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Modelling Methods for Large Masonry Structures

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Summary

A large part of the built cultural heritage is affected by structural damages which may lead to infringements of the essential quality requirements of the buildings. Structural analysis contributes to the safety assessment and design of the necessary interventions, therefore accurate results are needed in order to avoid inappropriate rehabilitation solutions. This paper describes the modelling methods of masonry structures taking into consideration different strategies of analysis in correlation with the complexity of the investigated elements and with the type of the expected results. Advantages and disadvantages of different modelling techniques and the applicability of the latter in the field of old masonry structures assessment are presented. Also, a case study composed of different FEM analysis for a masonry monumental building is presented. Aspects resulted from modal and linear static analysis are discussed.

KEYWORDS: masonry monumental buildings, modelling strategies, modal and linear static analysis.

1. INTRODUCTION

From a structural point of view, masonry historical buildings are characterized by: high degree of static indetermination, complex geometry given by the overlapping elements, high variations of transversal cross section, and differences in rigidity or irregular mass concentrations.

In general, unreinforced masonry structures are characterized by complex structural system, being composed of massive walls on which, arches, vaults and domes rest. The structural over strength evaluation, especial to seismic action, is made by the identification of the areas with high stress concentration. Thus, a realistic modelling of the structural system is required.

Linear analyses are not always appropriate due to the complexity of historical masonry structures, which, besides the anisotropic character behave different in tension and compression. Moreover, because of the insignificant tension strength of the masonry, linear analysis can be considered inaccurate even at low levels of loads. Masonry structures, especially those with arches and vaults, during the degradation process (which comes with local failures and dislocations), create numerous subsystems that are no longer subject to the initial conditions and therefore their shape and boundary conditions cannot be described anymore. However, the linear analysis is effective in identifying the global tendency of building behaviour, the modal characteristics and the areas in which the structure is subjected to stress concentrations which may lead to gaps in the continuity of the material. The required input data consists in the masonry specific weight and the modulus of elasticity. Despite all the restrictions, in recent decades, linear analyses were used to simulate the structural behaviour of a large number of masonry buildings with high cultural value [1].

1.1. Modelling strategies

Masonry is a composite material with direction-depended properties related to the geometry and to the mechanical properties of its constituents (brick or stone and mortar). Due to the low resistance of the mortar in both tension and compression, the masonry joints may lead to horizontal and vertical failure surfaces.

Depending on the complexity level corresponding to the structural analysis, three main strategies have been developed for masonry modelling: detailed micro-modelling, simplified micro-modelling and macro-modelling.

The decision of choosing a suitable modelling strategy depends on the expected analysis accuracy and on the size of the model (fig. 1). Micro-modelling provides a more realistic representation of the structural behaviour of masonry, but it has a prohibitive character due to the large number of degrees of freedom that are used, because of the increased volume of input data and also, due to the complexity in defining the failure criterions for masonry.

Thus, this method has proved suitable for studying the local behaviour of masonry structures, with a low level of complexity, especially for modelling masonry elements tested experimentally, being able to capture all possible failure modes of masonry.

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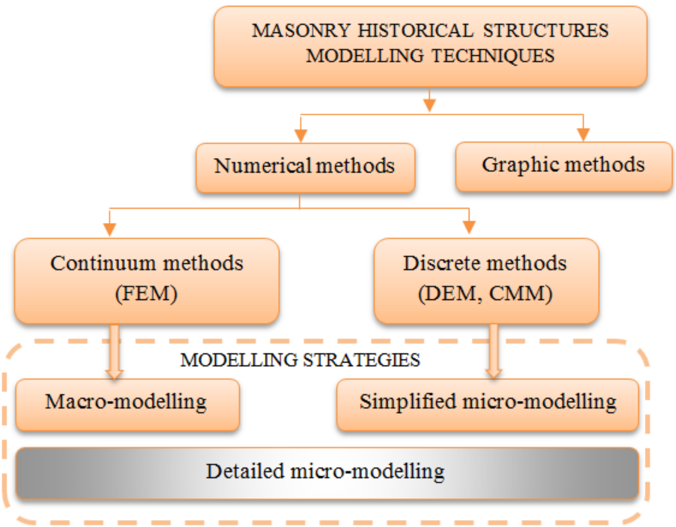

Figure 1. Masonry modelling techniques and strategies

Between micro-modelling and macro-modelling, the homogenization concept plays an important role in the analysis of masonry, referring to a unique continuous medium and aiming to determine the mechanical parameters of a fictitious homogeneous material which is able to simulate the real heterogeneous material.

