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INNOVATIVE USE OF THE STONE IN SEISMIC RESISTANT ARCHITECTURE

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ABSTRACT :

A new structural approach allows the use of stone also in seismic areas. It consists in avoiding the weak point of stone's structural behaviour - the absence of a significant tensile strength - by assembling the elements through discrete monolithic blocks joined together with solution of continuity. Blocks are kept together by the effect of vertical loads resting on the structure or by internal pre-stressing cables. When the structure undergoes relevant horizontal forces (associated to seismic actions), the joints among the stone blocks can freely open, so that a collapse mechanism is turned into a sort of "controlled movement". The relationship between lateral force and displacement or between moments and rotations presents an elastic-softening behaviour. The structural systems can also be equipped with dissipating elements giving an energy dissipating capacity to the structure. These units can be located at the ends of the cables, overworking the extension of the cables or near the connection between the ashlars, overworking the opening of the joints. The study focuses on the numerical simulation of the response of simple models whose results can be extended to complex structures.

KEYWORDS: Stone, earthquake architecture, advanced technologies, energy dissipation

1. PAST, PRESENT AND FUTURE IN THE STRUCTURAL USE OF STONE

Stone has been always used in the history of constructions of all the civilizations. For the human feelings, stone represents the material of the eternity, material "mother", coming from the earth, and material "son", that can be degraded and re-assembled in other shapes. Because of its use through thousands of years, stone tells about human history and reconnects us to our roots. It is the basic material in the history of construction (Acocella, 2004) and is the hallmark of the monuments of ancient and recent past: as an example, Figure 1a shows the *Parthenon*, that together with the *Erechtheion* and *Propylaea* of the *Acropolis of Athens* represents one of the most relevant sign of the Greek civilization.

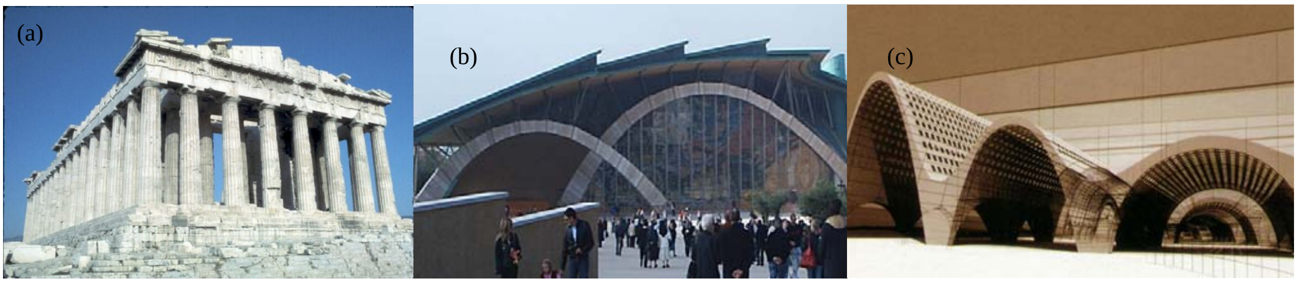

Figure 1 (a) Parthenon of Athens; (b) Church of Padre Pio in S. Giovanni Rotondo, Italy (Renzo Piano);
(c) Proposal for the Sea Front of Crotone, Italy (Paolo Verducci) in (D'Amato Guerrieri, 2006)

Even in recent past, it is possible to find widespread examples of the greatness of stone. At the present time, a relevant modern stone-based structure is the world-wide known *Church of Padre Pio* in San Giovanni Rotondo (Italy), designed by Renzo Piano and completed in 2004 (Figure 1b), built using a reinforced stone technology.
The project of Piano show that some recent predominant aesthetic and cultural models, become hegemonic in

countries characterized by the advance of technological research and spread of architectural experimentation, can be overcome, regaining possession of the masterly skills. Figure 1c reports an example from the last Biennale di Architettura in Venezia where the exhibition Cities of Stone proposed a number of projects based on the re-use of the stone in some Mediterranean areas, according to their tradition. New structural approaches can reappraise the use of stone also in terms of seismic protection, merging together the mechanical characteristics of this material (high stiffness and compressive strength) with up-to-date technologies.

