The Seismic Behaviour of Maniace Castle, Syracuse: a First Numerical Comparison Between the Current Condition and a Hypothetical Complete Reconstruction

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LISBOA 2012

SUMMARY:
The seismic behaviour of Maniace Castle, built on the Ortigia island in Syracuse (Italy) during the thirteenth century by Emperor Frederick II, was investigated by a numerical approach with the aim of comparing different strategies for structural reinforcement. The original building consisted of a square perimeter made by 4 m thick limestone masonry walls and round towers at the corners, embedding a large hypostyle hall. The roof of this main hall was supported by a system of arches, five on each side span. The current state of the castle is the result of subsequent interventions following the explosion that devastated the interior of the castle in 1704. Accordingly, at present the indoor hall consists of only 2/5 of the original covered area, and the primitive structural concept has greatly changed, since the double symmetry of the plant was substantially lost. Buttresses and transverse walls were added to improve the mechanical response to horizontal loads.
Previous studies, both experimental and numerical, proved that the interior columns supporting the arches experience a level of vertical stress that is quite high in comparison to the actual strength. The situation is particular serious accounting for the seismicity of Syracuse, as a the significant increase in axial stress in the columns due to their flexural deformation might occur. In the present study, the behaviour of the castle is studied by means of a detailed full 3D FE model, both under vertical and lateral loads. The results of the analysis are used for a proposal of reconstruction of the hypostyle hall, bringing it back to the original geometrical configuration of the XIII century, by the use of modern building materials.

Keywords: masonry, full 3D FE analyses, case study, seismic actions, gravity loads

1. INTRODUCTION

The Maniace Castle stands on the tip of the island of Ortigia (Syracuse), where it was built in the first half of the XIII century by the Holy Roman Emperor Frederick II. Built of sandstone blocks bonded by thin mortar joints, it owes its name to the Byzantine general who besieged and took Ortigia from the Arabs in 1038. The story of this building, featuring layer upon layer of characters and events, its distinctive type and enigmatic layout, and its present ruinous, state which demands urgent actions and even poses problems of stability, make the castle an exemplary case study. Although it was badly damaged by the earthquake that devastated the southeast of Sicily in 1693, giving rise to numerous reconstructions in baroque style, it still conserves its characteristic 13th century structure – i.e. a square plan, with four cylindrical towers at the sides (Figure 1, left). In the original configuration, the inner structure presented a single big hypostyle hall ("salone") covered by twenty-five cross vaults supported by slender columns (Figure 1, right), with a monumental fireplace in each of the four corners. During its long lifetime, earthquakes have been a cause of damage for the castle. Indeed, a few years after the earthquake of 1693, in November 1704, a lightning struck the castle during a storm and a huge explosion of the ammunition dump completely destroyed 3/5 of the vaulted hall which had never been rebuilt in its original shape. Presently, only two spans of the original "salone" survive on the S-E side. A plan of the castle as it appears nowadays is sketched in Figure 2.

Figure 1. Perspective view of the Maniace Castle and a detail of the hypostyle hall.

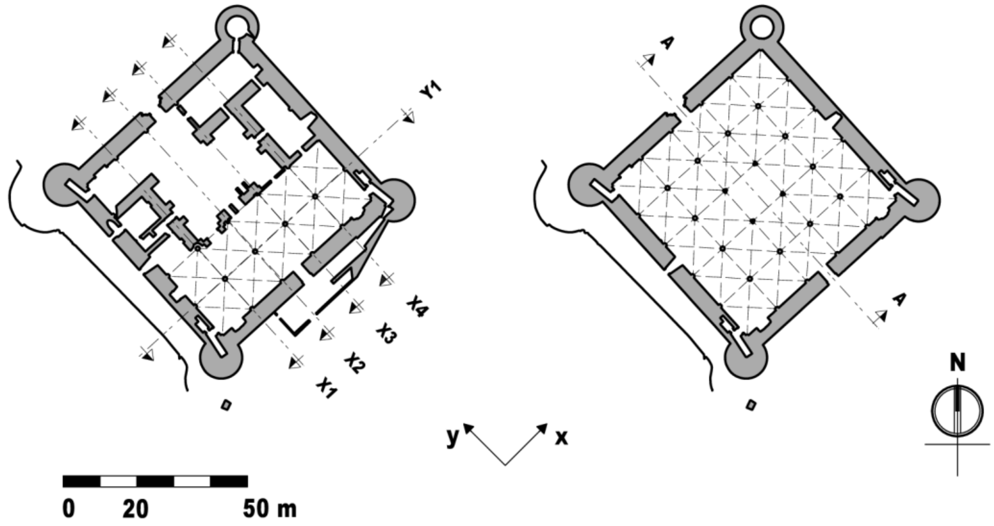
In recent years, the deterioration of some elements of the building has caused concern for its structural safety when subjected to a possible seismic event. In particular, the remaining four central columns of the hypostyle hall present a number of vertical cracks, clearly suggesting that these elements are subjected to severe compression conditions. As a consequence, steel hoops have been provisionally installed on the drums and on the capitals, as shown in the photo of the interior hypostyle hall reported in Figure 1 (right).

