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'HYBRID' FULL MODELS FOR SEISMIC ASSESSMENT OF MASONRY AGGREGATES THROUGH PUSHOVER ANALYSIS

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Abstract

Most of the historical city centres in Southern Europe are made up of masonry buildings clustered in aggregate, which are a result of the urban tissue transformation over time. Recent earthquakes have shown their high vulnerability because buildings were built without any anti-seismic criterion, relying on simple rules of thumbs. Since the seismic behaviour of masonry aggregates cannot be a priori predicted - because of complex geometries, presence of materials having different behaviours and interactions among adjacent buildings – accurate analyses, such as pushover analyses, shall be performed. Masonry aggregates are typically characterized by the presence of different structural typologies, thus pushover analyses are generally performed on partial models, representing significant portions of the whole aggregate. The critical point in this type of analysis is the identification of the minimum length of the portions of the neighbouring walls that actually contribute to the extra-redundancy of the structural system, which cannot be taken into account within partial models. Hence the idea to consider "hybrid" full models, in which the material behaviour is assumed non-linear only for the portion subject of investigation, while it is assumed linear elastic for the context.
This contribution shows the results – part of a wider work – obtained by means of pushover analyses performed for the ex-monastery of Santa Maria della Pace in Piacenza, Italy, on full and partial models of the entire aggregate with different material modelling assumptions, and the model that best represents the actual behaviour of masonry aggregates is proposed.

Keywords: Masonry aggregates, Pushover analyses, FE models, Non-linear material behaviour.

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1 INTRODUCTION

Historical city centres of several countries are characterized by masonry buildings clustered in aggregate, often erected in continuity with one another, and generated over the centuries by the progressive transformation of the urban tissue, without any anti-seismic criterion, so their vulnerability is expected to be quite high. The vulnerability assessment of buildings belonging to aggregates is of crucial importance, because they are typical of many countries in Southern Europe (e.g. Croatia, Greece, Italy and Portugal) that are earthquake prone areas.

The behaviour of a building aggregate is never standard and cannot be a priori known with sufficient accuracy, because, due to changes made over time, different structural typologies can be found in the same construction. Moreover, the behaviour of a specific aggregate is always dependent on the materials used, the global and local regularity of the structure, the presence of rigid floors and the effectiveness of the connections.

In [1] and [2] specify that any possible interaction resulting from structural contiguity with adjacent buildings must be carefully considered. Furthermore, the effects of thrusts on common walls of the structural units caused by the presence of floors at different heights, local mechanisms activated by the height irregularity and setbacks of the structural units, should be properly examined.

In the technical literature, several methods useful to increase awareness on those units of an urban aggregate that most likely require urgent retrofitting interventions have been developed, such as [3],[4]; however specific additional analyses should be performed to identify more precisely the causes of weakness and possible effective retrofitting interventions. On the other hand, many advanced computations have been carried out for specific case studies, such as [5]-[7].

In case of buildings clustered in aggregate, the role played by contiguous buildings in terms of stiffness, strength and dynamic behaviour turns out to be crucial and quite difficult to be understood. The research on the interaction with neighbouring buildings is still at a early stage and only very specialized investigations have been performed, as for instance [8], where the Gabbia tower in Mantua (Italy) was studied with the goal of evaluating the minimum extension of the buildings in aggregate to be considered in the analyses for a realistic prediction of its seismic behaviour.

Therefore, a reliable and easy model of masonry aggregates suitable for accurate analyses is needed to quantify the horizontal collapse acceleration and to accurately identify the most critical parts for seismic protection measures implementation.

Pushover analyses are generally performed on isolated partial models of the structure to assess the seismic vulnerability of significant portion of the aggregate; the critical point of such analyses is the identification of the minimum length of the portions of the neighbouring walls that actually contribute to the extra-redundancy of the structural system, which cannot be considered within partial models. The confinement given by adjacent buildings may sometimes have beneficial effects, resulting in a higher collapse acceleration for the different structural typologies constituting the masonry aggregate. In the present paper, which is an extract of a wider work [9], it is proposed an evaluation of the effects of the aggregate context on the seismic vulnerability assessment of different portions constituting the masonry aggregate; investigations were performed on a complex case study, namely the ex-monastery of Santa Maria della Pace in Piacenza (Italy). The results of pushover analyses performed on different numerical models, both in terms of context extension and material modelling, have been compared. The outcome of the study allowed to define the more accurate numerical model to be adopted in pushover analyses for an in-depth evaluation of the expected response of any masonry aggregate under the application of horizontal loads.