2. AIM OF THE STUDY

The first fundamental issue in the design and creation of a new stone architecture is to guarantee suitable safety standards to the constructions. When analyzing the seismic behaviour of stone structures, the critical point is their very low tensile strength that usually leads to critical collapse mechanisms. If the blocks are not really connected but simply drawn close, the opening of the interfaces between the blocks does even more represent the start of a fracture, but can be considered a sort of "controlled movement" of the structural element. In this way, the protection of the structure is guaranteed and the system substantially maintains an elastic behaviour. Figure 2 illustrates the principle of the opening of joints and the simple structural schemes examined.

2.1. Structural Schemes and Analysis Types

Even considering a complex stone building, the structural scheme is made of linear elements, such as columns and beams, and curvilinear elements working together with the frame systems. The research can be reconnected to the study of simple structural elements: *cantilevered column* and *round arch.* In fact, considering a simple 1-story frame, both the column and the beam can be analyzed studying the behaviour of a cantilevered sub-element having height equal half the column height or the beam length. Also from the analysis of the round arch it is possible to deduce the structural behaviour of a semi-arch or of a portion of the arch.
Two simple elements have been investigated; the first is a cantilevered column, 5 m high, made of cubic ashlars having dimensions 1x1x1m. The element can reproduce the behaviour of the frame's column 10m high or of the beam 10m long. The second element is a round arch with a rise of 4m, made of 0.3x0.3m section elements. Eight nodes plane stress continuum elements have been used for the numerical modeling. A frictional contact rule has been assigned to the interface, so that compressive and shear stresses can be transferred from a block to an other, while the opening in tension eliminates the tensile stress at joints. The characteristics of the material assumed in the analysis derive from tests carried out on typical Italian rocks: compressive strength = 100 MPa; tensile strength = 25 MPa; elastic modulus = 60 GPa; Poisson's coefficient = 0.3; density = 2650 Kg/m^3.
The analyzed elements have been submitted to vertical loads derived from an hypothetical configuration of global structure and to a vertical pre-stressing. The values corresponding to average compressive stress of 2.5, 5, 10 MPa have been investigated. Two types of analysis have been performed: non linear static, in which a prescribed displacement has been imposed at the top of the structure and incremental dynamic with the application of 3 artificially generated spectrum-fitting accelerograms at the base. The peak value of the accelerograms has been increased starting from 0.03g.

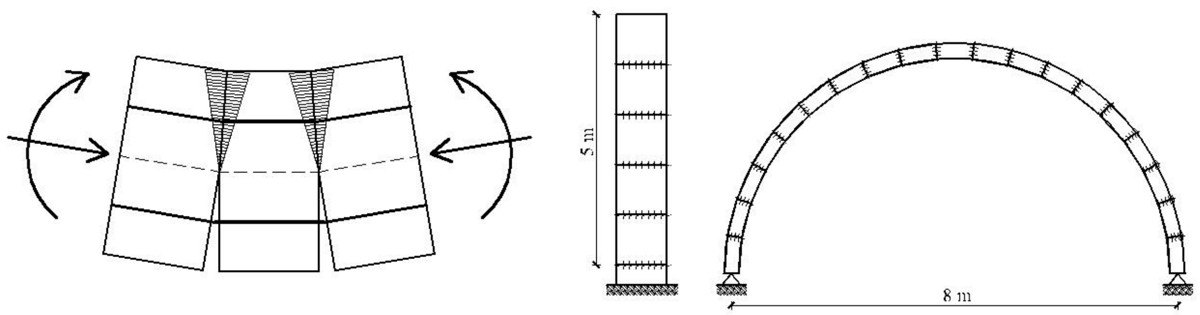

Figure 2 Opening of joints and examined structural schemes

3. BEHAVIOUR OF TRADITIONAL STRUCTURAL ELEMENTS

The traditional stone structure is made of modular stone elements jointed together with mortar layers. This system is particularly sensitive to horizontal actions which produces bending forces and, therefore, tensile stresses are induced in the stone, especially at the blocks interfaces, where the fractures are normally localized.
The first step of the research consists in investigating the behaviour of the two typologies of conventional stone elements, subjected to lateral forces. Both static and dynamic analysis have been performed. Vertical loads have been applied to the elements. A pre-stressed variant of the elements, capable to improve the performance of the structure, has been investigated. In order to evaluate the strength limit of the structural system, the following limits have been used: (1) the eccentricity of the axial force reaches the conventional limit imposed by the Italian standards (33% of the section's height); (2) the maximum compressive or tensile stress equals the corresponding material strength.
The results obtained confirm the fragile behaviour of this type of structures. The column gets quickly to collapse, because it reaches the limits of eccentricity and of tensile stress, this occurs for very low values of acceleration (0.03g for the column). Because of its shape, more suitable to resist to lateral actions, the arch has a better response even if the maximum peak value of acceleration (0.15 g) for the arch is lower than those normally prescribed by the standards. The structures are not able to give high levels of base shear (190 kN for the column, 15.6 for the arch) and top displacement (1.5 and 1.7 mm, respectively).

