual pieces of rock were collected together and manually superposed one by one. They were kept in gravitational equilibrium by dry friction only. Egyptian pyramids, for instance, were erected by that procedure. After a while, in regions scarce in stones, but rich in clayey soils, masonry was invented. The event was revolutionary regarded, like a quantic jump. Original masonry consisted of solid bricks, either dried or baked, with pure lime mortars. The verticality of structural members was controlled with the plumb-bob wire. This device was disclosed in the Bible. The same holly book also mentioned the energetic progress achieved then. By burning the inserted chaff in the clay of bricks their weight was somewhat reduced. In this way was born the ergonomy, the science of minimum mechanical work. To brick masonry, the friction between solid units, ones used for stone buildings, was replaced with ductile lime mortars. In this way, each brick receives six, very small degrees of freedom. Consequently, the number of DOF held by a masonry building became equal to six times its number of bricks. By this internal mobility brick masonry is self-protecting. For this reason, brick masonry became a very attractive construction material. Human civilization was built by masonry. The first masonry buildings in history were built in Mesopotamia as ziggurats. Babel Tower was one most representative of them. It was erected during the reign of Hammurabi the Great (1792-1750 BC). In 324 BC Alexander the Great found the Tower in ruin and intended to rebuild it, but he arrived too late. Much later, 83 years ago, in the year 1937, the sculptor, Constantin Brancusi, used 32 models of Babel Tower, at the scale 1/100 to compose his famous Endless
Column in Targu Jiu. The singular glory of brick masonry lasted until the Great Fire in Chicago that occurred on the 8th of October, 1871. The reconstruction of the town, on a territory free of earthquakes, started with tall buildings. For the higher heights, stronger masonry was required. The new trend quickly extended in all American States. In a few decades, the bricks were burned at higher temperatures, even over the vitrification point of clay. Then, they were made hollowed, with lower weight and much higher productivity. In the same period, the traditional lime mortar was upgraded in strength with English cement. 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 the advanced masonry. Anyhow, the two types of masonries do not exclude each other. The Cultural Heritage of UNESCO preserves many buildings and monuments built with old masonry. For their true maintenance, the original or historic masonry should be well known, correctly understood, and orthodontically applied on the site. [1]

2. **Original masonry (with solid bricks and pure lime mortars with free vertical joints, ductile with DOF)**
   - As already above-defined, the original masonry is composed of solid bricks and lime mortars. It is manually made with the aid of the gravitational force according to the principle „full-on joint”. That refers to the vertical joints. Usually, they are not filled with lime mortars. The horizontality of mortar joints is controlled by the water level. Due to the ductility of lime mortars, original masonry is endowed with the quality of adaptation. There is a spontaneous phenomenon consisting of small plastic deformations at constant volume.
   - As a consequence of the above-mentioned principle „full-on joint” the so-called „vault effect” comes true. That means decomposing a vertical force according to horizontal directions. It is useful for the decongestion of some geometrical imperfections of structures by the concentration of stresses.
   - Original masonry cannot be reinforced with steel bars because of rusting in lime mortars. Besides, the strength of steel is too high comparing with masonry strength. However, some sorts of polymer grids seem appropriate for such a purpose and would be worth trying.
   - Original masonry uses pure lime mortars, without cement, and therefore is non-polluting. Among the five oxides of cement, there is Silicium dioxide SiO₂ which is toxic for humans.
   - Maintenance of original masonry may ask special care when the porous bricks come in direct contact with water. Also, the rainwater and water coming from melted snow or ice may corrode lime mortars. [2]

3. **Advanced masonry (with holed bricks and cement mortar, no free joints, stiff and brittle, without DOF)**
   - This masonry, consisting of ceramic hollowed bricks and cement mortars, is based on advanced technologies of fabrication. They can reach high performances in strength. This masonry is brittle, very sensible to earthquakes and unequal settlements, and not able to the above-mentioned phenomenon of adaptation.
   - No vault effect, too.
   - Pollution due to SiO₂ of cement.
   - Reinforcement with steel bars allowed.
   - Maintenance with restrictions to fires higher than 300°C and direct shocks. [3]
4. Physical modeling

4.1. 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.