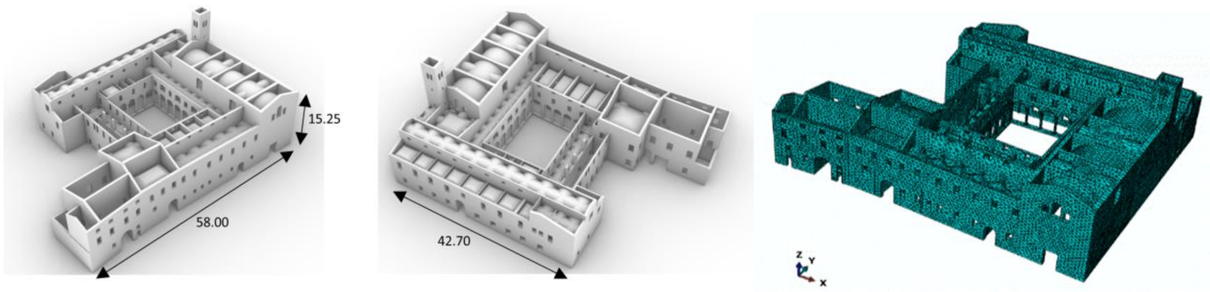
2 CASE STUDY: EX-MONASTERY OF SANTA MARIA DELLA PACE

The analyses have been performed on an ex-monastery built in the XVI century. The structure is mainly made of masonry and it is characterized by a cloister layout into two levels. The cloister and the corridors of the first floor are covered by cross vaults. Cloister vaults, sometimes with the presence of lunettes, cover most of the rooms. Few rooms are covered by decks made of timber beams and joists. The pitched roof bearing structure is made of timber beams and joists and is covered by tiles. The structure can be defined as a building aggregate because it is confined by adjacent buildings on two sides and in one wing of the complex a church and a bell tower are present. For further details about the structure see [9].

Starting from the 3D geometric model, see Figure 1a and b, the structural model of the building was implemented in the software Abaqus/CAE®. The decks and the roof were considered only in terms of applied load on the structure, because such elements are not stiff enough in their plane and the rigid diaphragm hypothesis cannot hold. In addition, in a masonry historical structure the wall-to-floor connection is generally quite poor.

Tetrahedral linear elements were adopted to discretize the model, see Figure 1c. The boundary conditions at soil level were defined using fixed constraints, where rotations and displacements were assumed equal to zero; they were also adopted to represent the interaction with the adjacent buildings.

In this case study, masonry is characterized by Young's modulus equal to 1230 MPa, Poisson's ratio equal to 0.25, and a density of 18 kN/m^3. In order to perform non-linear analyses, the non-linear behaviour of the material was de-fined. The Concrete Damage Plasticity (CDP) model [10]-[13] is rather suitable in the case of masonry. The parameters used to calibrate the CDP model are listed in Table 1a, they were taken according to the results found in the technical literature [8], [14]-[16]. The stress–strain curve [17] was used to define the post-elastic domain in compression, see Table 1b, while the behaviour of masonry in tension was defined through the fracture energy, see Table 1c. The columns of the cloister, made of granite, were modelled with an elastic material (Young's modulus 5000 MPa, Poisson's ratio 0.25, density 27 kN/m3) since their strength is much higher compared to the masonry one. For more information about the structural model and the modelling of the material behaviour refer to [9].



a) b) c)

Figure 1: Digital model (dimensions in meters) a) and b), structural model c) of the ex-monastery.

3 PUSHOVER ANALYSES ON 3D FE MODELS

The global behaviour of complex structures, characterized by massive walls, vaults and arches, can be studied by means of pushover analyses performed on 3D FE models. Using this approach, the actual geometry of the structure is accounted for and the results may be considered the most reliable. The drawback is that the modelling phase and the computations require much longer time than simpler models; in addition, it is required sufficient experience in advanced non-linear FE modelling and knowledge about masonry behaviour. Pushover analyses of 3D FE models allow to find a detailed crack pattern, which can be compared to the actual one (if existing) giving the possibility to understand and confirm the origin of the cracks, and the monitoring of displacements of different points on the structure under increasing values of horizontal loads, that is useful to study the triggering of local mechanisms characterizing this type of structures. In this work, pushover analyses on 3D FE models were carried out using the software Abaqus/CAE®.