Table 1. Measured and calculated frequencies of the first four natural modes.

Mode	*ISMES measures (ISMES, 1999) [Hz]*	*Università di Padova (Modena et al., 2001) [Hz]*	*Politecnico di Milano (Casolo and Sanjust, 2009) [Hz]*	*Present 3D model [Hz]*
1	5.16	5.40	5.78	5.99
2	9.55	8.90	8.08	7.02
3	9.58	10.1	8.81	7.71
4	10.6	10.4	9.03	9.05

A series of scientific studies and diagnostic investigations has been planned in the last two decades, by the Superintendence of Cultural and Environmental Heritage of Syracuse (Soprintendenza ai Beni Culturali ed Ambientali di Siracusa), to investigate the safety of the Castle with regards to static actions due to weight, as well as against the occurrence of seismic actions (ISMES, 1999; Modena et al., 2001; Ipertec, 2003; Casolo et al. 2007a, Casolo and Sanjust, 2007b; Casolo and Sanjust, 2009). The first studies date back to 1999, when ISMES carried out some in situ experimental tests, as flat jack tests, identification of principal vibrating modes and frequencies, georadar analysis of the ground and probing of the walls. The natural frequencies of vibration measured in situ by means of vibrodynes are compared with the results obtained by different numerical models in Table 1. In fact, a global 3D FE model of the whole castle was made by Modena et al. (2001) from University of Padua, whereas another model, using a rougher discretization, was implemented later by Casolo and Sanjust (2009) from Politecnico of Milan with the aim of studying the response to seismic loadings. In 2003, basing on Modena et al. (2001) numerical results, a new diagnostic investigation focused on the ultrasonic analysis of the columns was made by Ipertec (2003). A number of more detailed 3-D numerical predictions of the local stress conditions were also performed in order to deepen the knowledge of the response of some construction details regarding the columns and the arches of the hypostyle hall.

More recently, in collaboration with Politecnico di Milano, an innovative study was directed toward the exploration of a possible scenario which assumes the reconstruction of the entire hall in its original configuration (Maggioni, 2009). In particular, the research presented in this paper is inspired by the suggestion concerning a hypothetical restoration of the entire hypostyle hall, as a whole. In fact, this castle has taken on a special symbolic meaning ever since it was first built. Onto its precise and absolute geometry – a man-made object marking the final boundary between the city and the sea – has been grafted a representational role that has often been evoked in painting, drawing and literature, that of an urban building which even in modern times exemplifies its Mediterranean calling: the city as fortress, and the city as port. The present approach is fully numerical and provides an insight, from a structural point of view, on the seismic performance of the castle as it is, and after its hypothetical modification towards its original configuration. To this aim, two full 3D FE models built within the commercial code ABAQUS (Hibbit et al., 2005) are utilized in the linear range. The static analyses under gravity loads are preliminary performed, similarly to what was done by Mallardo et al. (2008), in order to quantitatively evaluate the state of compression of the main vertical structural elements - e.g. the columns of the hypostyle hall - which exhibit visible cracks, and the zones of the vaults undergoing positive principal strains. Eigenvalue analyses are also carried out on both models, to perform comparisons with available experimental data and assess the effectiveness of the proposed reconstruction project. Finally, elastic analyses under horizontal loads (conventionally representing a seismic action) are carried out and the results are critically discussed and compared.



-a -b

Figure 2. Plans of the castle, with identification of the sections where stresses patches will be plotted. a: present configuration. –b: hypothetic reconstruction of the original configuration.

