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# SEISMIC ANALYSIS OF MASONRY MONUMENTS BY AN INTEGRATED APPROACH THAT COMBINES THE FINITE ELEMENT MODELS WITH A SPECIFIC MECHANISTIC MODEL

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**Summary.** The paper presents a strategy for the non-linear dynamical analysis of ancient masonry structures through two case studies (”Maniace Castle” in Syracuse, Italy and the Qutb Minar in Delhi, India).

## 1 INTRODUCTION

The evaluation of the seismic behaviour of ancient masonry structures requires peculiar procedures, since their response to dynamical loads often differ substantially from those of ordinary buildings. In order to obtain a reliable estimation of the seismic risk, it is desirable to perform full dynamical analyses that describe the effective transmission and dissipation of the energy coming from the ground motion into the structure. In general, modelling the non-linear mechanical behaviour of ancient masonry structures by means of three-dimensional models require a great amount of computational resources that are not commonly available. Luckily, when performing complete dynamical analyses it is often effective to adopt a two-dimensional model rather than a three-dimensional, even if the definition of a simpler model often requires a process of tuning in order to approximate as well as possible the features of the specific kinematics that is of interest.

In this context, the use of two or more analysis tools allows to overcome the complexity of the study of the seismic behaviour of ancient masonry structures. The results obtained from one analysis tool are used as the basis for a better conception of another model which uses a different analysis tool. Moreover, by combining the results of the different models it is possible to obtain a better and more comprehensive interpretation of the seismic behaviour.

The two case studies presented in this paper (the “Maniace” Castle, in Syracuse, Italy and the Qutb Minar, in Delhi, India) show the application of this strategy of analysis combining the well-known Finite Element Method with the specific mechanistic rigid body and spring model (RBSM) [1], here named as *Rigid Element Method*. The first one allows a good three-dimensional discretization of the geometry of the structure while the second one allows fully non-linear dynamical analyses with few computational resources.

## 2 THE RIGID ELEMENT METHOD

The rigid element method (REM) [1, 3] idealises the masonry structure as a mechanism made of rigid elements and springs. The elements are quadrilateral and have the kinematics of rigid bodies with two linear displacements and one rotation. Three springs-devices connect the common side between two rigid elements or the restrained sides.These connections are two axial springs separated by a distance $2b$, and one shear spring. A volume of pertinence is assigned to each connection point. Out-of the linear elastic field, the main macroscopic constitutive aspects are: the very low tensile strength; the significant post-elastic orthotropy combined with the texture effects; the dependence of the shear strength on the vertical compression stress; the progressive mechanical degradation during repeated loading; and the energy dissipation capability. To do this, a simplified heuristic approach is adopted, based on the phenomenological consideration of the main in-plane damage mechanisms that is described at the meso-scale by adopting specific separate hysteretic laws for the axial and shear deformation between the elements [3]. This separation reduces the computational effort, even though a Coulomb-like law is adopted in order to relate the strength of the shear springs to the vertical axial loading.

## 3 THE MANIACE CASTLE

As first, we present the seismic analysis of the large medieval “Maniace Castle” in Siracusa, Italy. Three different numerical models [2] were implemented: a) a global three-dimensional finite element model of the whole castle; b) a detailed three-dimensional finite element model of the architectural part of the building that suffered the main static problems; c) a plane rigid element model. Only linear-elastic analyses were carried out with the first two models, while the third model was formulated with the aim to investigate the non-linear dynamical response and the seismic damage of the structural system constituted by the pillars, the buttresses and the arches of the masonry monuments.

The global model of Maniace Castle was made by means of a total number of 108625 solid tetrahedron elements. In this model the geometric details were simplified by disregarding the exact three-dimensional shape of the internal vaults, as well as many other structural details. A simple process of tuning allowed to approximate the basic fundamental modes of vibration, as well as the mean values of stress due to the gravity in the most critical parts of the building, the columns and the buttresses, as it resulted from the previously published experimental and computational studies.

