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HOMOGENIZED RIGID BODY AND SPRING MODEL (RBSM) FOR THE NON-LINEAR DYNAMIC ANALYSIS OF HISTORIC MASONRY CHURCH FACADES

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Keywords: Masonry, Homogenization approach, In plane loads, Out of plane loads, Earthquake, Non-linear static analysis (pushover), Non-linear dynamic analysis.

Abstract. *The present paper presents a series of FE non-linear dynamic analyses performed on masonry church facades subjected to seismic excitation. The facades are modeled as truly 3D structures, because a portion of the perpendicular walls is accounted for. Both pushover and non-linear dynamic analyses are carried out. The structures are discretized using a rigid body and spring model RBSM strategy, having previously homogenized the masonry material. The spring identification is carried out using classic energy equivalence on homogenized stress-strain relationships deduced by an ad-hoc meso-scale holonomic homogenization previously proposed by the authors for in-plane loaded masonries in the static field. The RBSM is implemented into the commercial software Abaqus, where all the discussed analyses are performed. The procedure proved to be robust and efficient and the following advantages are worth mentioning: (1) the homogenized mechanical properties can be directly implemented at structural level with a very limited computational effort, (2) it is not necessary to discretize with refined meshes the elementary cell; (3) the holonomic laws assumed for mortar joints allow for a total displacement formulation of the model, where the only variables entering into the homogenization problem are represented by displacements. On the other hand, it should be finally pointed out that the procedure adopted is intrinsically affected by a certain level of approximation, mainly linked to the simplified hypothesis done to describe the influence that the in-plane behavior has on the out-of-plane homogenized properties. As a matter of fact, the presence of membrane loads (mainly vertical gravity compression) is assumed a priori known for the determination of the out of plane behavior, as well as totally independent from the state of damage and deformation reached during the analyses. As a rule, such a simplification is however considered fully acceptable, allowing to reasonably take into account the increase of both out-of-plane carrying capacity and ultimate ductility.*

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1 INTRODUCTION

The determination of the non linear dynamic behavior of full scale tridimensional masonry structures by Finite Element software is still a tricky issue and considered rather demanding both at an academic level and in engineering practice. As a matter of fact, masonry exhibits quite peculiar mechanical features that must be taken into account when 3D non linear dynamic analyses are performed. At present two numerical techniques are at disposal, namely macro [1] and micro [2] modeling approaches. The first numerical strategy consists in the substitution of the heterogeneous assemblage with blocks and mortar with a fictitious homogeneous material exhibiting a-priori defined orthotropy and softening, but requiring costly experimental campaigns (repeated case by case) to calibrate the many mechanical parameters involved. On the contrary, micro-modeling approaches are characterized by the distinct modeling of all the constituent materials, considering their geometry, the assemblage into the masonry patterns as well as their inelastic constitutive laws. Clearly, such types of approaches can be hardly adopted when analyzing full scale structures in the dynamic field, being these analyses too demanding from a numerical and economical point of view. To overcome such limitations, in the present paper, homogenization concepts [3]-[7] are used. In particular, a simplified two-step homogenization approach [3][5][7] formulated by the authors to study in and out of plane loaded masonries is proposed. The model is herein benchmarked in the static and dynamic fields with respect only to the out of plane failure mechanisms (Figure 1) of masonry church façades.

The case study at hand is represented by the façade of the "Trasfigurazione" church, which can be considered an example of Romanesque architecture quite frequent in the small towns of Italy, in particular of those located in Friuli. Moreover, due to the huge amount of data available in [8][9], it appears an interesting benchmark for the proposed models especially at the macro-scale.