2. THE THREE-DIMENSIONAL MODELS OF THE WHOLE CASTLE

The finite element models presented in this paper are more refined in terms of accuracy, discretization, materials and geometric representation compared to global three-dimensional (3D) models which have been previously developed for the analysis of Maniace castle (Modena et al., 2001; Casolo et al., 2007a; Casolo and Sanjust, 2009). Moreover, the static behaviour of the structure after the hypothetical reconstruction of the hypostyle hall (according to the original plan dating back to the time of Frederick II) is investigated, probably for the first time, by considering a full three dimensional approach. The global behaviour of the castle under gravity loads and lateral acceleration is studied by means of two large three-dimensional finite element models: one devoted to the analysis of the present situation, the other based on a hypothesis of reconstruction (Figure 3).

When dealing with the present situation, hereafter labelled as *Mesh 1* for the sake of clearness, the numerical 3D FE model consists of 32436 solid elements, 51402 nodes and 154206 degrees of freedom. The model representing the hypothetical reconstruction, hereafter called *Mesh 2*, required the utilization of much more elements, namely 48404 solid elements, 84306 nodes and 252918 degrees of freedom.

The hypostyle hall was modelled with quadratic 20-node solid brick elements (named *C3D20R* into the adopted ABAQUS computer code), whereas 10-node tetrahedral elements (*C3D10M*) were adopted for the parts of minor interest. The geometry of this model was slightly simplified by disregarding many architectural details of minor importance, but modelling very accurately both the shape of the internal vaults and the actual geometry of the columns.

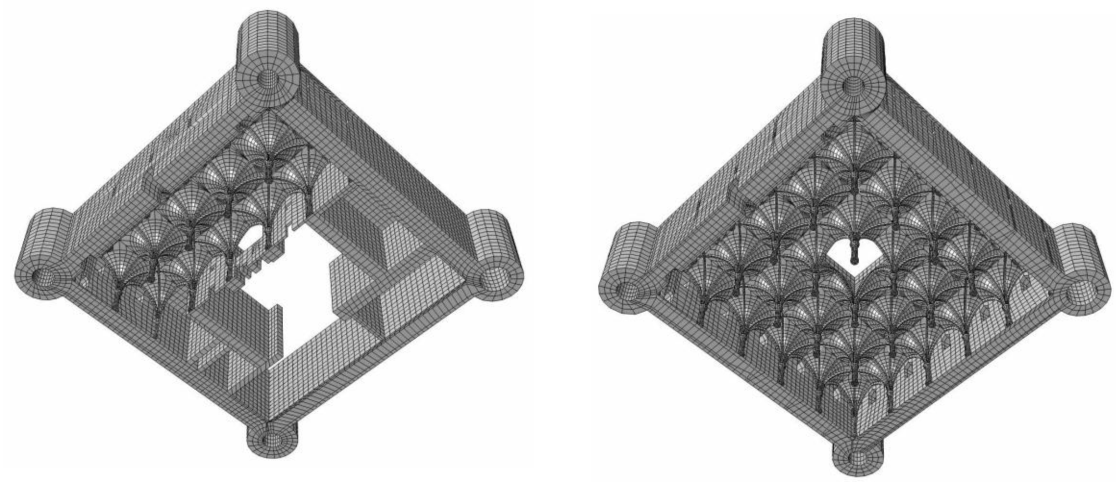


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Figure 3. FE discretization of the castle. –a: present configuration, *Mesh 1*. –b: hypothetical reconstruction of the original configuration (ISMES, 1999), *Mesh 2*.

The elastic moduli of the different construction materials are given values that basically agree with data already published about this building (Modena et al., 2001; Casolo et al., 2007a; Casolo and Sanjust, 2009). However, an accurate trial-and-error calibration of the experimental data is adopted in the paper, to match the measured frequencies as close as possible.

On both models, the following numerical simulations were performed:

1. Eigenvalues extraction. This numerical analysis allows the first global eigen-modes and frequencies of the structure to be determined and compared with experimental data in case of the discretization representing the existing structure (*Mesh 1*). The numerical results given by the FE models representing the castle in its present and hypothetical original configuration are also compared.
2. Preliminary elastic analyses for both models subjected only to gravity loads. These analyses allow the compression levels and the zones which undergo positive principal stress to be simply estimated, thus giving indirect information on the possible crack pattern.
3. Lateral load analyses. The structural response under horizontal actions is obviously more complex to interpret compared to that under gravity loads. In the framework of a schematization of the seismic excitation by equivalent static loads, relevant horizontal actions must be applied to the model.