The numerical analysis made on the whole Castle showed that in the case of seismic excitation the most critical part of the building is the vaulted room, i.e. the rest of the ancient hypostyle chamber named Salone. In particular, the load bearing capacity of the four columns and of the two buttresses in the internal courtyard are particularly at risk. Thus, a refined three-dimensional finite element model was also assembled in order to get a deeper knowledge of the kinematics and the stress situation of this part of the building in the linear elastic field. In this case, the geometry was modelled with great detailed, and the real shape of the cross-vaults, the ribs, and all the structural details that can be significant for the stress analysis were implemented. Moreover, the different construction materials adopted in the real building could be assigned with some precision within the limits of the linear elastic field. This detailed model has a total number of 48004 8-node brick elements.

The three-dimensional models showed that the kinematics of the whole castle is dominated by the first natural mode of vibration, that can be very well described on the basis of a plane model. Clearly, to do this, it was necessary to perform a fine tuning on the characteristics the different materials that constitute the model with the objective of obtaining a good approximation of the real three-dimensional behaviour. Six different materials were assigned to this discrete model. The numerical response of this model proved to be satisfactory in the linear elastic field. The first natural mode of vibration was in good agreement with the previous finite element models, both in terms of frequency and of global shape. Moreover, also the estimated values of stress were correct, in particular for what regards the vertical axial component in the columns and in the buttress that were the more critical parts of this structure.

## 4 THE QUTB MINAR

Three different numerical models were considered to evaluate the structural behaviour of the Minaret [4]. The first model uses 3-D solid elements based on Finite Element Method (3-D Model), the second model was performed with 3-D composite beams based on Mindlin-Reissner theory (Beam-Model) and 2D in-plane elements based on the Rigid Element Method were used in the third model (Rigid- Model).

The Three Dimensional Solid Model (3-D model) was implemented by using the Finite Element Method. Eight-node isoparametric solid brick elements, based on quadratic interpolation and 3x3x3 Gauss integration, were employed. The foundation, the doors and windows of the minaret were also modelled. The full model involves 65,912 elements with 57,350 nodes, resulting in about 172,000 degrees of freedom (DOF). As a boundary condition, it was considered that the base of the foundation was fully restrained.

The three dimensional beam model (Beam model) was performed based on the Finite Element Method. Three dimensional beams elements of three nodes based on the Mindlin- Reissner theory were used. In order to model the different layers of materials, as well as the centre core of the minaret, composite beams were used. The model has 41 nodes (120 DOF) and 20 elements. Each composite beam element was defined with four different pipe sections in order to take into account the different layers and one circular section that defines the centre core. In this model is not possible to model the influence of the staircase as in the three-dimensional solid model and a perfect connection between the shaft and the core is considered.

A simplified in-plane model of the minaret based on the Rigid Element Method (REM) was developed. In total, the numerical model has 39 elements and 117 DOF. The rigid elements used can be only defined with a rectangular cross section. For this reason an equivalent square cross section and equivalent isotropic material were considered.

The advantage of this simplified model is that it is possible to perform non-linear dynamic analysis with few computational resources and in less time than Finite Element Models (Beam and 3-D models). For example, the Beam model requires 23 hours to perform a non-linear dynamic analysis, while the RE model needs only 20 minutes. Therefore, this simplified model was used to have preliminary results about the global dynamic behaviour of the structure.

## 5 CONCLUSIONS

1. The use of a simplified model (REM) allowed performing non-linear dynamic analyses with few computational resources with less time than other more complex models, allowing to obtain valuable results about the global behaviour of the structure.

2. The use of two or more analysis tools allows to overcome the complexity on the study of the seismic behaviour of ancient masonry structures.

3. The results obtained from one analysis tool are used as preliminary results for the better conception of another model using a different analysis tool. Moreover, by combining the results of the different models it is possible to obtain a better and more comprehensive interpretation of the seismic behaviour.

4. The approach followed in the Maniace Castle was to create three-dimensional linear finite element models in order to find the most critical part of the structure. The Rigid Element Method was then used to perform non-linear dynamic analysis of the critical part of the structure.

5. In the case of the Qutb Minar, the Rigid Element Method was used to obtain preliminary results about the global behaviour of the structure, in which the more complex finite element models were based.

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