Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

The Pompeii Basilica: Knowledge for Conservation in Seismic Region

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ABSTRACT: This paper presents the results of a 3D FEM analysis by means of a multi-scale approach accounting also for aging effects. A detailed analysis at micro-scale, involving discrete elastic model of single brick units and mortar joints and studying the interaction of structural components and innovative brick staggered pattern, was performed to assess the global mechanical properties of homogenized columns (meso-scale). Finally, at macro-scale the vulnerability of the entire structure has been assessed. The aim of this study is to prospect a multi-scale approach method that is applied to a case study to investigate the history of Pompeii Basilica and so to improve the knowledge for conservation in seismic regions. According to up-to-date relieves, current numerical analyses and historical interpretations, comparing tensile stresses results, the outcomes are compatible with seismic events occurred during the service life of the Basilica.

1 THE ARCHITECTONIC HISTORICAL ANALYSIS OF THE BASILICA.

This study is proposed as a first synthesis of results obtained by crossing information coming from various disciplinary specificities. The recognition of the known historical data as well as the hypotheses on the constructive (and destructive) vicissitudes of the Basilica of Pompeii, has been compared to a numerical model relative to the mechanical behavior of the structure to give an objective interpretation of the earthquake (62 A. D.) legacies and to demonstrate the compatibility of the actions with the conditions in which the building appeared at the moment of its discovery.

1.1 Main historical events.

The discovery of the Basilica of Pompeii happens in 1813, during the campaign of excavations that interested the *Forum* and buildings around it. Since the first recoveries, due to the dimensions and proportions of the building (approximately 56 m x 24 m), there were no doubts about interpretation/attribution regard to its function; misunderstandings were frequent above all before the archaeological systematic excavations in Pompeii. A general agreement with the description of that type of Basilica in Vitruvio, and especially the position nearby the *Forum* led to immediate recognition that a sort of stock exchange and justice administration building was obviously found. Therefore, since from first annotations in the excavation journal, it is described like a Basilica and, perhaps just from the comparison with other similar buildings, from the beginning archeological excavation were carried out to trace the perimeter of the building.

The great amount of workers in such an operation and the length of jobs prove the great amount of material that obstructed the outside and the inside of the building. The necessity to proceed at the same time on the two sides of the perimetric outer walls, were obviously enforced by the risk to have an mass pushing on a single side of the walls. It has always referred to as earth-like and ash detritus and it did not refer to building materials from inside the Basilica. All this leads to believe that after the 62 A. D. earthquake, for a building of such dimensions the ancient Pompeii inhabitants were able only to proceed with ruins removal.

Tests carried out and comparison of the constructive techniques validate the hypothesis of the Basilica edification in the pre-Roman period of Pompeii, making it the oldest basilican episode in the world of which there is still trace.

The seismic history of Italy, and in particular of southern Italy, had already required that they developed advanced constructive techniques. Every reconstruction in Pompeii between the 62 A. D. earthquake and the volcanic eruption testifies how much the consolidation expertise was employed with familiarity in the situations that demanded this type of intervention; it is not difficult to find cases of reconstruction realized with techniques that already show a greater attention to the details in an earthquake zone.

In the building history of the Basilica, it is possible to recognize constructive wisdom already in the phase of the early construction. The dimensions and the proportions of the building are considerable and the realization of the brick pillars of the central nave has been interpreted like the necessity of execution rapidity with particular attention to the overall economy of the whole work.

The two hypotheses of covering - with open roof on the central porch, so-called hypaethral- and with double pitch roof - have seen periods of greater or smaller success, with proneness to the second model. In XIX century it was probably attempted to find agreement between the Pompeian building and similar models of basilica and above all with the description of this architectonic type supplied by Vitruvio; someone wanted to see in the opened porch an indication of a Greek origin more than Roman. Then, Superintendent Antonio Sogliano tried to find inidications of this reconstructive hypothesis, which survived for all the first years of XX century, until Amedeo Maiuri supplied an interpretation that restored the hypothesis of a cover roof scheme.

Previously the *pensionnaires* of the Academy of France in Rome proposed the two solutions exactly in the periods in which the variants of the monument were formulated on the base of the ruins discovered.