As is well known, masonry exhibits very low tensile strength; non-linearity is activated at very low levels of the external loads, meaning that the most appropriate analysis within the assumption of static loads would be pushover. Nevertheless, a linear elastic analysis remains a standard approach in common practice (see e.g. Italian codes NTC 2008) and in presence of complex structures for which the reduction to an equivalent frame scheme is unfeasible (Milani et al., 2008a, 2008b). In addition, elastic analyses are preliminarily useful to identify the possible zones where damage may occur, in view of more sophisticated analyses to be carried out on individual structural elements.

2.1. Natural frequencies analysis

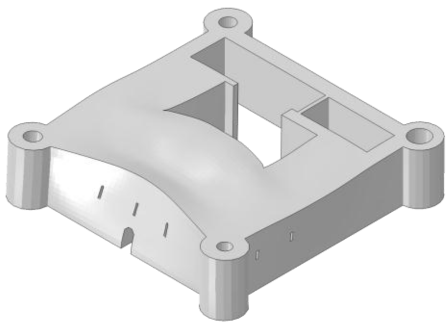
To calibrate the mechanical properties of the materials defining the numerical model, with the aim of comparing the numerical predictions in terms of free vibration frequencies and modes with existing experimental and numerical data, full sensitivity analyses were carried out.

The values for the elastic moduli utilized in the first step were deduced from previous contributions in this field (Modena et al., 2001; Casolo and Sanjust, 2009). Starting from these values, a parametric study varying Young moduli and density of the materials has been made, evaluating the subsequent changes induced on the global behaviour of the structure, especially in terms of the first four eigen-modes frequencies. From the huge amount of sensitivity analyses conducted by the authors, mechanical properties adopted for the materials have been re-defined as reported in Table 2, in order to minimize the gap between the current predictions and the experimental data.

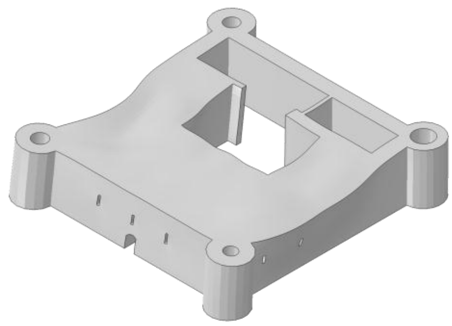
Table 2. Mechanical properties adopted for the materials employed in the numerical analyses after tuning of eigen-frequencies

Architectural elements	**Density [kg/m³]**	$E_1=E_2=E_3$ **[N/mm²]**	$\nu_{12}=\nu_{13}=\nu_{23}$	$G_{12}=G_{13}=G_{23}$ **[N/mm²]**
Vaults hypostyle hall	2000	5000	0.1	1200
Columns	2200	Isotropic	E=10000	ν =0.1
Arches	2200	Isotropic	E=8000	ν =0.2
Internal walls	1800	Isotropic	E=1100	ν =0.2
Vaults infill	1100	Isotropic	E=400	ν =0.1
Perimeter walls external leafs, towers	2000	Isotropic	E=4400	ν =0.1
Perimeter walls internal leafs	1800	Isotropic	E=350	ν =0.1

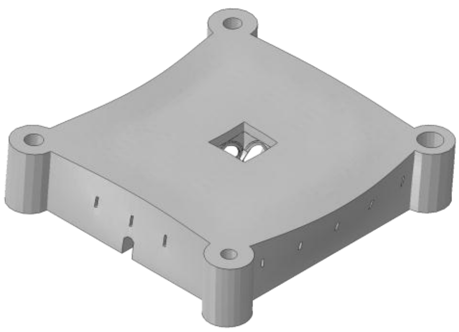
For both the current configuration (*Mesh 1*) and the hypothetical complete reconstruction (*Mesh 2*), the results of the eigenvalue analysis (first two modes) are summarized in Figure 4.



Mode I. Frequency Hz 5.99



Mode II. Frequency Hz 7.02



Mode I. Frequency Hz 5.37

Mode II. Frequency Hz 5.40

Figure 4. First two eigen-models and corresponding frequencies.
Present configuration (top) and original configuration (bottom).

According to the authors' experience, the first five modes of vibration along the two in-plane directions are sufficient to describe the fundamental seismic behaviour of the castle as a whole.
The most meaningful aspect of the investigations in the dynamic field, well demonstrated by both the experimental tests and the numerical modelling, is that besides the first mode (which involves symmetrical flexural distortions of the masonry structure and which, as expected, gives the most important contribution to the mass participation), the third and fourth modes are quite complex, involving bending and torsion of the hypostyle hall and one of the big external walls. According to the deformed shape corresponding to mode 1, the vaulted system appears subjected to a coupled torsional and flexural deformation, with significant bending deformations of the columns.