3D pushover analysis can be performed on the whole structure or on significant portions of the building aggregate. In common practice, portions representing the behaviour of a characteristic part of the compound are isolated, and the analyses are performed on partial 3D FE models. The outcomes of partial analyses are conservative; indeed the interaction among the parts of the building aggregate, that is neglected, may have beneficial effects and the structure may withstand higher horizontal seismic actions, as reported in the literature [4],[5],[7].

With the purpose of studying the influence of the context on the seismic vulnerability of the different portions of the aggregate, the results obtained performing pushover analyses on partial models have been compared to those coming from pushover analyses performed on the full model and on "hybrid" models. Reference is made to the results obtained from pushover analyses carried out on partial models in [9], where three significant portions of the structure, see Figure 2, were isolated and their behaviour was studied using pushover analysis.

a)

Kc – Shape factor	0.667
e - Eccentricity	0.1
fb0/fc0 – Compressive yield ratio	1.16
ψ [°] – Dilatancy angle	10
μ - Viscosity	0.001

b)

f_m [MPa]	$\varepsilon_{inelastic}$ [-]
1.80	0.0000
1.90	0.0004
2.00	0.0013
1.90	0.0022
1.80	0.0026
0	0.0101

c)

f_t [MPa]	G_f [N/mm]
0.2	0.02

Table 1: a) CDP parameters, b) stress-strain curve in compression, c) fracture energy.

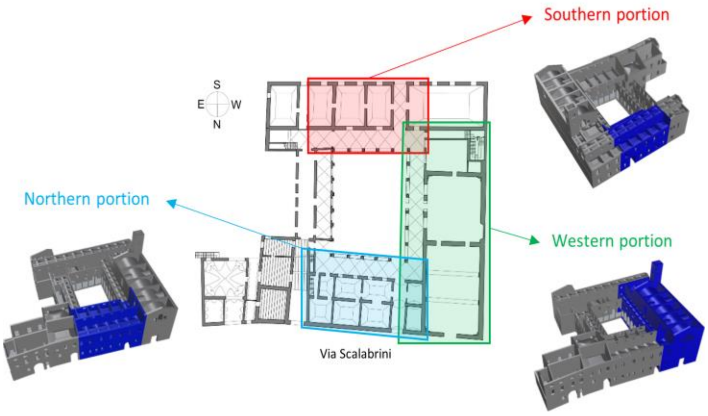


Figure 2: Portions of the ex-monastery object of study.

3.1 Analyses with the full 3D FE model

In order to show that isolating portions of the structure and performing pushover analyses on partial models reflects in finding conservative results, a full 3D FE model of the entire structure was used to perform non-linear static analyses (Figure 3).

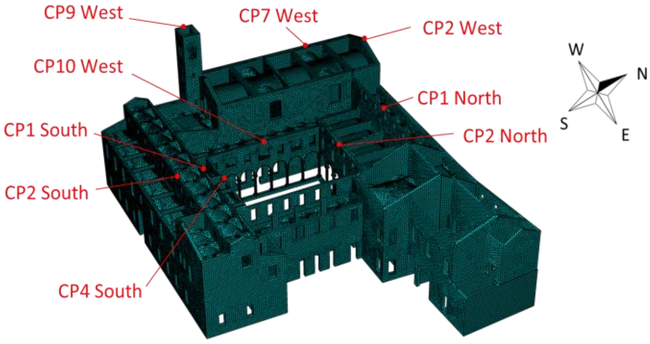


Figure 3: Full model control points [9].

The results in terms of capacity curves, for both positive and negative East-West and North south loading directions, are shown in Figure 4-Figure 6 (equivalent plastic strain colour patches at failure and ultimate deformed shapes are depicted in [9]).

An insight of all the pushover curves reveals that the initial stiffness is very similar between full and partial models. Furthermore, isolated models generally have a larger ductility and reach their ultimate resistance at lower values of horizontal acceleration. Such behaviour was expected, since it has been demonstrated in the literature that isolated buildings exhibit higher ductility than aggregates. According to the simulations, the ultimate load carrying capacity of the full 3D-model is higher than that of partial models, because of the larger redundancy. The only exception was found for the East-West load direction for the northern and southern portions, where lower collapse accelerations were found (Figure 4, Figure 5). This may be explained by the activation of the local mechanism of the wall belonging to the eastern portion, where confined horizontal flexure is activated, see [9].