Constitutive structural macro-models are relatively simple to use, they require less input data and the failure criterion for masonry is defined, in general, by a simplified law. Constitutive equations of the material, in this case, are suitable for studying the behaviour of the entire masonry structure because it reduces computation time and performance. The difficulties in macro-modelling consists in the formulation of quasi-brittle materials behaviour laws considering, in general, different failure criteria in tension and compression [2].

1.2. Shell and solid elements

Geometric representation of the structure can be made using two-dimensional elements (shell elements) or three-dimensional elements (solid elements). No element is superior to the other, the decision of choosing one depending entirely to the complexity of the problem (fig. 2).

For example, it would be unnecessary to use solid elements for the out of plane investigation of a masonry wall. Instead of solid elements, it would be enough to use shell elements for such a kind of investigation. When the concern is the investigation of a thick wall for in-plane loading, using shell elements (Fig. 2) would be an inappropriate decision since it would be very difficult to investigate the stresses through the thickness of the wall.

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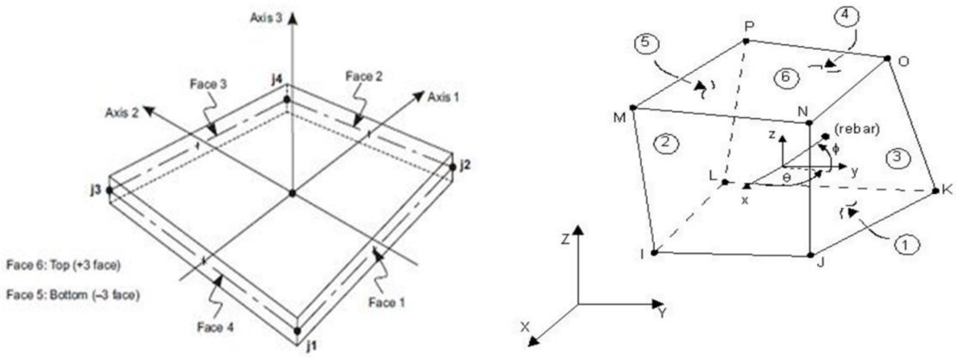

Figure 2. Shell and solid elements in masonry modelling

Because the two-dimensional elements are defined by a small number of nodal connections, their use in modelling masonry structures leads to efficient and practical analysis. In contrast, solid-type elements allow the control of the stress evolution within the structural elements, a necessary information regarding masonry structures with thick walls.

One of the basic principle of creating an analytical model is creating a geometrical model. However, it is difficult to distinguish between the structural and decorative elements in case of historic masonry structures. As a general rule, the geometric idealization should be as simple as possible.

In ETABS software, a shell is a three or four-node area object used to model membrane and plate-bending behaviour. Shell objects are useful for simulating floors, walls, 3D curved surfaces and components within structural members. Often, an eight-node solid brick element was used to model masonry.

These elements include a smeared crack analogy for cracking in tension zones and a plasticity algorithm to account for the possibility of concrete crushing in compression regions.

2. CASE STUDY

The “Al. I. Cuza” University of Iasi is an historical monument, and it was built between 1893 - 1897 on the site of the former Grand Theatre from Copou and School of Fine Arts, being designed by the Swiss architect, Louis Blanc.

The building has been further developed and strengthened in several stages, of which the most important after the Second World War and after the 1977 earthquake. The building is still used, serving as educational and research spaces.

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In order to assess historical masonry buildings, linear and nonlinear dynamic analysis, based on FEM, offer important information and contributes to their classification in seismic risk classes and in the development of the intervention solution.

The finite element method (FEM) is a technique based on numerical analysis in order to obtain approximate solutions further used to determine the variation of parameters characterizing continuous media (field displacements, strains, stresses).

The basic idea of the FEM is based on the possibility of describing the real strain field through their values in a finite number of points. Usually finite elements are defined in the process of meshing, which occur as the result of decomposition of a domain into several compatible subdomains with disjunctive interior. The method was widely used in the evaluation of historic masonry buildings in linear and nonlinear analysis, offering good results in describing the structural response of the buildings [3].