Within this context, the numerical analyses point out some critical situations, with particular attention to the safety conditions of the columns and the vaults.

As it is possible to notice from a detailed analysis of the results, the level of compression attains about 5 MPa (4.60 for *Mesh 1* and 5.80 for *Mesh 2*) in the central columns, in very good agreement with both experimental tests and previous numerical analyses conducted by different authors.

In the remaining structure, the state of stress seems to be less critical. Some stress concentrations found experimentally are not matched by the numerical predictions (e.g. in the south tower), and are likely to be connected to the effects of the explosion that partly destroyed the castle. All these aspects of degradation should be taken into consideration for planning structural upgrading interventions (e.g. injections, limited reconstruction). In conclusion, the columns of the hypostyle hall appear to be the most problematic elements of the castle.

Other interesting considerations may be related to the very limited presence of significant positive principal stresses, as shown in Figures 5 and 6 for the present situation and for the original hypothetical configuration, respectively. Apparently, the shape of the castle was correctly designed to avoid the presence of tensile stresses due to the simple gravity load.

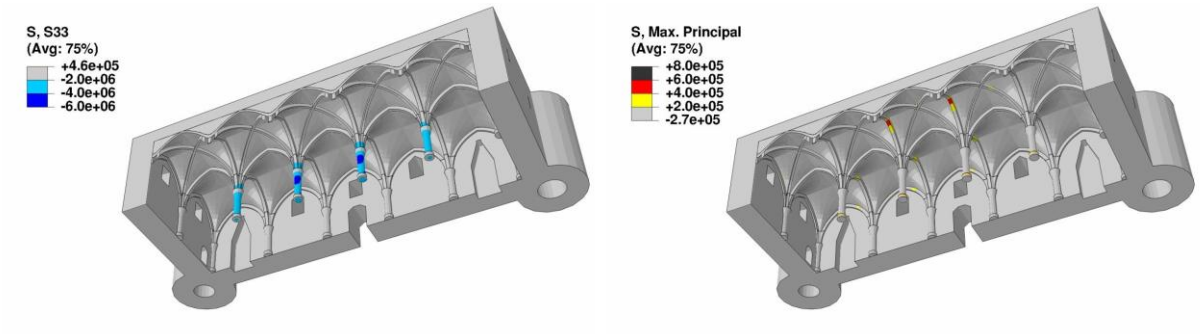


Figure 5. Present configuration. Vertical stress (left – Pa) and maximum principal stress (right – Pa) for gravity loads acting on elements belonging to the hypostyle hall.

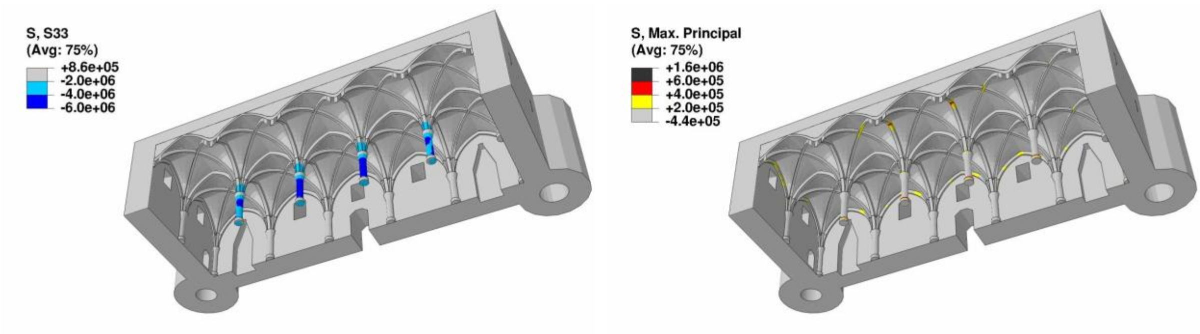


Figure 6. Hypothetical reconstruction of the original configuration. Vertical stress (left – Pa) and maximum principal stress (right – Pa) for gravity loads acting on elements belonging to the hypostyle hall.

2.2. Static analysis under horizontal loads

Static analyses under horizontal loads are performed along both the *x* and *y* directions (Figure 2). The lateral acceleration applied is equal to 2.5 m/sec^2, which corresponds to a design ground acceleration a_g of 0.25g, for rock soil (type A according to Eurocode 8) and a return period T of 475 years, as provided by the former Italian sesmic code (OPCM 3274, 2003) for seismic zone 2.