To briefly recap, taking isolated portions of the aggregate as reference can be considered conservative only if the load carrying capacity is assumed to be the main parameter to maximize. The ultimate displacements, on the other hand, show an opposite trend; however, they are very difficult to be accurately determined for historical buildings and in complex 3D FE models. For this reason, a displacement-based assessment is not recommended for such kind of structures.

3.2 Analyses adopting an "hybrid" model

Pushover analyses performed on partial models provide results quite different from those obtained using a full 3D FE model. Furthermore, the fact that numerical simulations are affected by premature halting because a portion of the structure is involved by the activation of partial failures, could make impossible the correct characterization of the seismic vulnerability. The more wide and complex the model, the more likely this condition is. As a result, there is the need to operate with partial models. On the other hand, identifying the minimum length of the portions of the neighbouring walls that actually contribute to the extra-redundancy of the structural system, which cannot be taken into account within partial models, would be difficult. Therefore, it may be of interest to consider "hybrid" full models, in which the behaviour of the materials is assumed to be non-linear only for the portion under investigation and to be linear elastic for the rest of the context.

The material behaviour of the vaults is considered both linear elastic and non-linear in the analyses performed in [9] on "hybrid" models. The results, for the three portions of the structure analysed, are shown in terms of capacity curves in Figure 4-Figure 6.

"Hybrid" models with linear elastic vaults lead to capacity curves similar to those obtained with the full model, but with a larger global ductility, implying that the analyses do not stop due to premature local collapses of other portions of the aggregate; thus, the characterization of the studied portion is more accurate. However, the capacity curves are sometimes stiffer than the full model, as shown in Figure 5 for the analysis performed in the North-South direction. Instead, the capacity curves obtained with the "hybrid" model with non-linear material behaviour of the vaults have a similar initial stiffness and a lower collapse acceleration when compared to those obtained with the full model, but a higher collapse acceleration when compared to those obtained using partial models. Since analysis is not interrupted due to local collapses of other portions of the building, this type of model allows for a more accurate evaluation of the structural behaviour of the studied portion of the aggregate, taking correctly into account the confinement provided by the neighbouring portions and the non-linearity of the materials. Furthermore, all the possible local collapse mechanisms can be taken into account because the vaults are considered non-linear, as for instance the horizontal flexure of the church façade (CP2), see Figure 6 and [9].