4. A NEW STRUCTURAL APPROACH FOR ENHANCING THE PERFORMANCE OF STONE

The next step of the research is the analysis of the same stone elements previously described, modelled with solution of continuity among the blocks. In actual applications, it is necessary to carefully set up the interfaces to avoid the sliding of the ashlars. Steel plates with particular treatments of their surface can be inserted. They seem to be useful also as protection tools, for avoiding the damage of the blocks during the relative rotation. These plates have also been structurally modelled to investigate their contribution to contrast the tensile stress developed at the interfaces. However, their presence do not significantly affect the numerical results.

4.1. Results for Cantilevered Column

The analysis has been performed for three different levels of pre-stress corresponding to average compressive stress of 2.5, 5, 10 MPa. The action has been modeled simply applying a vertical load on top of the structure or assigning a constraint to 2 unbounded cables located along the column. Figure 3(a) illustrates the results obtained from the non linear static analysis. The curves show the non linear elastic behaviour of the column made of discrete blocks and the positive influence of partial pre-stressing that gives more compactness to the structure and limits the second order effects, that lead to the structure collapse. Anyhow, the increase of the axial force level determines a monolithic behaviour of the column. The light curves of Figure 3(b) show how the modeling of the cables gives an hardening effect, that is less evident when the pre-stress level is increased.
Graphs in Figure 4 reports the curves, derived from incremental dynamic analyses, obtained averaging the values of displacement and base shear resulting from the application of 3 different accelerograms. The comparison with the results of static analysis confirms its validity. The results match the data presented before, even if a gap appears between the curves when they reach the maximum base shear. This gap is caused by the inertial forces associated to the dynamic response of the structure, that are not computable in the static analysis. The coordinates of the curve of the dynamic analysis correspond to the highest values of displacements-shear computed from each accelerogram. Therefore it represents an upper bound of the actual trend.
Figure 5 summarizes the results obtained for the pre-compression level of 2.5MPa. The non-linear trend represents the capacity curve of the enhanced model that reaches collapse at a peak acceleration of 0.17g. The corresponding point is represented by an X on the graph. The square spot represents the seismic demand for the conventional structure associated to the same level of acceleration, instead the circular spot is the performance point for the structure, corresponding to a peak value acceleration of 0.03g. It is evident how the model with solution of continuity among the blocks guarantees an enhanced capacity to the structural system.