Here, only results referred to the direction *y* are reported, for the sake of conciseness, as they are more significant. The choice of not performing a full spectral analysis is simply connected to the need of obtaining a mean to compare in the clearest way the responses of the two different geometrical configurations (*Mesh 1* vs. *Mesh 2*) when subjected to horizontal loads, recalling that this research is just a preliminary investigation of the 3D structural behaviour of the complex hypothetical project of reconstruction. An effective seismic assessment of the project is beyond the scope of the present study. From a gross analysis of the elastic deformed shapes, it is rather clear that the behaviour of *Mesh 2* is globally much more regular, but the local bending of the central columns remains critical and essentially unchanged when compared to the present situation. Conversely, the global behaviour may be comparable to that exhibited by box buildings, with external walls providing the most important contribution in terms of stiffness and strength. The inner columns, however, appear once again to be the most vulnerable part of the structure, especially the central ones. This is not surprising, since this is the zone where the horizontal deformations localize.

Results in terms of internal stresses are represented for the two models in Figures 7 and 8. In particular, the contours of the vertical stress S33 and the maximum principal stress are plotted. Whereas the vertical stress gives an important insight into the state of compression of the columns, the zones that could be critical with regards to the possibility of formation of cracks can be detected according to map of maximum principal stress.

In both models, the static analyses under both horizontal and gravity loads highlight considerable peaks in the compressive stresses, close to the crushing values for good limestone in the central columns of the hall and in the buttresses. When horizontal loads are applied, compression values increase in *Mesh 1* from 4.60 MPa to around 6 MPa, and from 5.80 MPa to 7.20 MPa in *Mesh 2*, at the base sections of central columns. The simultaneous presence of vertical compression and considerable bending results into a strong reduction of the active base section, with the consequent increase in stress in the compressed region. Bending was present in the central columns even under gravity loads only. The model corresponding to the original hypothetic configuration of the castle provides nearly the same results, but with slightly increased peaks, meaning that the behaviour under seismic loads of the castle in its original configuration has a similar performance with respect to the castle as it appears nowadays.

Analogously to what observed in presence of gravity loads only, positive principal stresses exceeding the masonry tensile strength are present in both models in limited regions of the vaults and at the top of the arches. Again, as expected, the horizontal load results into a spreading of these critical zones, meaning that a diffusion of cracks throughout the vaults is expected to occur in case of seismic events. Regarding the spreading of the areas subjected to significant principal tensile stresses, the configuration including the hypothetical reconstruction of the vaulted hall (*Mesh 2*) seems to perform better than what meets the current configuration (*Mesh 1*) – see Figure 9.

To establish quantitatively if the application of a horizontal load will result into the (partial or total) collapse of the vaults belonging to the hypostyle hall, for activation of a failure mechanisms in correspondence of the cracks (regarded as plastic hinges), a full 3D limit analysis of the “salone” by means of consolidated non-commercial homogenized limit analysis codes (Milani et al. 2008a, 2008b, 2009) is planned by the authors.

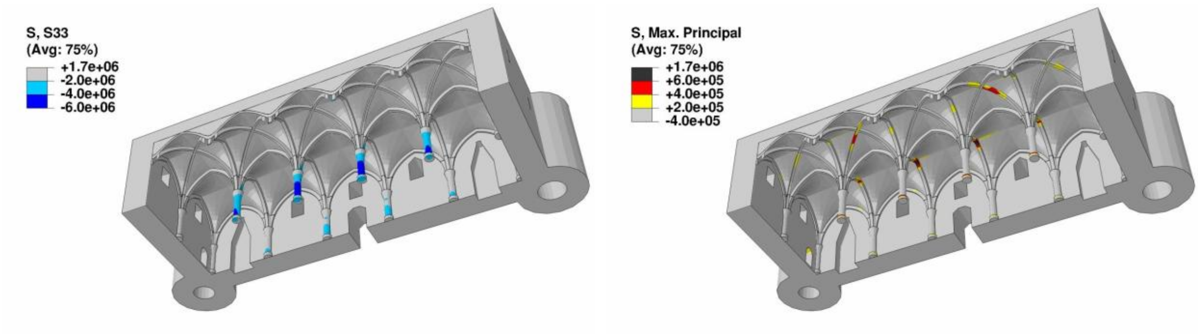


Figure 7. Present configuration. Vertical stress (left – Pa) and maximum principal stress (right – Pa) for lateral loads acting on elements belonging to the hypostyle hall.