2.1. Finite element model

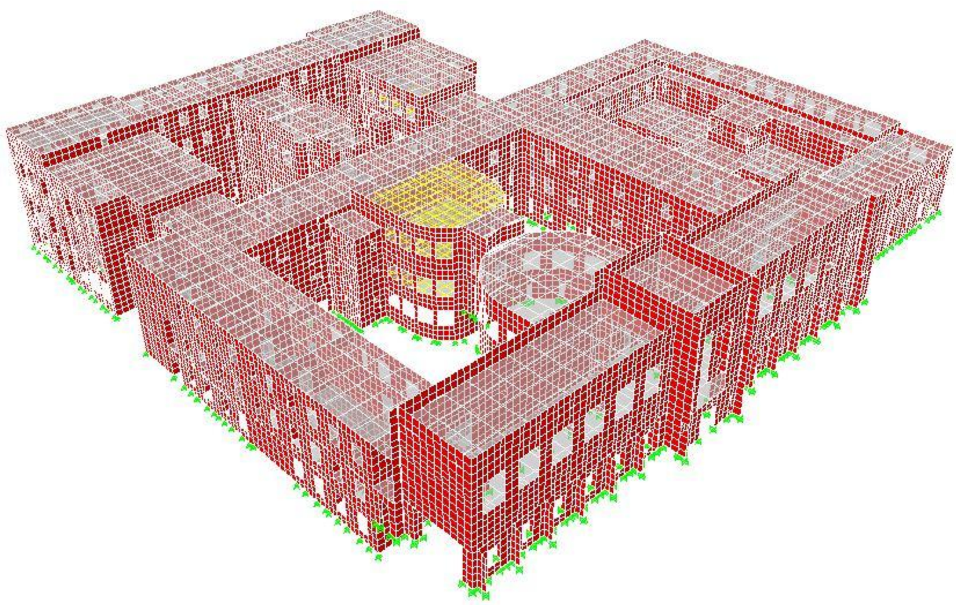

Figure 3. Structural analysis of "Al.I. Cuza" University, based on macro-modelling strategy

The analysis models were developed by using Etabs V9.7.2. software (fig. 3). The model has 90.000 shell elements both for walls and floors, with a meshing step of 0.4m and 1m. The difficulties in the modelling process consisted of simulating the

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geometry of the very large sized building, with curved walls and floors at different levels.

3. MODAL ANALYSIS

In the first step, a modal analysis has been carried out, revealing the characteristic deformed shapes and periods of the building for each vibration mode. After preliminary analysis, it has been observed that significant modal masses are present only for the modes with the vibration period of 0.48 to 0.16 s. outside this range, the vibration modes are insignificant in terms of deformations and tensions induced by seismic loads.

A number of 100 vibration modes were included in the analysis to obtain the sum of the participation mass factors over 90% on both directions. The first 4 vibration modes are presented in figures 4 to 7.