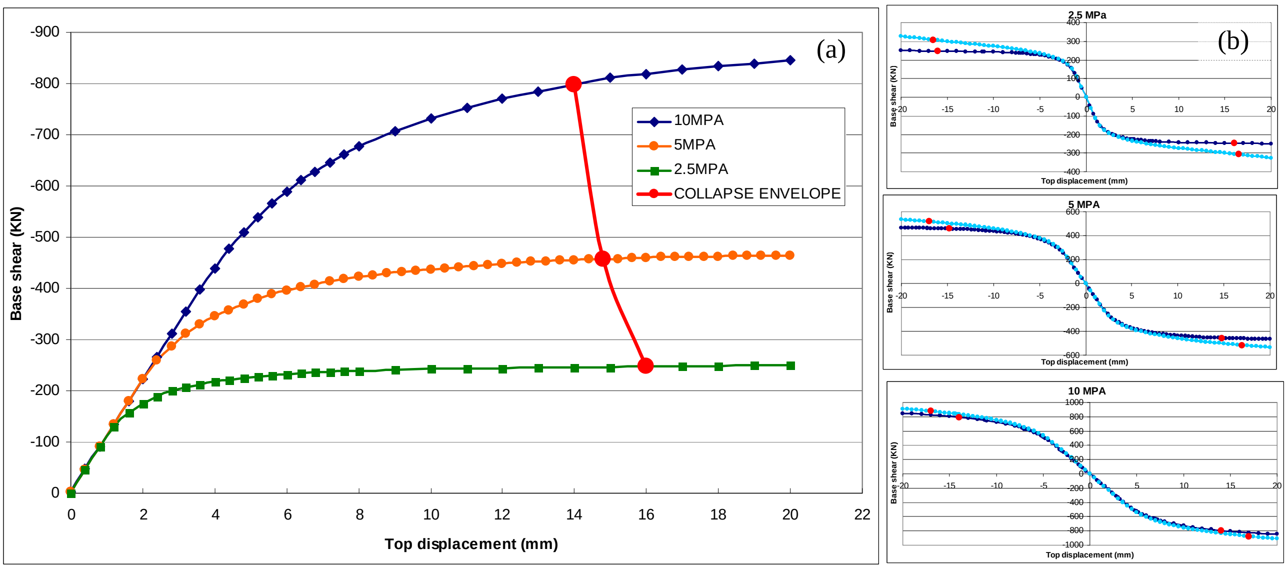

Figure 3 (a) Top displacement vs Base shear; (b) results with and without modeling of cables.