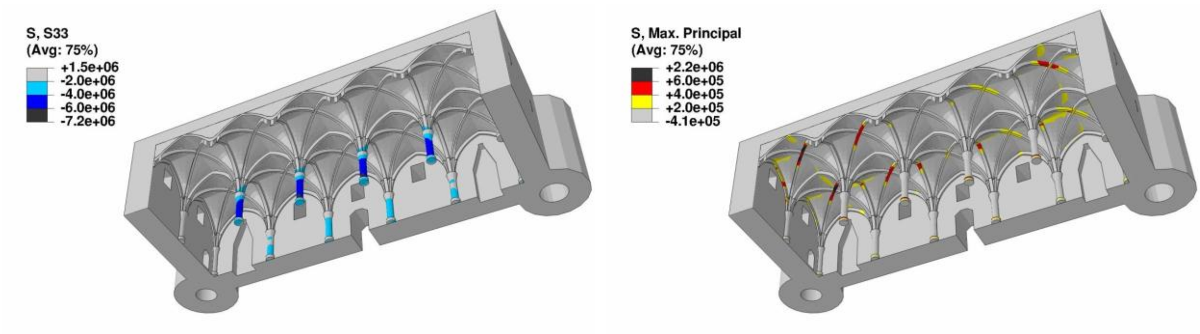


Figure 8. Hypothetical reconstruction of the original configuration. Vertical stress (left – Pa) and maximum principal stress (right – Pa) for lateral loads acting on elements belonging to the hypostyle hall.

Figure 9. Maximum principal stress for lateral loads in section X2, present configuration (left) and hypothetical reconstruction (right).

3. RECONSTRUCTION PROJECT

Encouraged by these results, which relate mainly to the mechanical response of the building, a partial rebuilding of the hypostyle hall has been proposed also considering the architectural issues (Maggioni, 2009). The aim of the architectural project is to reconstruct the hypostyle hall of Castello Maniace with the objective to maintain the extraordinary and unique idea of punctuating a large space with insistent repetitions of discontinuous elements over a broad area. In fact, the spatial universality of the Castello Maniace's interior, balanced in every direction inside the great hypostyle hall, makes this space unique, an abstract one in which the only clear demand for convergence is a reiterated affirmation of symmetry: the single source of light in the middle, which spreads out uniformly in a measured diminution of colour gradually fading towards the edges.

Thus, the project restores the spatial unity of the ancient building by removing the parts built in the eighteenth century, and the reconstruction of the demolished vaults due to the explosion of the powder magazine in 1704. The vaults are made of bright concrete blocks, according to the design of the original ashlars, and manufactured in special molds with a rougher surface finish (Figure 10, top left). The new pillars are made of extruded and welded steel, with zinc-silver surface finish. A slight enlargement at the top of the pillar marks the extent to which, in the original columns, the capitals are set (Figure 10, top right).

The reconstruction of the castle in its complete form, reproducing the original symmetry of the building and connecting the still existing vaults to the perimeter walls (Figure 10, bottom), contributes to the improvement of the seismic behavior of the monument, especially as regards the vaults. The use of modern materials may be useful to decrease the stresses in the existing structures, especially the central pillars, and make the rebuilt part recognizable. A study of the restoration project, with regard to the seismic behaviour, which includes additional and more accurate numerical simulations, is in preparation by the authors.