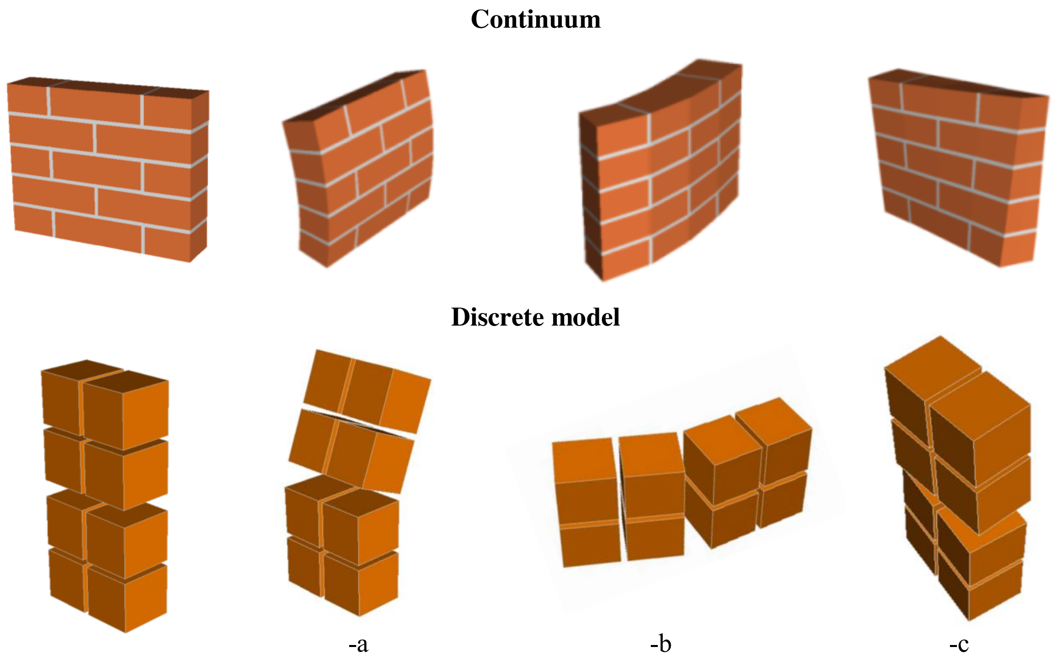


Figure 1: Failure mechanisms allowed in the proposed homogenisation model: (-a) horizontal bending, (-b) vertical bending and (-c) torsion.

2 THE HOMOGENIZED SPRING MASS MODEL

In the present section, the homogenized mechanical properties deduced using the models proposed in [3][5] are implemented on an existing FE code to simulate entire masonry buildings in the non-linear dynamic range.

All the proposed simulations have been carried out using the FE commercial software Abaqus. The structural implementation is made with rigid infinitely resistant quadrilateral elements and non-linear interfaces exhibiting an orthotropic behavior. On interfaces, the homogenized masonry material is modeled with non-linear flexural/torsional springs placed between adjoining rigid elements and characterized by the mechanical properties estimated during the homogenization at the level of the elementary cell. The stress-strain relationship to be used at structural level requires an identification of the spring elastic properties, in order to make the rigid body-spring assemblage model compatible with the homogenized orthotropic continuum. The reader is referred to [3][5] for further details.

3 NUMERICAL ANALYSES

A series of simulations have been performed with respect to the façade of the "Trasfigurazione" church located in the North-East of Italy. Approximately, the façade has a width of 16.30 meters, with a maximum height (tympanum top) of 18.05 meters and small openings in correspondence of the symmetry axis with walls 55 cm thick. In order to study the seismic response of the church when subjected to seismic loads, a series of non linear static and dynamic analyses have been carried out. The Rigid Body and Spring Model briefly described in the previous section has been adopted to model the façade of the church within a portion of the perpendicular walls belonging to the single nave of the church.

The authors decided to include the transversal walls into the analyses in order to evaluate the tridimensional seismic behavior of the structure. As a matter of fact, such monumental constructions are frequently affected by overturning failure mechanisms which take place with a partial or total detachment of the front walls with respect to the lateral ones. The numerical predictions obtained using the proposed homogenization model have been comparatively assessed with respect to the results found by Casolo and co-workers adopting a different numerical strategy. The mechanical properties of the constituent materials as well as the external restraints are assumed in agreement with the information available in the literature [8][9] and are not reported here for the sake of conciseness. Previous numerical analyses confirmed that the Church was particularly prone to experience severe damages during a seismic event. Such finding results in full agreement with the collapse occurred during the 1976 Friuli earthquake. In particular, the tympanum appeared the most critical element inside the structure. The formation of a horizontal cylindrical hinge in the upper part of the façade mainly suggested the activation of an overturning mechanism. In addition, a vertical splitting of the façade into two portions was detected at the end of the simulations performed in [8][9].