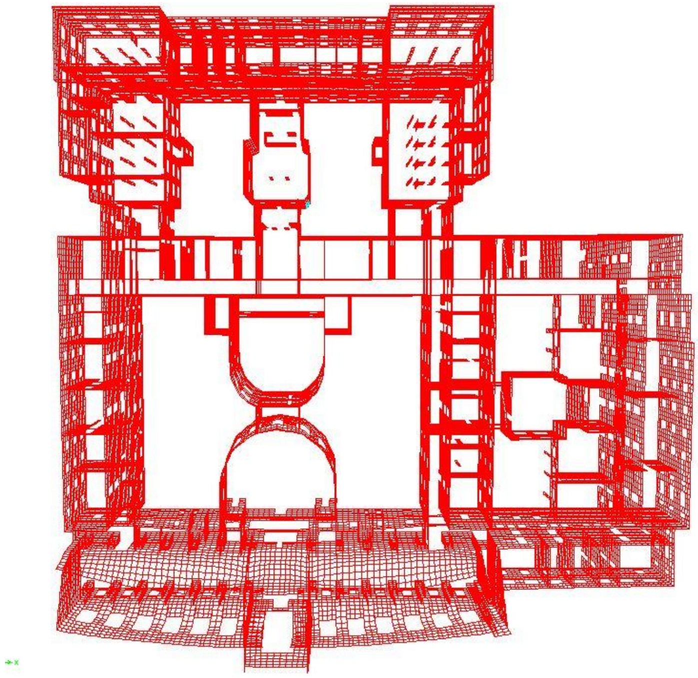

Figure 4. First vibration mode T=0.480s

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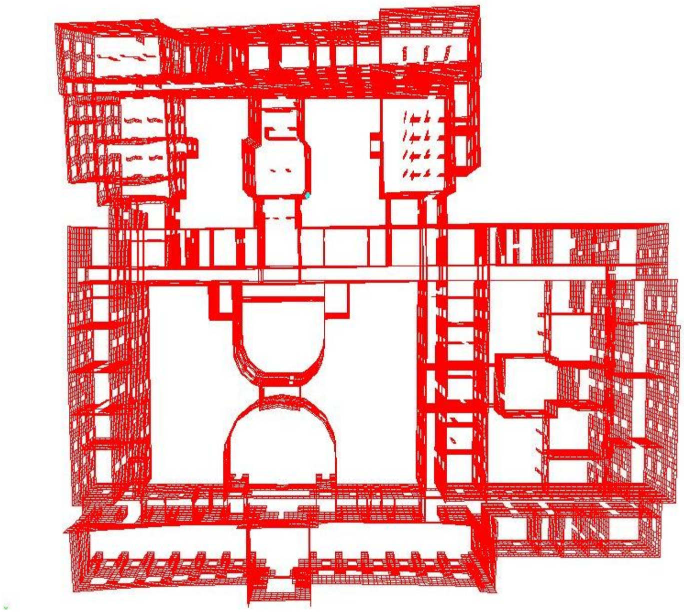

Figure 5. Second vibration mode T=0.409s

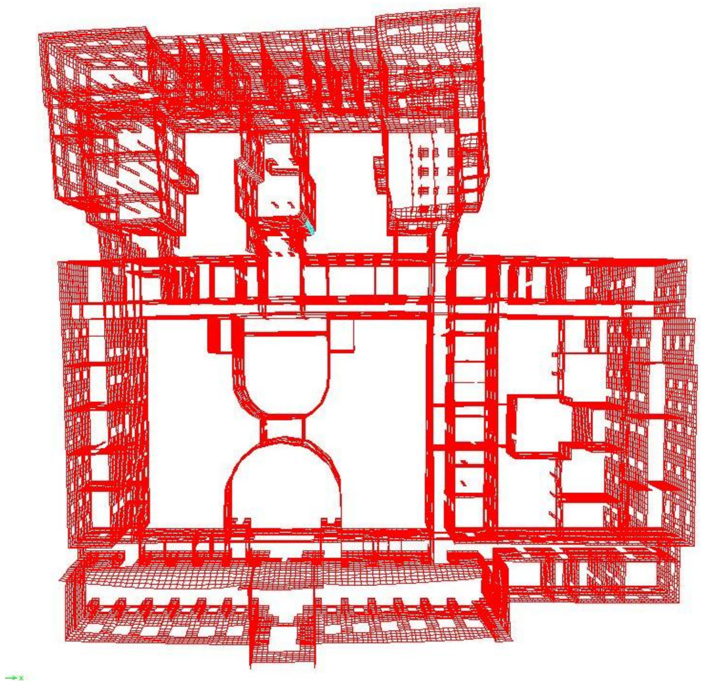

Figure 6. Third vibration mode T=0.395s

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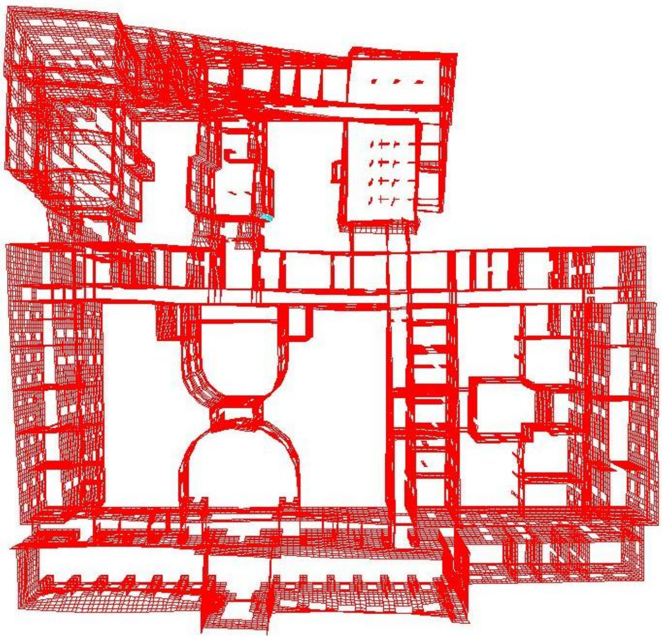