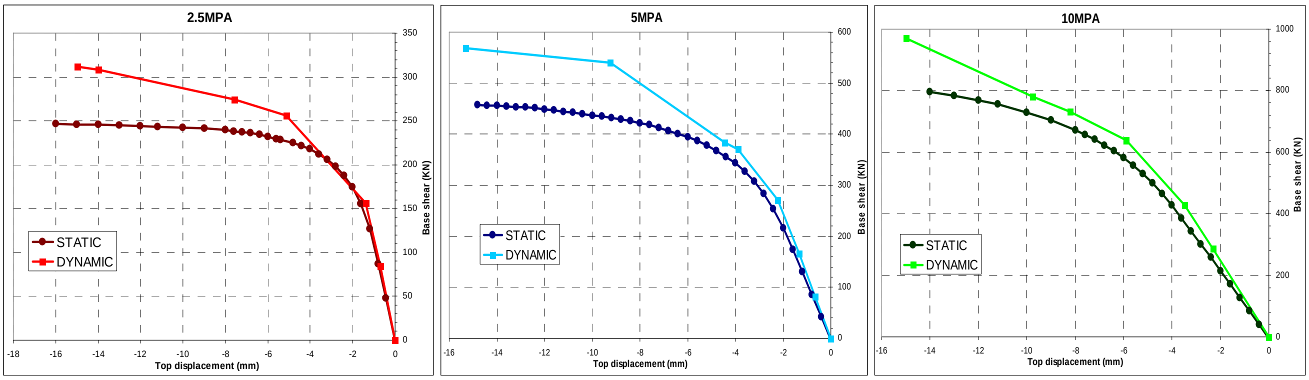

Figure 4 Incremental dynamic analyses compared with the static ones

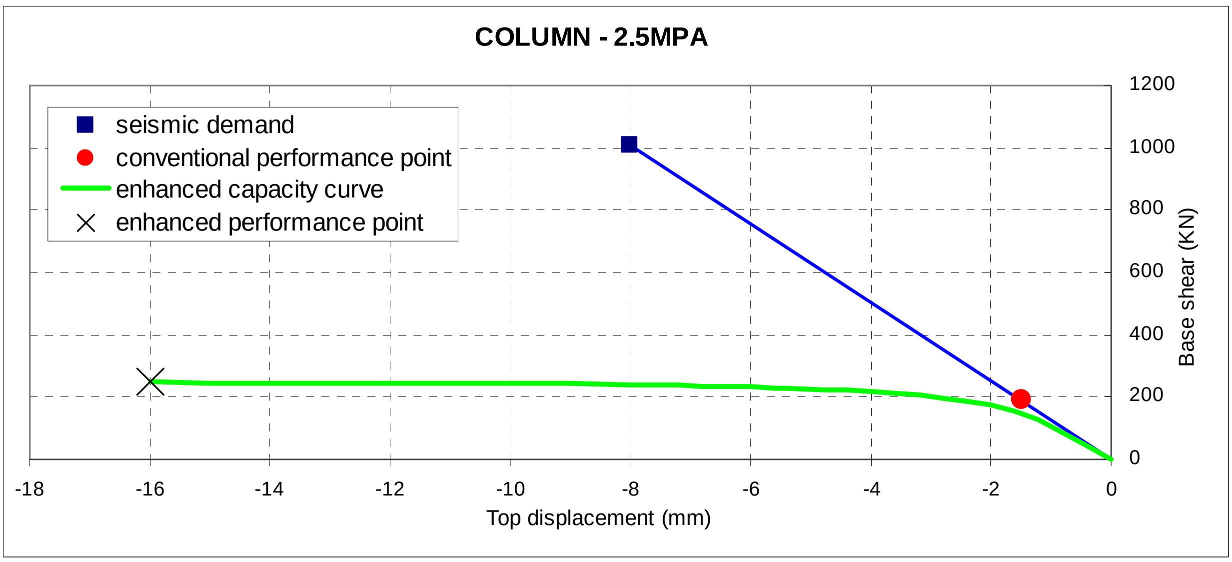

Figure 5 Comparison of the performances of conventional and enhanced column.

4.2. Results for Round Arch

The same approach used for the column has been also applied to the investigation of the round arch. An axial cable has been modelled in the structure through which a pre-stress of 2.5MPa has been assigned. The results for the two semi-arches derived from a static non linear analysis are reported in Figure 6.
The results obtained for the entire arch are summarized in Figure 7 and not reported in an extended way for the sake of brevity.

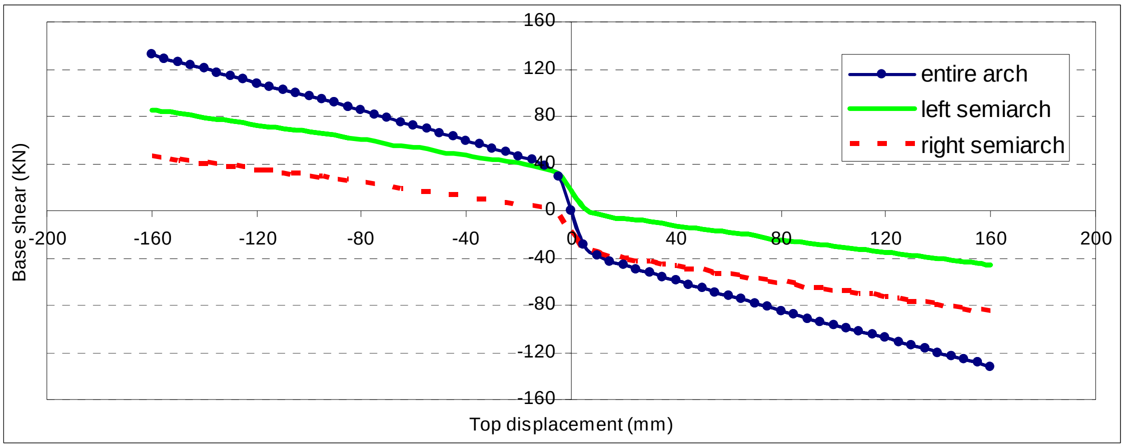

Figure 6 Results from non linear static analysis of the arch.