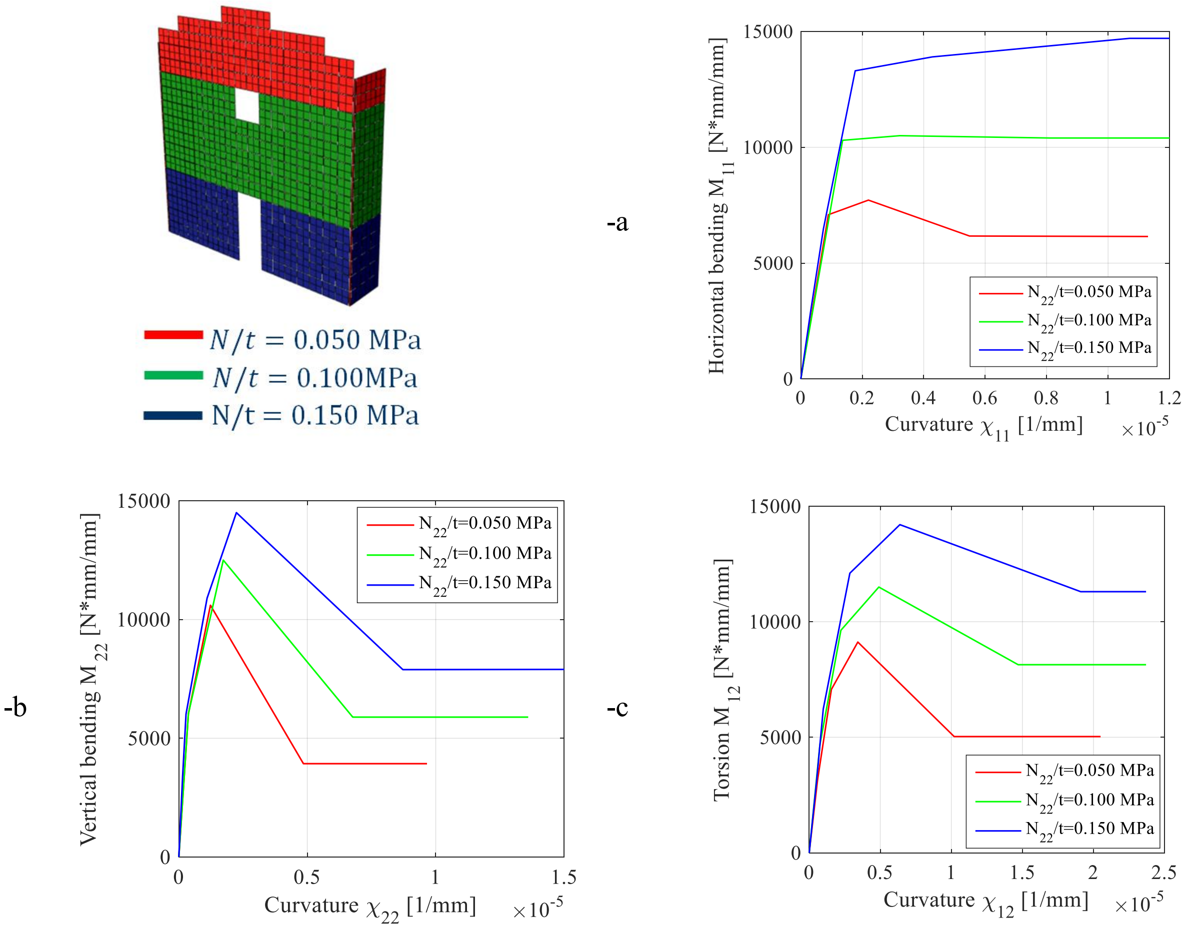
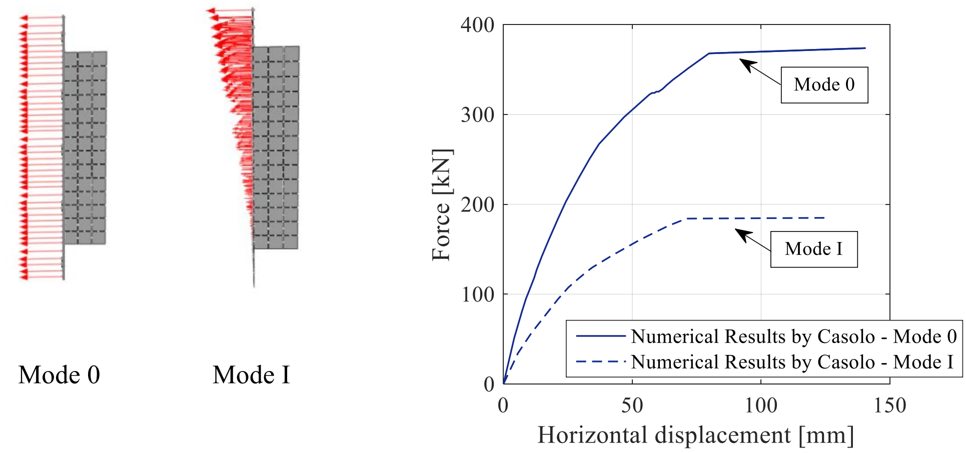