Figure 7. Forth vibration mode T=0.371s

Overall, the allure of the deformed shapes of the structure does not fit precisely in the main directions of the structure (transversal and longitudinal) but rather seems a mix of simultaneous translational and torsional modes in different parts of the buildings, mainly due to the in-plane shape.

Obviously, the modal analysis obtained by computer simulation has a degree of precision and detailing far superior to any manually approach, regardless of the used method.

4. LINEAR STATIC ANALYSIS

The structural analysis of the monumental building was performed by subjecting the finite element model to three types of actions: dead load, live loads and seismic loads. The actions were defined in accordance with Romanian standards, in agreement with Eurocode 8. Table 1 presents the load cases defined by the code.

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Table 1. Load cases

The fundamental loading cases	$1.35\sum_{j=1} G_{k,j} + 1.5Q_{k,i} + \sum_{i>1} 1.5\Psi_{Q,i}Q_{k,i}$
The special loading cases	$\sum_{j=1} G_{k,j} + \gamma I A_{Ek} + \sum_{i>1} \Psi_{2,i}Q_{k,i}$

Where: G_{kj} – the dead load; Q_{ki} – the live load; Q_{kj} – the predominant live load; Ψ0,1 – the live load factor equal to 0.7; A_{Ek} – the earthquake action for a recurrence interval of 100 years, P100 - 2006; $\Psi_{2,i}$ – the live load coefficient equal to 0.4; γ_I – the coefficient of importance equal to 1.20 for importance class 2.

The seismic actions have been introduced in the program in a response spectrum analysis using the design accelerations spectra (fig. 8) according to the national code P100/2006.

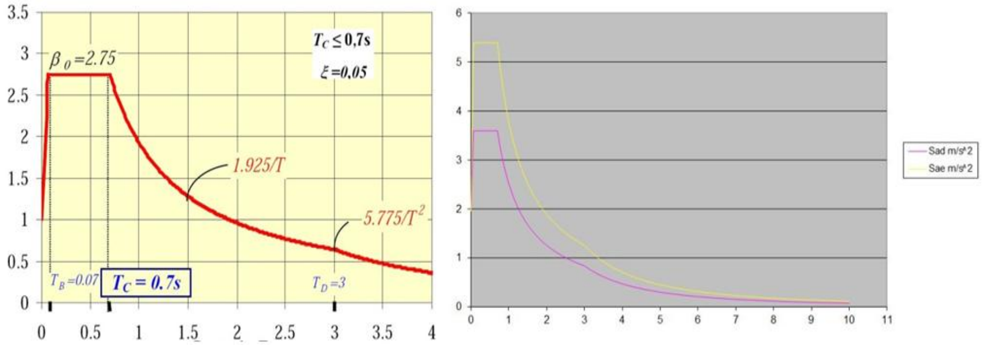

Figure 8. Elastic and design accelerations spectra

On the basis of modal analysis, further seismic analysis on the two main directions of the building was performed. The deformed shapes of the construction, in the two main directions, parallel and perpendicular to the central core, are shown in figures 9 and 10.

From the following figures it is clear that the seismic action parallel to the central body, leads to a state of deformation more pronounced on the secondary façade bodies, while an earthquake action on perpendicular direction tends to deform predominantly the central body.