With the aid of the above-mentioned construction materials, wall panels were prepared with dimensions 875x240x874. The results are presented in $\sigma$ - $\varepsilon$ diagrams. (Figure 1 and Figure 2) [3]

![Figure 1](image1.png)  Wall panels submitted to axial compression  
![Figure 2](image2.png)  Wall panels submitted to diagonal tension

4.2. Full-scale 2D models of walls tested on the resistance wall→JRC Ispra, Italy
Inside of 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. (Figure 3)

![Figure 3](image3.png)  ELSA reaction wall in Ispra  
![Figure 4](image4.png)  The panel with openings, unreinforced after pseudo-dynamic tests

In the panel of plain masonry, the cracks appeared at the corners of both openings. The central zone of the panel, namely that between door and window, exhibits wall behavior, and double diagonal cracks occurred. Also, many bricks crashed, and some were even expelled. It was proven again that hollowed and perforated bricks are not suitable for structural members submitted to seismic loading. (Figure 4) [3]
4.3. Full-scale 3D models of buildings tested on the shaking tables→ENEL Seriate, Italy

Inside of the Ecoleader program, in 2001, tests were performed on the Master seismic for two models. The first 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 230x105x60mm and mortar lime-cement M1. (Figure 5) The second model was made with three rectangular openings for doors and windows, but also a solid wall curved out of its plan. The reinforced concrete floor was made directly on the model, without the existence of a belt. The bricks used were cored bricks with dimensions 200x400x230mm. (Figure 6) The models were tested to Vrancea ’77 tectonic earthquake by using two DOF, the translation on the principal directions. The cracks were inclined at 45° and they started from the corners of the door and window, where they also dislocated at the intensity of +18dB, the collapse occurred, and the model broke in certain portions.

\[\text{Figure 5. The model of masonry with solid bricks} \]

\[\text{Figure 6. The model of masonry with cored bricks}\]

From Figure 7 and Figure 8 it can be observed that with the increase of the excitation, intensity discontinuities appear after the appearance of cracks, which produces a sudden increase of accelerations. In this case, the vibrations induced in the building influenced the movement recorder of the seismic mass. Due to the fastening system, additional stress was induced, which led to cracks at the corners at the bottom. [3,4]

\[\text{Figure 7. Induced and peak response acceleration on the horizontal direction E-W for the model with solid bricks}\]
5. Comparative analysis
To determine the influence of geometric characteristics on the behavior of masonry, we created, using finite element methods, wall panels in which we used solid bricks with dimensions 60x120x240mm, with typical strength 7.5MPa. For the advanced masonry we used cement mortar, and for original masonry, lime mortar with a thickness of 10mm. The models were created according to ICOMOS-Iscarsah Recommendations. [5] The results are shown in Figure 9 to Figure 29.

5.1. Comparison of stresses

Figure 9. Normal-tension $\sigma_{11}$[MPa] 

Figure 10. Normal-tension $\sigma_{11}$[MPa] 

Figure 11. Normal-tension $\sigma_{22}$[MPa] 

Figure 12. Normal-tension $\sigma_{22}$[MPa] 

Figure 13. Tangential tension $\sigma_{12}$[MPa] 

Figure 14. Tangential tension $\sigma_{12}$[MPa]
5.2. Comparison of strains

Original masonry

Advanced masonry

Figure 15. Normal deformation $\varepsilon_{11}$ [%]

Figure 16. Normal deformation $\varepsilon_{11}$ [%]

Figure 17. Normal deformation $\varepsilon_{22}$ [%]

Figure 18. Normal deformation $\varepsilon_{22}$ [%]

Figure 19. Tangential deformation $\gamma_{12}$ [%]

Figure 20. Tangential deformation $\gamma_{12}$ [%]

Figure 21. Displacement in horizontal direction [mm]

Figure 22. Displacement in horizontal direction [mm]

Figure 23. Displacement in the vertical direction [mm]

Figure 24. Displacement in the vertical direction [mm]
5.3. Comparison of potential energy

Figure 25. Dissipative energy [J]

Figure 26. Dissipative energy [J]

Figure 27. Dissipative energy of the masonry wall

Figure 28. The strain energy of the masonry wall
Figure 29. Monitored vertical displacement $v$ at the top of the wall [mm]

6. Conclusion
During the twenty-first century, the World Cultural Heritage of UNESCO has recorded the irrecoverable loss, because the difference between original, historic masonry and advanced, modern masonry, was ignored. Both masonries are nonhomogeneous, but the original masonry is non-composite because its deformations do not satisfy Saint Venant’s condition of geometric continuity, while the second one is a composite material. As demonstrated in the numerical modeling, in the case of the original masonry it is possible to decompose the vertical force in horizontal directions, thus appearing the vault effect. Due to the ductility of the lime mortar, the movement of the bricks is not restricted, taking place distribution of efforts over a large area, but also a reduction of effort values. In this way, the bricks are protected from damage. As a corollary, the original masonry can’t be reinforced with any kind of fibers, while the advanced one yes. Also in the numerical study, it was demonstrated that from a gravitational point of view the original masonry is alive, while the modern masonry is dead. In the case of physical modeling, it was demonstrated that hollowed and perforated bricks are not suitable for structural members submitted to seismic loading. The two types of masonry are incompatible between them. Finally, since the original masonry is ductile and can be easily repaired while the second one being brittle the damaged region should be fully detached and rebuilt.

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