Figure 2: Moment curvature diagrams used at a structural level, Transfiguration Church. Diagrams are plotted at different levels of vertical pre-compression.



-a -b

Figure 3: Numerical results obtained by Casolo et al. at the end of the non linear static analysis (-b) for the Church of Trasfigurazione assuming two distributions of the lateral load (-a).

The results obtained by Casolo and co-workers are depicted in Figure 3. According to the Italian Code, they carried out two series of non-linear static (pushover) analyses assuming two distributions of the horizontal load, as showed in Figure 3-a. As expected by the authors, a reverse-linear along the height distribution is associated to lower collapse acceleration, as confirmed by the capacity curves found at the end of the simulations. In the present work, the façade of the Church is modelled using a coarse discretization, which is composed by a total of 354 rigid quadrilateral elements. Homogenised moment-curvature diagrams obtained with the model proposed are depicted in Figure 2, assuming to subdivide the façade into three levels of constant vertical pre-compression.

4 NUMERICAL RESULTS

In the present section, the results obtained by a series of non-linear static and dynamic analyses are comparatively assessed with respect to the numerical outcomes provided by Casolo and co-workers in [8][9]. The damage patterns resulted particularly accurate in the description of the activation of a peculiar failure mechanism, which took place mostly in the upper part of the façade. Globally a satisfactory agreement is found with respect to the results obtained at the end of both static and dynamic analyses, as briefly described in what follows.

4.1 Pushover analyses

The results obtained using the proposed model are compared to those provided by Casolo and Uva [8] in Figure 4. The displacements have been monitored in a control point located in the upper part of the façade, being the tympanum centre the most vulnerable zone of the structure to a seismic event. As can be noted, a global satisfactory agreement with previously presented results is found adopting both distributions of the lateral loads. Such finding confirms the accuracy of the proposed homogenisation approach to describe the elastic and inelastic behaviour of real scale structures starting exclusively from the knowledge of the constituent materials mechanical properties.