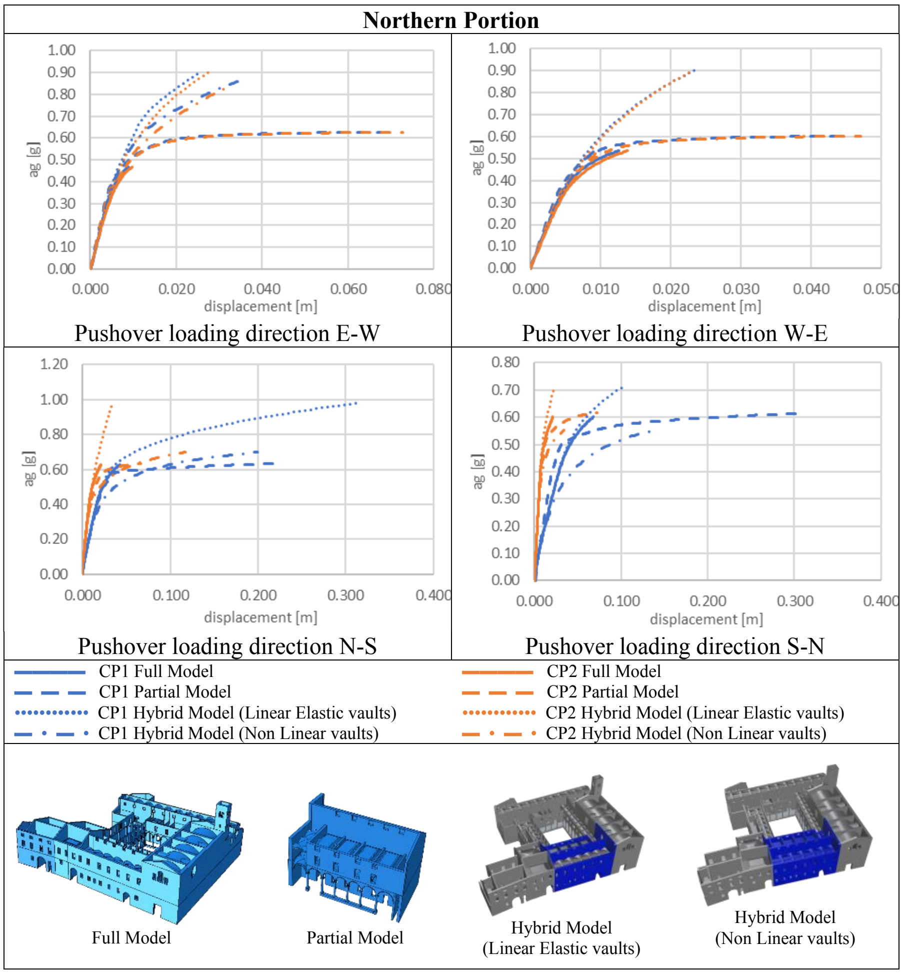


Figure 4: Comparison of the capacity curves of the northern portion obtained with the full model, the partial model and the "hybrid" model [9].

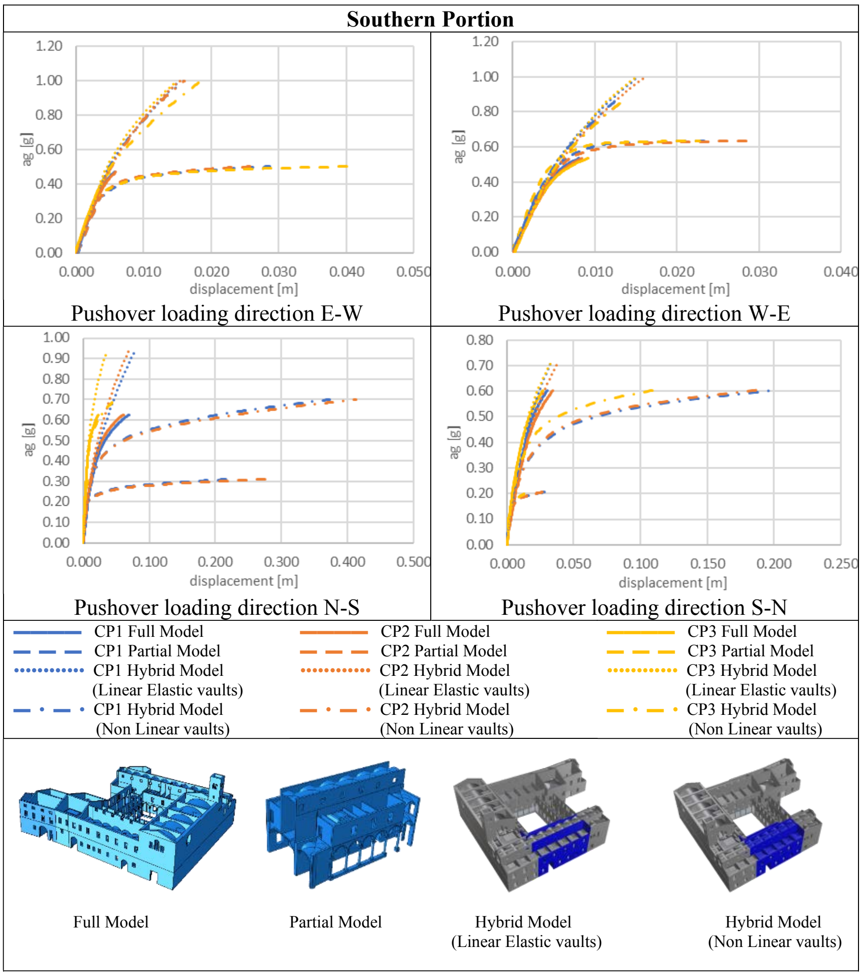


Figure 5: Comparison of the capacity curves of the southern portion obtained with the full model, the partial model and the "hybrid" model [9].

Based on the findings of this case study, it is possible to conclude that the “hybrid” model with non-linearity of all the elements, including the vaults, is the more suitable model for characterising the structural behaviour of a building aggregate portion. Partial models tend to provide excessively conservative results, largely underestimating the global stiffness not considering the beneficial effects given by the constraints provided by the rest of the structure. On the other hand, the hybrid model with linear elastic behaviour of the vaults exhibits a too large stiffness, because the curved elements do not crack during the deformation process, in contrast with their observed experimental behaviour.