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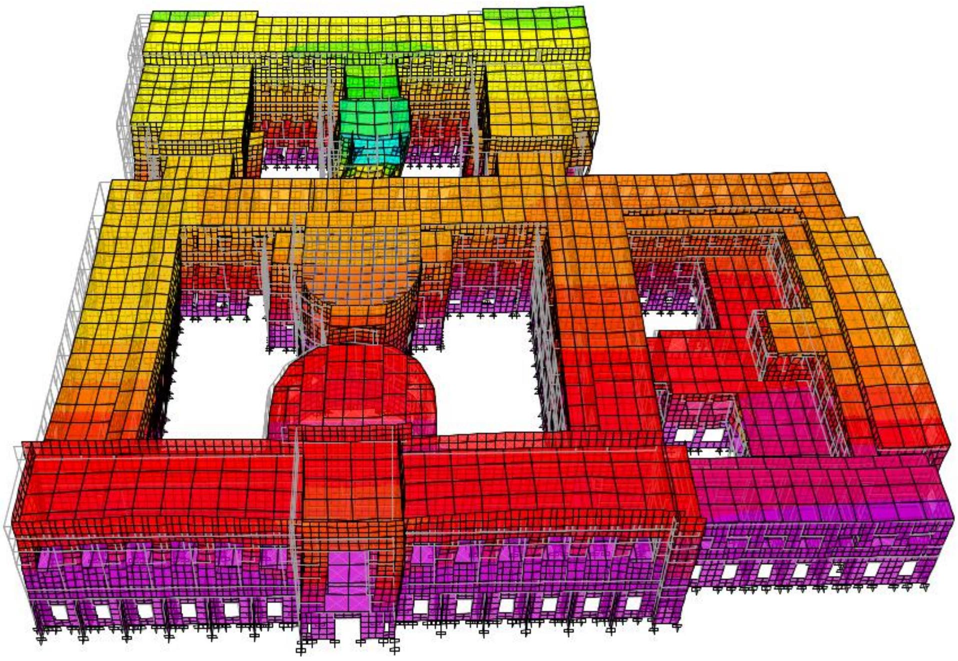

Figure 9. Deformed shape – seismic action on longitudinal direction

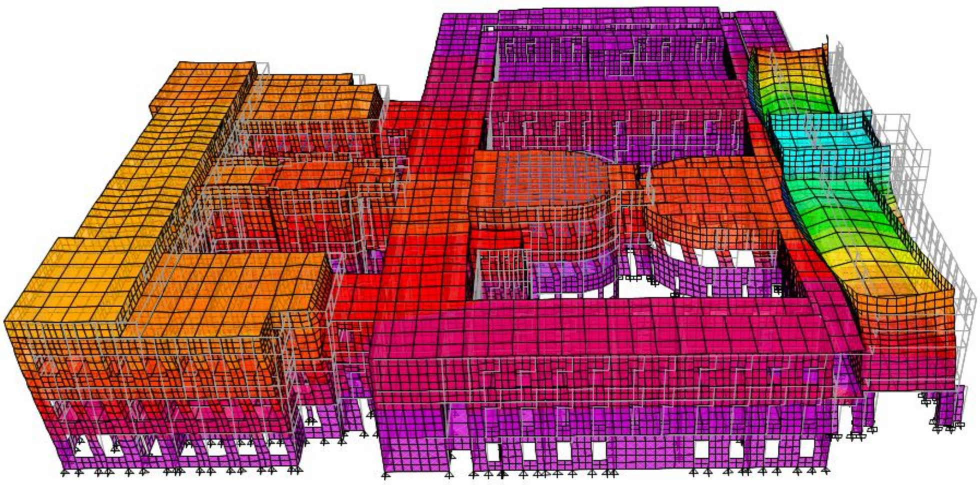

Figure 10. Deformed shape – seismic action on transversal direction

Obviously, the differences in stiffness of the bodies that compose the structure, in relation to the each direction of the earthquake, determines an almost different way of structural response for each individual body.

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Analysing the stress state in the walls of the main and secondary façade (fig. 11), it has resulted that compression stresses are close to the masonry compression bearing capacity of 4.5N/mm^2, determined through experimental investigations.