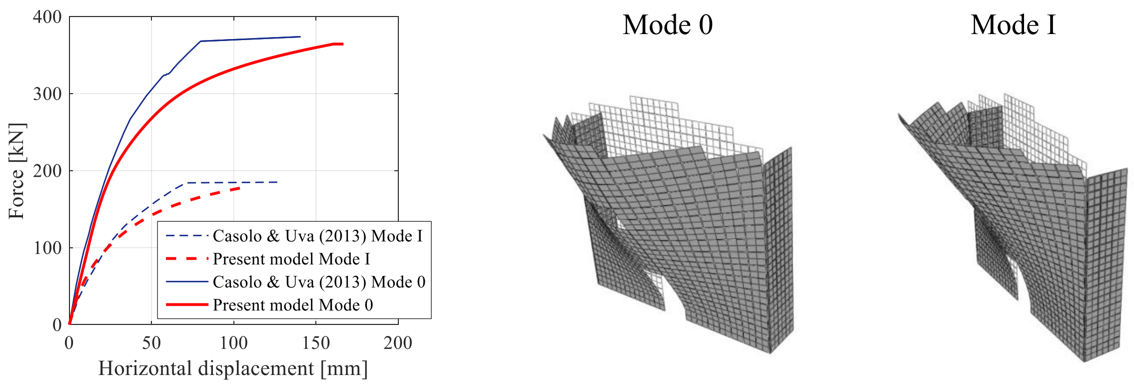
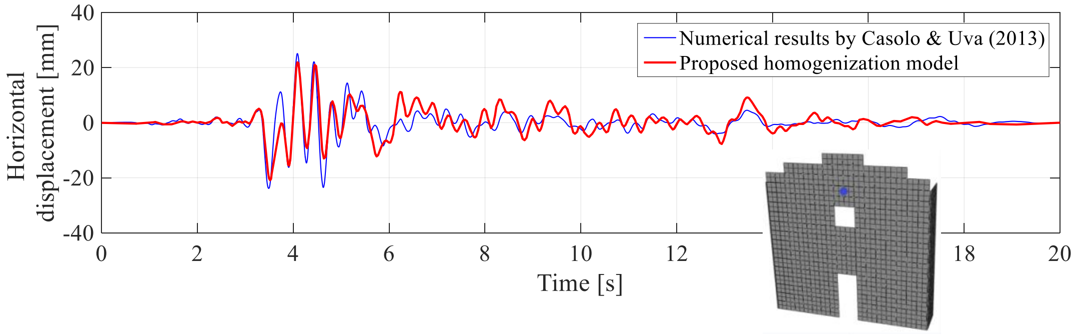


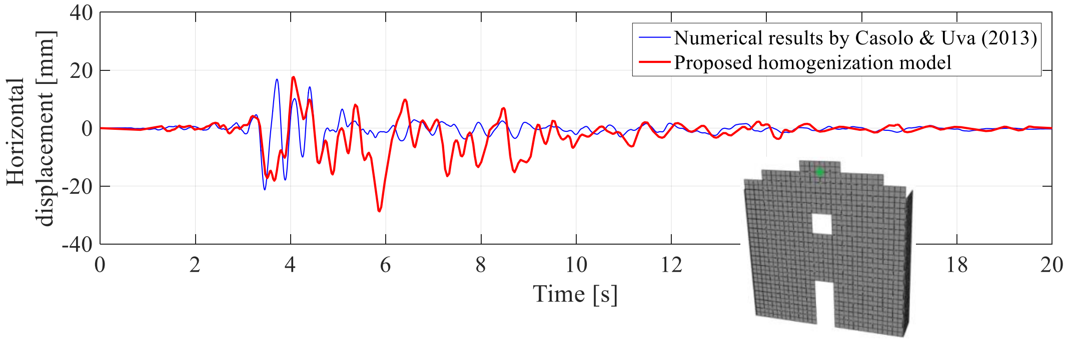
Figure 4: Pushover curves obtained (left) and corresponding deformed shapes (right).

4.1 Numerical analyses

The vulnerability of the structure has been analyzed also by means of a series of non-linear dynamic analyses. In particular, the Fogaria natural accelerogram, recorded during the Friuli 1976 earthquake, is applied at the base of the façade. The results obtained at different heights of the control point are summarized in Figure 5, whereas Figure 6 shows the façade deformed shape and crack patterns numerically obtained at the end of the simulations (-a: vertical bending and -b: horizontal bending). As can be noted, good agreement is found between the results obtained using the proposed approach and those achieved in [8][9], in terms of both time-displacement history and damage patterns found at the end of the simulations. The façade exhibited a collapse mechanism that mainly involves the upper part, with the resultant overturning of the tympanum. Such finding suggests the activation of a slightly different failure mechanism with respect to that found in [8] where again the upper part is the most vulnerable, but with the formation of two inclined yield lines spreading from the upper corners down to the central rose window. Damage patterns at the end of the simulation are depicted in Figure 6, separately for flexion and torsion. The deformed shape of the façade clearly indicates the activation of a failure mechanism involving the overturning of the tympanum. In addition, high levels of damage are reached in correspondence of the horizontal line where the out of plane mechanism of the tympanum takes place. It is worth noting that severe damages are visible also in correspondence of the vertical edges and near the central opening, in quite reasonable agreement with the results found in [8][9].



z = 14.20 m -a



z = 16.72 m -b

Figure 5: Comparison between previous models and present numerical results for the Transfiguration Church at different heights of the control point (Forgaria accelerogram).