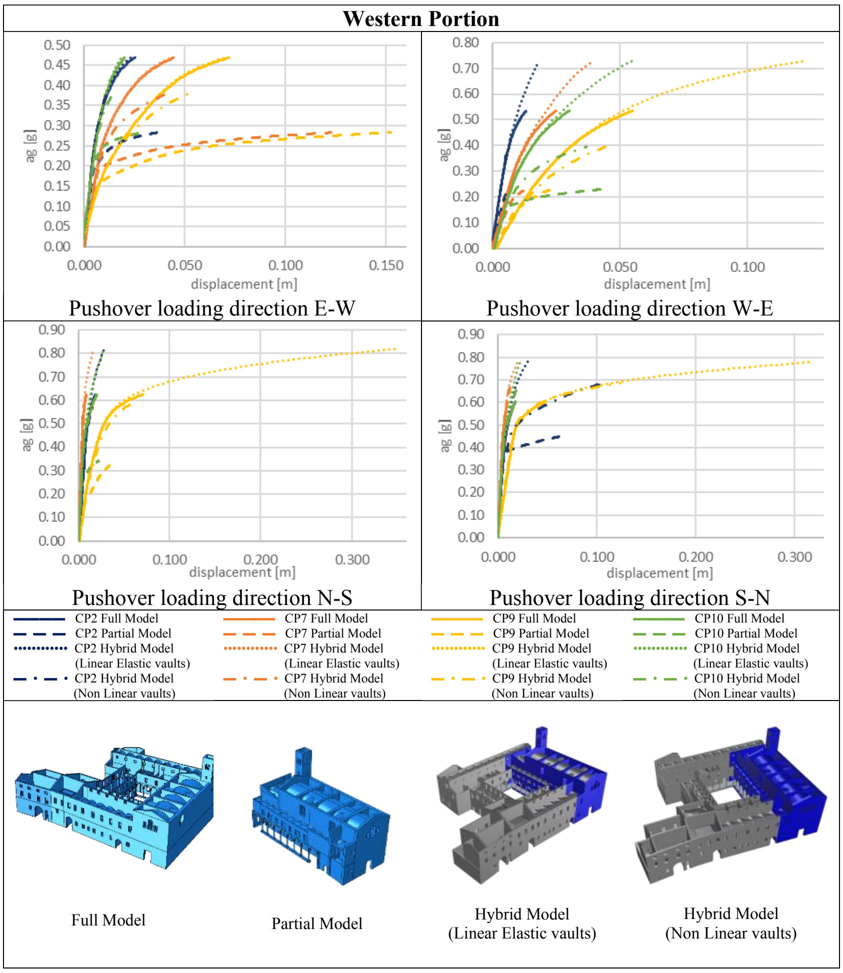


Figure 6: Comparison of the capacity curves of the western portion obtained with the full model, the partial model and the "hybrid" model [9].

4 CONCLUSIONS

Based on what was deeply presented in [9] and developed here, the following conclusive remarks can be drawn.

Different 3D FE models, both in terms of model extension and material modelling, have been analyzed to assess the seismic vulnerability of masonry buildings clustered in aggregate through non-linear static analysis, which nowadays is probably the most accurate type of analysis commonly used by practitioners. The comparison of the results allows to identify the most suitable model for considering the influence of the context on the seismic response of masonry aggregate portions. Indeed, structural interaction modelling is critical, because adjacent structures may have beneficial effects on the seismic response of buildings clusterd in aggregate. By means of such accurate analyses, effective retrofitting interventions to reduce the seismic vulnerability of the aggregates can be carefully evaluated.

The models have been benchmarked on a case study in Italy: the ex -monastery of Santa Maria della Pace in Piacenza. The seismic response of different portions of the structure has been studied using full 3D FE models and non-linear static analyses through the commercial software Abaqus/CAE®. Masonry non-linearity has been accounted for with the CDP model.

The results obtained using partial models have been compared to those coming from push-over analyses on the full 3D FE model of the entire aggregate and “hybrid” models. The results show that the full model has higher collapse accelerations and lower ultimate displacements, as expected, because its geometry makes it stiffer than the partial models, which are isolated portions of the structure. However, the results for a portion of the building aggregate using the full model could be sometimes influenced by local collapses of other portions of the compound, thus a so-called “hybrid” model has been used to avoid the activation of collapses outside the portion of the aggregate under investigation. According to the results, it has been found that the “hybrid” model, where masonry non-linearity is only accounted for the portion under investigation including the vaults, is the most suitable model for the characterization of building aggregate portions.

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