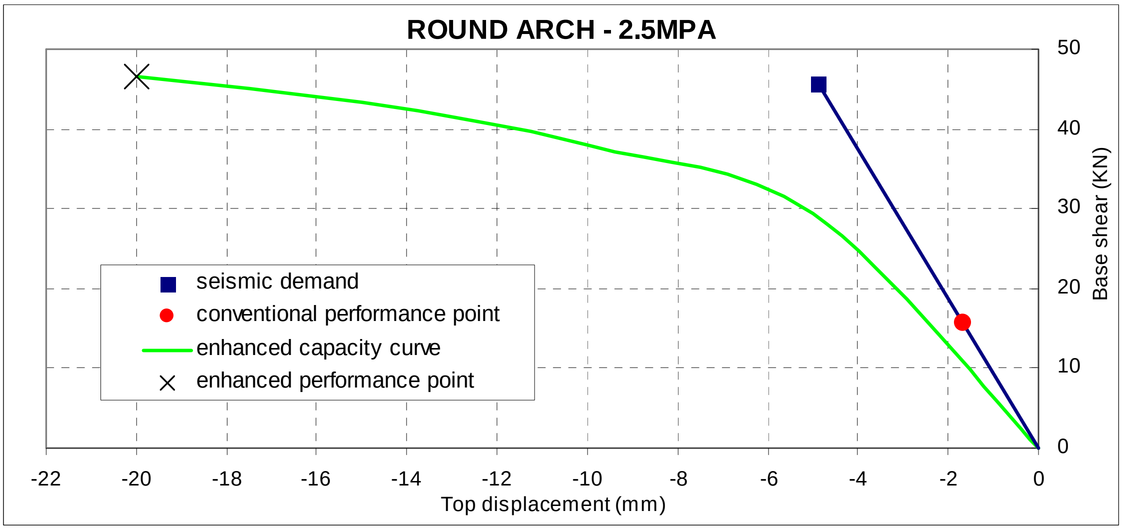

Figure 7 Comparison of the performances of conventional and enhanced arch.

As in the previous case, the non-linear trend represents the capacity curve of the enhanced model; in this case, the collapse is not caused by the exceeding values of the stress, but by the loss of stability of the structure. In fact, the high values of inertial forces, in some cases acting perpendicularly to the joints, overcome the pre-stressing force, producing the opening of the interface with the consequent collapse of the structure. This situation has been pointed out for a peak acceleration of 0.25g; the static analysis, through which inertial effects are not computable, cannot evidence this behaviour, presenting a higher displacement capacity, as reported in Figure 7. The square and circular spots on Figure 7 has the same meaning previously explained for Figure 5; the conventional performance point corresponds to a peak value acceleration of 0.15g. Also in this case, the model with solution of continuity among the blocks shows a better response, that can also be enhanced by increasing the pre-stressing level.

4.3. Energy dissipation

The successive stage of the research consists of investigating the effects of the insertion of dissipating units between the blocks that overwork with the opening of the interfaces, occurring under the effect of lateral actions. These tools are made of mild steel and present a very low elastic limit so that, when the joint opens, they deform undergoing plastic hysteretic cycles and dissipating energy as unreturned plastic work. Both static and dynamic analysis have been performed calibrating the parameters characterizing the devices.
The analyses performed, on both the column and the arch, confirm that the introduction of the dissipating devices allows for enhancing the structure performance, increasing the level of peak acceleration that it can support. Figure 8 shows how the structure with the dissipating units is able to sustain the accelerogram with a peak value of 0.2g, that was over the performance point of the previous analyzed structure. The mechanical characteristics of the devices (elastic displacement limit, maximum tensile force, hardening of the post-elastic trend) have been set to optimize the effect. The best results have been obtained, for the same level of starting stiffness, giving a percentage of hardening to the post-elastic trend. Figure 9 and 10 show the comparison in terms of force-displacement curve and plastic work, respectively, between the devices with and without the hardening effect. Even if the elastic-perfectly-plastic unit involves a higher level of plastic work, as confirmed by a wider dissipating cycle, the analysis shows that a percentage of hardening (assumed equal to 2% of the starting stiffness) guarantees a higher peak value of acceleration that the structure is able to sustain, because of a stiffening effect that limits the displacements of the system.

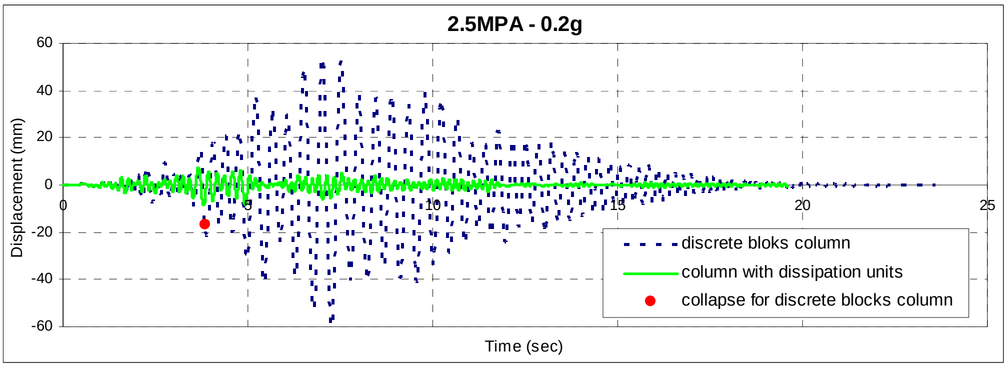

Figure 8 Comparison of displacement time history of the column with and without the dissipating units.