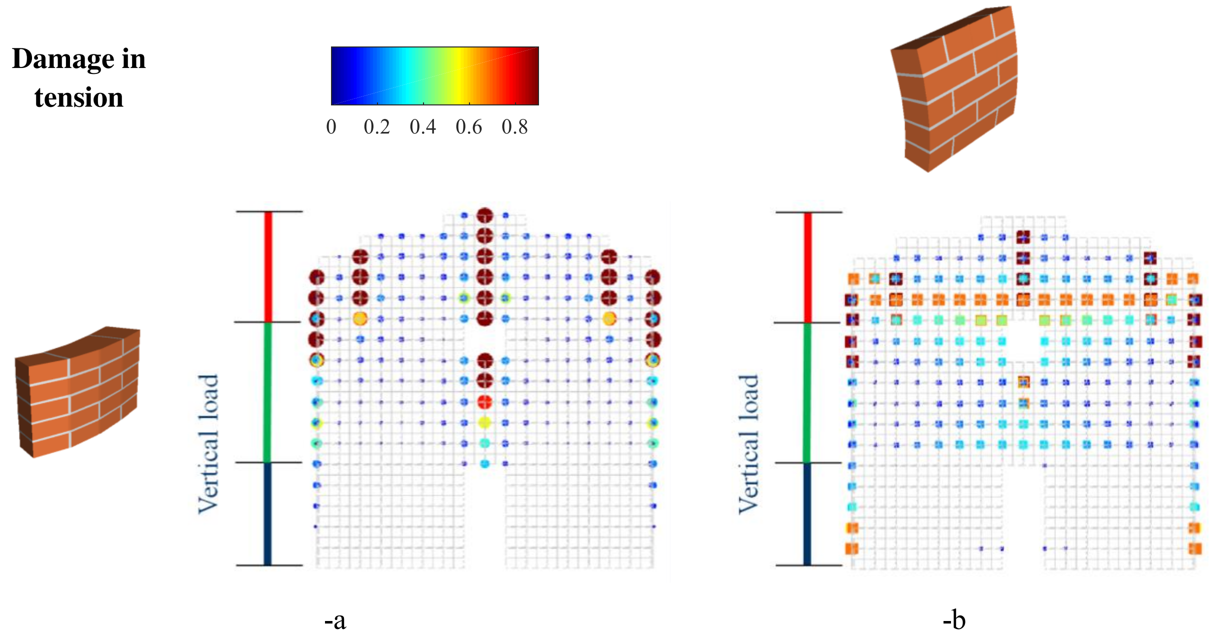


Figure 6: Deformed shape and crack patterns numerically obtained at the end of the application of the Fogaria accelerogram: vertical bending (-a) and horizontal bending (-b).

5 CONCLUSIONS

In the present paper, the seismic behavior of a portion of the "Trasfigurazione" Church has been modeled by means of a simplified two-step homogenization model formulated by two of the authors to analyze in and out of plane loaded masonries. In the case study at hand, the extension of the proposed model to out of plane actions only has been benchmarked in the static and dynamic fields. The study has been carried out modeling the façade of the Church with a portion of the perpendicular walls, being that part one of the most vulnerable for such kind of monumental constructions. The studies have been performed conducting two series of non linear static and dynamic analyses and assessing the numerical predictions with the ones obtained by Casolo and co-workers. In the first set of simulations, two distributions of the horizontal loads have been considered, according to the Italian Code, whereas in the second set, the natural ground motion recorded in Fogaria during the Friuli 1976 earthquake has been employed. In both cases, a general satisfactory agreement is found for all the proposed simulations, meaning that the simplified two-step homogenization model is able to accurately describe the seismic behavior of the structure with a very limited computational effort. Moreover, the damage patterns obtained at the end of the dynamic analyses, confirmed the activation of a failure mechanism that involved the overturning of the upper part of the façade. Again, such findings are fully confirmed by the experimental collapses found in several churches subjected to dynamic excitations and in partial in agreement with what found by Casolo et al. [8][9].

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