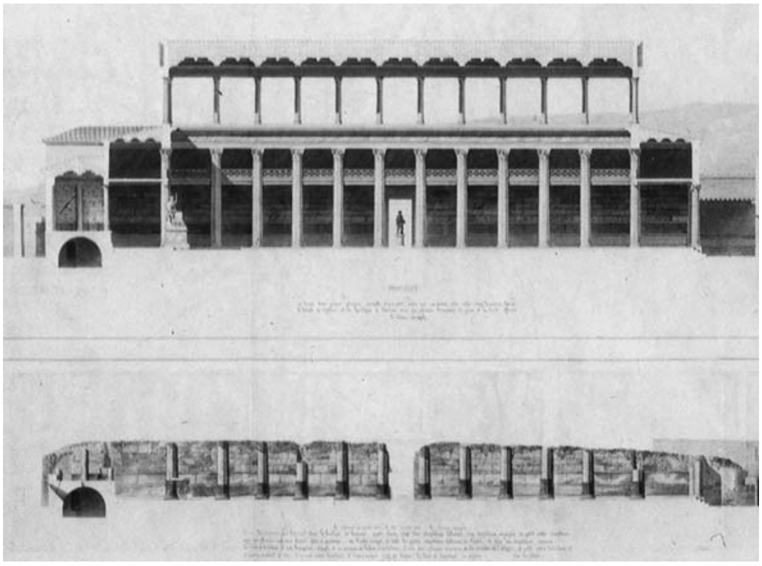


Figure 1 : Félix-Emmanuel Callet, Comparison between ruins and reconstructive hypotese of the Basilica, 1823.

The absence of the Corinthian capitals on the central columns has been explained considering that such a valuable material was set off already in the years immediately after the eruption of the Vesuvius. Magistrates were sent from Rome in order to make a report about the conditions of the cities hit from the eruption. For Ercolano they could only certify the total loss of the city, while for Pompeii, also irrecoverable, still could catch a glimpse of some higher buildings, right nearby the *Forum*.

It has always been well known spoliation activity of the valuable materials in this phase immediately after an eruption, and the case of the Basilica should have been included in such usual procedure above all for the ease to remove statues and capitals like as other architectonic element for a simple reutilization.

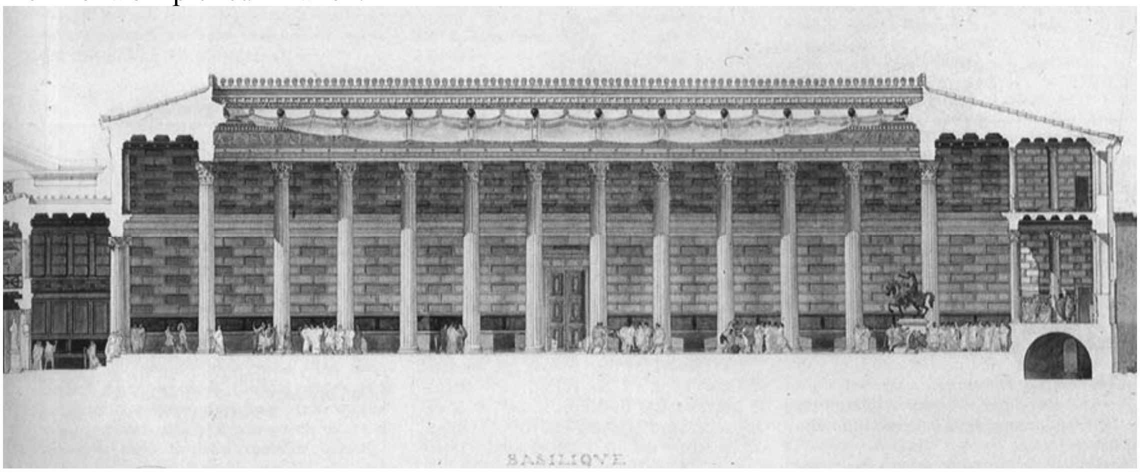


Figure 2 : Léon Jaussely Ideal reconstruction of the Basilica with the hypaethral roof scheme, 1910.