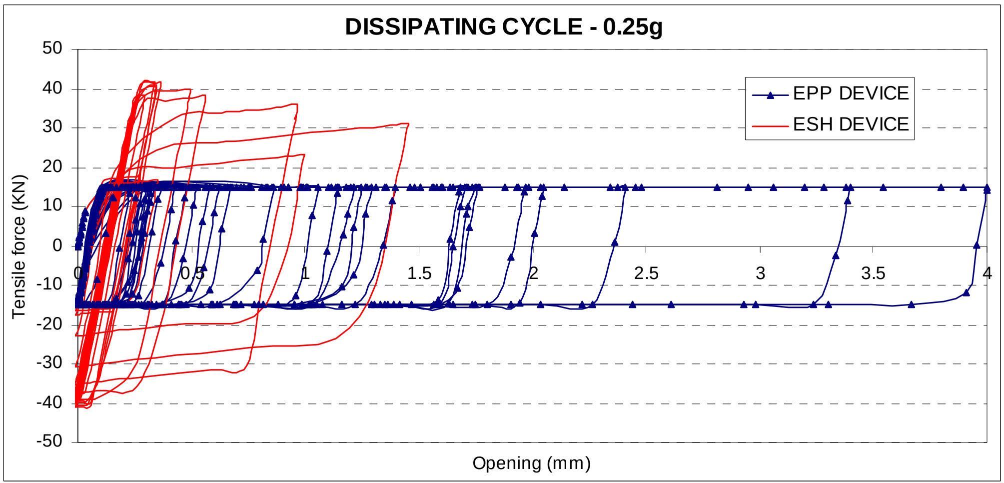

Figure 9 Effect of the hardening in dissipating units on their force - displacement response

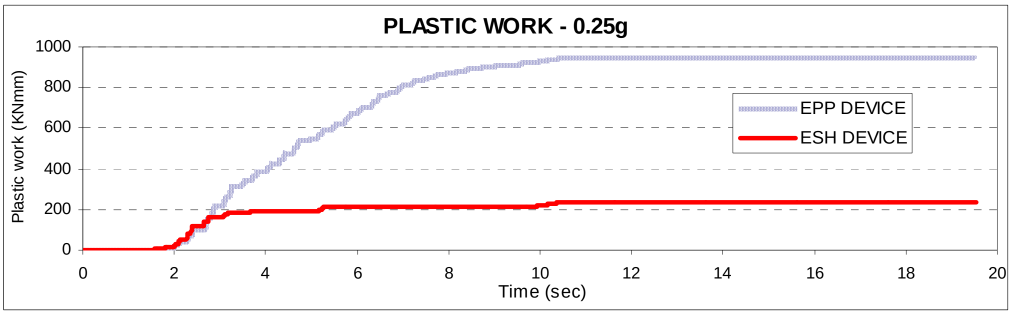

Figure 10 Plastic work of the dissipating units with and without the hardening

5. EXTENSION TO COMPLEX CONSTRUCTIONS

The results obtained for basic structural elements can be extended to more complex structures such as framed systems. In fact, as previously explained, the behavior of a column or beam of a 1-span 1-story framed system can be extrapolated from the results obtained for the column of half the length. The analyses have been also performed to investigate the behavior of the beam, using the same numerical model defined before.
In this case, the effect of self weight and top load not only gives a compressive tension to the structure but also a bending and shearing one. A distribution of external forces has been assigned to the structure in the pre-stressing phase to reproduce the effect of these actions, as presented in Figure 11 (a). These forces lead to a non-symmetric base shear-top displacement curve, as shown in Figure 11 (b), obtained with a nonlinear static analysis.