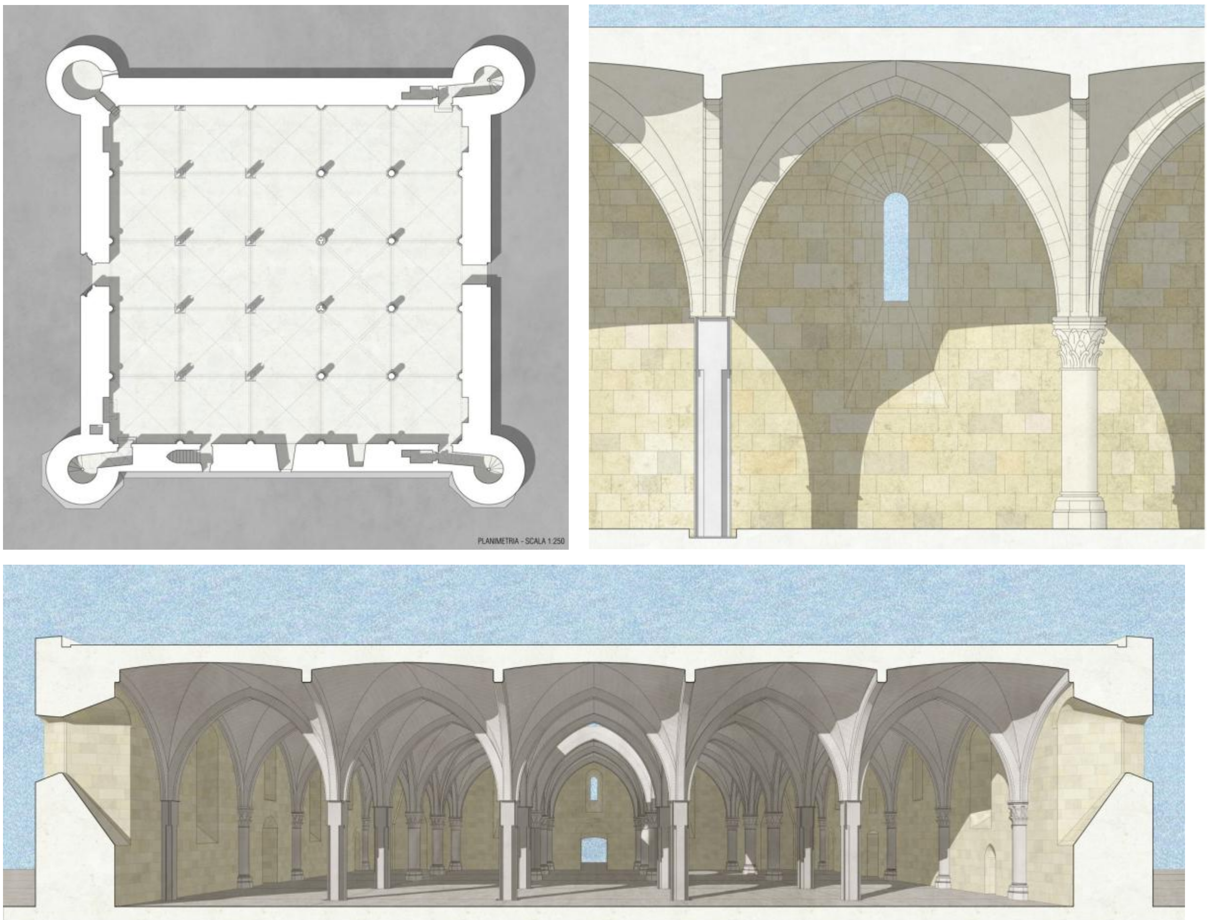


Figure 10. Project of partial reconstruction of the castle. Plan (top left), detail of the hypostyle hall with the new steel columns (top right), perspective section of the castle (bottom).

4. CONCLUSIONS

Two numerical models for the structural analysis of Maniace Castle in Syracuse, Italy, in the present condition and after an hypothetical restoration, have been presented. Although the models are fully elastic and the analyses are performed with a commercial code, they give some interesting insight into the actual behaviour of the castle in presence of gravity loads and lateral actions. When dealing with gravity loads, even elastic numerical models may be able to provide quite accurate results as far as the vertical compression stress is concerned. Conversely, the contours of the maximum principal stress provide an effective picture of the zones where tensile cracks are likely to occur. According to the results of the simulations, there is apparently a critical static situation at the base of the columns belonging to the hypostyle hall, especially in the central part. The state of compression is quite close to the experimentally determined strength of these structural elements, especially near the base. Significant tensile stresses are also diffused at the top of the vaults: this appears to be quite usual for this typology of traditional double curvature elements, since even gravity loads result in considerable bending of the vaults. An intervention bringing the castle back to its original configuration would have, globally, little effects on the state of stress in the columns under gravity loads, with a slight increase in the stress peaks. This is largely expected, since in the hypothetical original configuration the hypostyle hall geometry remains essentially unchanged. The remaining three sides would host three new halls conceived by the same architectural system of the existing hypostyle hall, thus making the castle fully symmetric, but essentially exhibiting the same static response of the existing hall. This symmetry, on the contrary, helps the castle behave monolithically under the horizontal loads caused by seismic actions, with a reduction of the vaulted areas subjected to tensile principal stresses, and improves the global response in terms of eigenvalue analyses. Finally, an architectural proposal for the restoration is also proposed, which takes care of both problems, by rebuilding the original symmetry of the castle and by using modern materials to reduce the stress due to gravity loads.

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