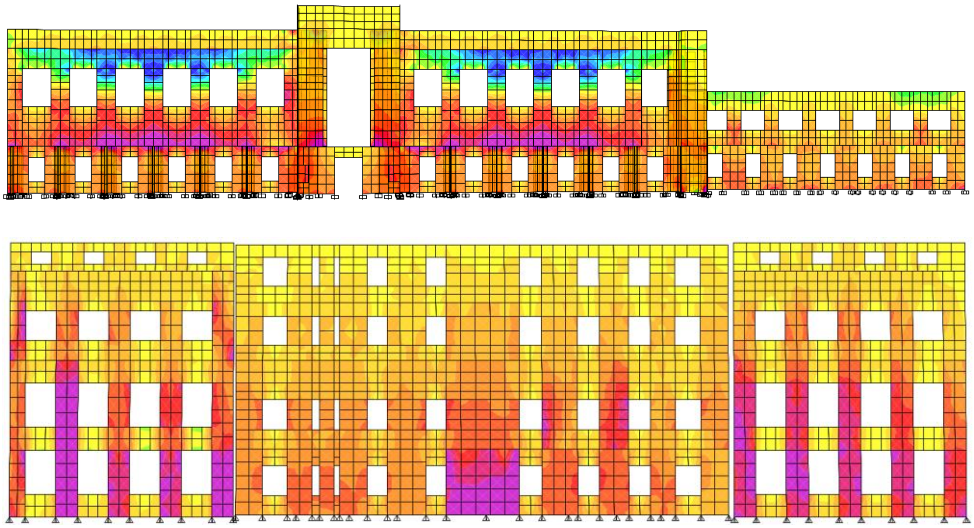

Figure 11. Compression stresses maps at main and secondary façade walls

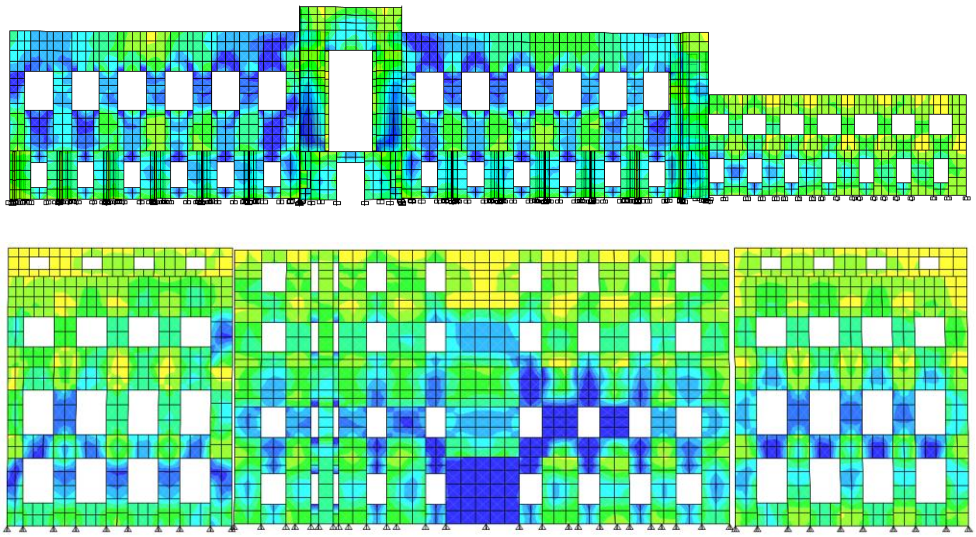

Figure 12. Tension stresses maps at main and secondary façade walls

At the secondary façade wall, the stresses in the central and marginal piers, at the ground level, are about 3.6N/mm^2. At the main façade, the maximum compression stresses are reached in the piers wich support the metallic girdes of the floors.

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The tension stresses (fig. 12) are with maximum values of 1.6N/mm^2 at the secondary façade walls and 1.8N/mm^2 at the main façade walls, mainly in the zones that suffered most damage during the 1977 seismic action.

5. CONCLUSIONS

In the mechanical analysis of historical masonry buildings, the structural evaluation, especial to seismic action, is made by the identification of the areas with stress concentration therefore a realistic modelling of the structural system is required.

Constitutive structural macro-models are relatively simple to use, require less input data and are suitable for studying the behaviour of the entire masonry structures because it reduces computation time and performance. The difficulties in macro-modelling relates to the formulation of quasi-brittle materials behaviour laws considering, in general, different failure criteria in tension and compression.

The linear model is effective in identifying the global tendency of building behaviour, modal characteristics and areas in which the structure is subjected to stress concentrations able to interrupt the continuity of the masonry.

Linear analyses can be efficiently and successfully used to simulate the structural behaviour of masonry monumental buildings with realistic results in the process of their structural evaluation.

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