The hypotheses about the condition of the basilica between the earthquake and the eruption refer to the reconstruction activity of the whole city of Pompeii. The functions of the great public buildings seriously damaged - in particular the temples - were temporarily moved in buildings of better conditions to relaunch enterprises quickly and to find financial funds immediately in the post-seismic phase. The reconstruction of the greater buildings, and the Basilica for sure, needed not only economic availability, but also workers, that in this period were certainly engaged by privates.

1.2 Present situation

At the present time the area appears with the outer walls erected approximately up to the height of the first columns order. There only pieces of the 28 brick columns remain, with an average height of approximately 1.70 m.

Figure 3-4 : Present situation and a detail of a remaining brick column.

The tribunal has been partially reconstructed in the early years of XX century by the architect Luigi Iacono who attempted to supply an idea of the proportions that such part of the building must have. The outer walls, partially integrated at the top with the so-called sacrifice surfaces have been consolidated and now they are visible to us, as they were after the discovery. A giant order for columns of the central nave corresponds to a double order realized from pilaster along the lateral aisles. Between the two orders, the frame is connected to the tribunal.

One of the building's peculiarity is surely related with the constructive technique of the pillars-columns made of masonry with the external surface simulating marble in order to reproduce the apparence of stone columns. This technique, widely used in the roman architecture, has never found such a peculiar model for the single lateritious elements, almost a *unicum* in which aesthetic and technical are joined in a perfect way.

2 MULTI-SCALE NUMERICAL STUDY

One of the aims of this study was to develop finite-element models (F.E.M.) that could simulate at multi-scale levels the behaviour of this Pompeian building, as it has been virtually reconstructed, to achieve a more fundamental insight of the history and last days of this structure. Masonry is a material which exhibits distinct directional properties due to the mortar joints which act as planes of weakness. The large number of influence factors, such as anisotropy, material properties of the bricks and mortar, arrangement of bed and head joints and quality of workmanship, make the simulation of masonry structures extremely difficult.

Multi-scale is a viable approach to reduce/eliminate uncertainty and empiricism in the simulation of complex engineering systems. Bridging length scale from micro-interaction (millimetres) to macro-capacity (meters) reduces computing power rapidly, and it is a valuable way to deeply investigate the knowledge of Romans about building techniques and to asses the behaviour of monumental buildings. To assess the aging effect, the elastic modulus ratio n of the mortar E_m over the brick E_b has been gradually reduced from a reference case of homogeneous material *(n=1)* to a heavily degraded case *(n=0.1)*.

2.1 Micro-Scale: Brick-Mortar Interaction

At the micro level, the interaction between mortar joints and brick units is analyzed by means of a detailed analysis involving discrete elastic model of single elements layered according to different patterns. Page (1978) made the first attempt to use a micro-model for masonry structures. In Fig. 5 is the mortar-bricks pattern found in the columns' ruins that is different from the aligned patterns found in other older masonries. The usual mortar-bricks pattern found in other ancient buildings has all the vertical mortar joints aligned, while in Pompei was found an unprecedented staggered pattern realistically to increase the seismic performance of the columns.

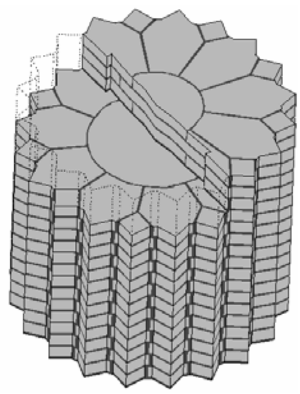


Figure 5 : A segment of the F.E.M. micro-scale model adopted: Pompeii's pattern detail.

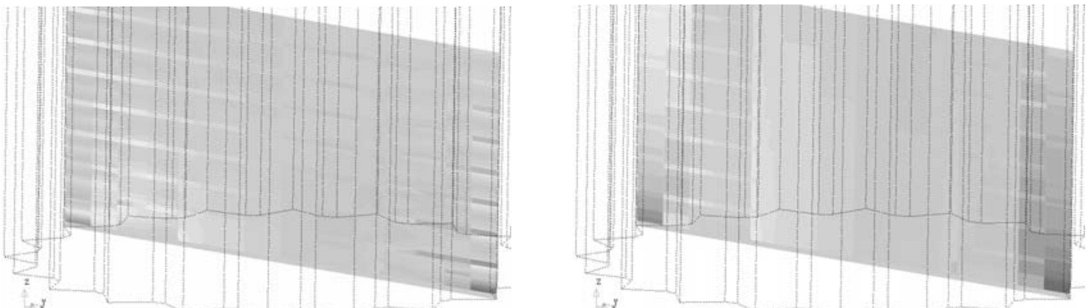
The beneficial effects of this innovative staggered pattern have been assessed. Starting from on-site relieves, a single column modelling, wherein masonry components are modelled separately, has been performed using the multipurpose finite-element analysis software DIANA v9.1, which can handle accurate three-dimensional analyses (Rots 1991,; de Witte and Kikstra 2005).