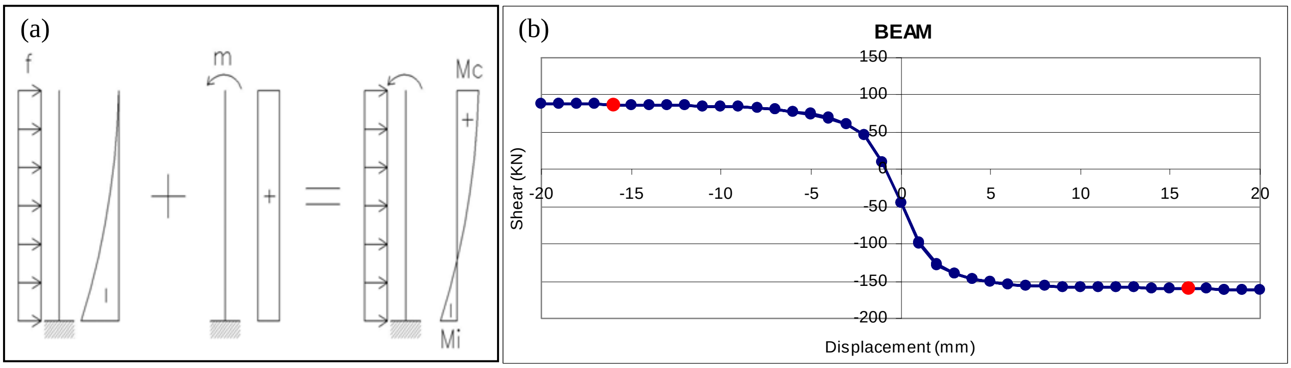

Figure 11 (a) Modelling the dead load and top load effects in beam analysis; (b) Non linear static analysis curve.

The moment-deflection correlation of the beam can be extrapolated from the relationship between base shear and top displacement obtained from the half-length column. Also the corresponding axial force-vertical displacement can be investigated or disregarded because of the relevant dimensions of the sections, that lead to high values of axial stiffness.
The complete structural behavior of the frame can be reconnected to the calculation of the stiffness matrix of the system. Each element forming the frame can be described by a 12x12 matrix in which the terms express the element's stiffness to axial, bending and shear forces. Each term represents the non linear correlation among the external force and the associated generalized displacement. Once obtained the matrix for each element forming the structure, it is possible to investigate the behavior of complex constructions.

6. INNOVATION FOR A NEW VISION IN STONE APPLICATION

Nowadays the urban landscape is undergoing a drastic mutation because of the advent of a modern, high tech architecture. This change involves also those cities, like the Mediterranean ones, conceived and built with stone, undermining their founding identity. In this context, a new sensibility that invokes a re-appraisal of the use of stone is facing these tendencies. As already reminded, one of the sections of the last "Biennale" held in Venice on 2006, was entitled to the "Cities of Stone" (D'Amato Guerrieri, 2006). One of the project presented at the exhibition, designed by the architect Paolo Verducci, concerning the competition for Punta Perotti site in Bari, provides for a relevant stone construction as a solution for a big Christian temple - Figure 12 (Mezzi & Verducci, 2007). The conceived structural solution is illustrated in (Mezzi, 2007), where also some other references can be found. The structural concept design provides for the application of new advanced solutions to guarantee the seismic protection of the structure; in particular, stone pre-stressed elements composed of disconnected ashlars are hypothesized, like the ones analyzed in this paper.

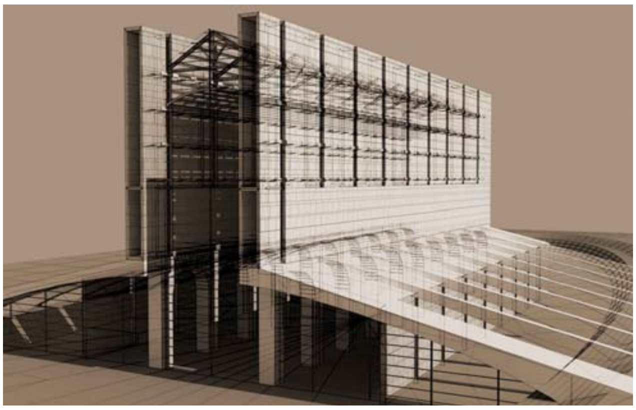

Figure 13 Virtual view of the Temple of Punta Perotti (design Paolo Verducci).

5. CONCLUSIONS

An advanced structural use of the stone has been proposed, referring also possible actual applications, allowing for the comeback of stone as construction material in seismic areas. Basic structural elements has been investigated through numerical simulations, modeling the elements with solution of continuity among the blocks and the pre-stressing action given by dead load or unbounded cables. The effect of inserting dissipating devices at the interfaces has been analyzed. The analyses demonstrate the enhancing effects of these technologies, with an increasing of the seismic performance of the structure. The possibility to extend the obtained results to more complex structures has been investigated.

ACKNOWLEDGMENTS

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