A segment of one meter of the column was modelled by 72960 eight-node, three-dimensional solid brick elements, based on linear material properties to have a reasonable run time for the program. The structural materials properties are reported in tab. 1 for the main structure. The column was loaded by its own weight and by the roof (timber for the truss, tiles,…) at the top.

Table 1 : Materials Properties.

	Young Modulus E kN/mm^2	Poisson Ratio -	Unit Weight kN/m^3
Brick Units	6.0	0.2	21.0
Mortar Joints	6.0 - 3.0 - 1.5 - 0.6	0.2	15.0
Roof (average)	-	-	7.0

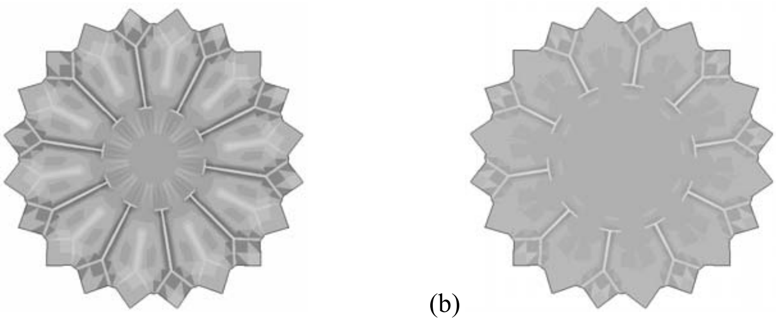
Sixteen analyses has been performed for the dead load only and for an horizontal increasing load applied at the top of the column on a cantilever scheme. It is clearly seen that in an aligned pattern (Fig. 6a) some stress concentrations are present and a weak plane is found in correspondence of the mortar head joints when the column is horizontally loaded.



(a) (b)

Figure 6 : Vertical stress Contour Plot. Vertical sect. *(n=0.25)*: (a) aligned pattern, (b) Pompeii's pattern.

The pattern found in Pompei (Fig. 6b) allows some main advantages. It makes the stress field more homogeneous (Fig. 7), avoids weak planes and reduces maximum tensile stresses while increasing the confining pressure acting on the mortar joints. This is a performance enhancement.



(a) (b)

Figure 7 : Vertical stress Contour Plot. Horizontal sect. *(n=0.25)*: (a) aligned pattern, (b) Pompeii's pattern.

In the case of $n=0.25$, compared for example to aligned case, there is a maximum tensile stress reduction of about 36% for axial load and 69% for shear type load, while the confining horizontal stress increase is about 19% and 13% respectively.

The interface brick/mortar tensile stresses are responsible for most cracking as well as slip, which is degradation, and from a micro-scale point of view there are effective benefits from the pattern found in Pompeii compared to the aligned one.

2.2 Meso-Scale: Global Column Response

The meso-level does not make a distinction between individual blocks and joints but treats masonry as a continuum homogenized composite. Studies on micro-modelling applications are preliminary to give deeper insight about the local behaviour of masonry structures, but composite modelling is probably more practice oriented due to the facility of mesh generation, reduced time and memory demand. This type of modelling is most valuable when a compromise between accuracy and efficiency is needed.

Starting from historical studies, the height and constraints of a single column has been evaluated and the global response has been estimated according to the micro-scale analyses homogenizing that complex structure and considering the aging effect through the *n* ratio.

It has been found that the elastic lateral homogenized stiffness E_bI_n, as well as the elastic homogenized axial stiffness E_bA_n, reduces with aging (that is *n* reduction), while at this scale level it is difficult to adequately represent all the phenomena described in the previous section. In Fig. 8 the stiffness is reduced (normalized to the *n=1* stiffness case) when reducing *n*, which is aging: when n from 1 reaches the value of 0.1, a stiffness reduction of about 58% is observed.

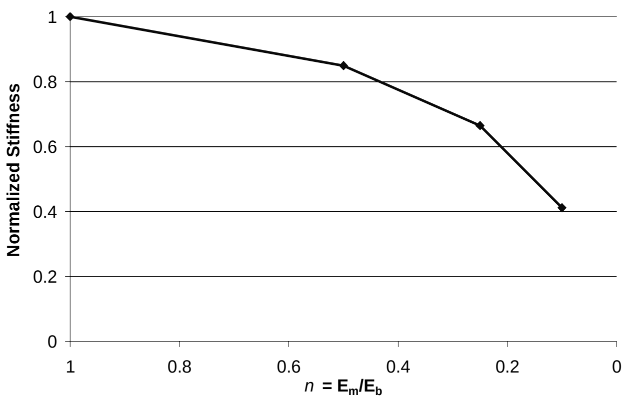


Figure 8 : Normalized stiffness reduction vs. *n* ratio (aging).

2.3 Macro-Scale: Global Structure Response

Once the structural members have been characterized, at the macro-level a three-dimensional structure is considered and an initial simplified and conservative modelling is performed. Starting from historical studies and in-situ relieves, a 56 m x 24 m (approximately) structure is identified with a column height of 11m. The outer walls are considered not to be structurally connected to the inner columns because the roof truss, made of timber, is a very weak restraint. Modal analyses has been carried out considering the columns as single cantilever with the previously defined homogenized mechanical properties due to the very weak restraint and connection made by roof truss to outer walls and other columns. The unit weight of the columns is about 20 kN/m^3 and the weight of the roof, axially loading the column, is about one third of column's weight. The first three natural frequencies in the longitudinal direction are reported in Tab. 2.

Table 2 : Natural Frequencies: longitudinal principal directions.

	Natural Period T in seconds			
	n=1	*n=0.5*	*n=0.25*	*n=0.1*
1st mode	0.790	0.858	0.894	1.013
2nd mode	0.104	0.113	0.118	0.134
3rd mode	0.034	0.038	0.039	0.044

The analysis is at first performed using the artificial Italian Code OPCM 3431 elastic (5% dumped) response spectrum considering, on safe side, a poor soil type D and a Peak Ground Acceleration (P.G.A.) a_g=0.25g (zone II according to Design Code). Roughly in a rigid body analysis, considering the column as a free rigid body grounded on the soil neglecting tensile strength (contact analysis), the overturning moment is due to a P.G.A. a_g=0.07g that can be considered a lower-bound P.G.A. value.

Then a refined elastic modal analysis concerning a continuum elastic medium fixed at the base on a cantilever scheme is performed and correlation is found between P.G.A. a_g/g and maximum tensile stress (σ) induced by the seismic action related to the P.G.A. at the fixed end (see Fig. 9, i.e. if a_g=0.25g, maximum tensile stress is about 2.0 MPa if *n=1* or 3.8 MPa after aging if *n=0.1,* while if it is considered, according to past seismic activities, a value of a_g/g=0.1, σ is about 0.7 MPa if n=1 or 1.1 MPa if n=0.1).

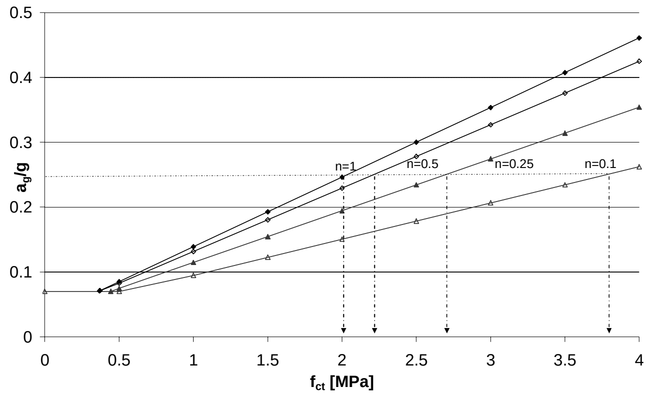


Figure 9 : P.G.A.s vs. minimum tensile strength requirement.

In Fig. 10 demand response spectra at different P.G.A.s and structural capacity curves at different aging (*n*) levels are plotted in the spectral acceleration vs. spectral displacement domain. The maximum values of tensile stress, also reported in the Acceleration Displacement Response Spectra (A.D.R.S.) format, are higher than ancient mortar typical strength and the base cracking and loss of equilibrium as observed in several collapsed stone block structures, such as Selinunte and Agrigento temples, is confirmed.

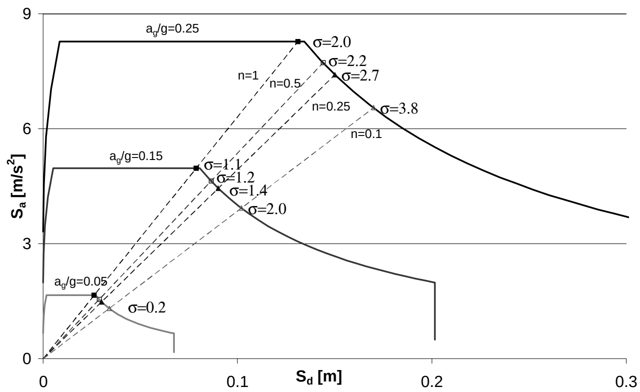


Figure 10 : A.D.S.R. plot of tensile stress evolution (σ in MPa) with aging and several P.G.A. values.

3 CONCLUSIONS

The aim of this study is to prospect a multi-scale approach method that is applied to a case study to investigate the history of Pompeii Basilica and so to improve the knowledge for conservation in seismic regions. In Pompei was found an innovative staggered pattern realistically to increase the seismic performance of the columns and the beneficial effects of this pattern have been assessed. Multi-scale analyses has been conducted to reduce/eliminate uncertainty and empiricism in the simulation of complex masonry system. However the results of F.E.M. analyses are strongly dependent on the historical interpretations of the structure geometry. At micro-scale, effective benefits from the masonry layered pattern adopted in Pompeii are remarked. At meso-scale the influence of aging on structural response and on stress assessment is pointed out. The parametric macro-level analyses, accounting for aging through an homogenization factor *n*, are an effective tool to support historical studies. Modal analyses has been carried out and their outcomes have been conveniently plotted in A.D.R.S. format to easily evaluate seismic vulnerability of historical structures during centuries according to P.G.A.s historical interpretations and aging effects. According to up-to-date relieves, current numerical analyses and historical interpretations, tensile stresses induced by P.G.A.s in agreements with past seismic activities matching up to ancient masonry typical strength, the outcomes are compatible with seismic events occurred during the service life of the Basilica.

REFERENCES

Adam J. P. 1988, *L'arte di costruire presso i Romani*, Longanesi, Milano.
Corti E. 1957, *Ercolano e Pompei*, Einaudi, Torino.
de Witte F.C. and Kikstra W.P. 2005. DIANA Finite Element Analysis. User's Manual. Analysis Procedures. Delft, The Netherlands. TNO DIANA bv.
Fiorelli G. (ed.) 1813, *Pompeianarum Antiquitatum Historia*, Napoli.
Maiuri A. 1942, *L'ultima fase edilizia di Pompei*, Istituto di Studi Romani, Napoli.
Maiuri A. 1973, *Alla ricerca di Pompei preromana*, Società Editrice Napoletana, Napoli.
Marco Vitruvio Pollione 1990, *De Architectura*, Edizione Studio Tesi, Pordenone.
Ohr K., 1991, *Die Basilika in Pompeji*, de Gruyter, Walter, GmbH & Co., Berlin-New York.
Page, A.W. 1978. Finite element model for masonry, *J. Struc. Div.*, ASCE, Vol. 104(8),1267-1285
Rots, J.G. 1991. Numerical simulation of cracking in structural masonry, *Heron*, Vol. 36(2),49-63
Sogliano A., 1911, La Basilica di Pompei. *Memoria letta alla R. Accademia di Archeologia, Lettere e Belle Arti di Napoli*, p. 118-129. Napoli.
VV. AA. 1981. *Pompei e gli architetti francesi dell'ottocento*, Gaetano Macchiaroli editore, Napoli.