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Numerical Investigations on the Seismic Response of Masonry Building Aggregates

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Abstract The work focuses on the analysis of the seismic response of masonry building aggregates for a better understanding of the vulnerability of single structural units and of their behaviour within the aggregates. Idealized representative models are developed based on the typical characteristics of the *row conglomeration* typology. The seismic response of the models is evaluated and discussed by means of nonlinear dynamic analyses.

Keywords: Response, masonry, building aggregate, row conglomeration

Introduction

Problem Overview A building aggregate is constituted by an assemblage of masonry buildings which is a result of an articulated, but not unitary origin, due to multiple factors that determine the evolution of its characteristics in time. As frequently seen in Italy in many historical town centres subjected to earthquakes, the potential interactions due to the structural contiguity within the aggregates is one of the main factors influencing the seismic response and damage mechanisms. As general practice, the safety assessment would mainly regard a single building within an aggregate, but a preliminary analysis should be extended to the conglomeration itself. A rigorous approach would require a detailed analysis of the entire aggregate, but because of the inherent complexity of the aggregate itself some approximations must be introduced. The objective of this work was to investigate the effects of length of row conglomerations and of flexible floors on the seismic response of masonry building aggregates, by means of nonlinear dynamic analyses. Furthermore, the opportunity/possibility to "extract" the single structural unit to be analyzed separately from the aggregate was examined.

Masonry Building Aggregates

Main Characteristics and Typologies As suggested by the Italian building code (NTC08 2008), in order to have a better knowledge of the structural behaviour of a building aggregate, the preliminary analysis should focus on those different features that are peculiar of the aggregate itself (Carocci et al. 2009). For instance, the morphological characteristics of the site and the environmental context in which the conglomeration is located will determine the typologies of buildings and their plan configuration, although this may vary during the evolution process undergone by the aggregate itself. Furthermore, the analysis of the constructive technique and of its workmanlike application is needed to examine the mechanical characteristics of the construction materials. Other vulnerability factors should also be investigated, such as the characteristics of the open spaces in between buildings, which may affect the relationship between the dimensions of the internal areas with the front portion of the building, or the relative height of adjacent buildings and the degree of connection between them.

One of the most common typologies in Italian historical centres is the so called *row conglomeration (row housing)*, constituted by a series of structural units aggregated in line. The street system layout has great influence on the dimensional characteristics and planar configuration of the structural unit. A concentrical system, where the street configuration is parallel to the ground contour lines, will determine the presence of *single-room units*, while *two-rooms units* will be typical in a radial configuration. The structural unit, being constituted either by single or two rooms per floor, is characterized by façade dimension (length) of about 4-6 m, room depth around 5-9 m for *single-room* structural units (or around 10-12 m for *two-rooms* units), openings on both front and back façade varying between one and two per floor, number of storeys between two and three, with interstorey-height increased at ground floor.

Modeling and Assessment Procedure

Structural Models A proper assessment of the response of building aggregates should include the analysis of both *single-room* and *two-rooms* structural unit aggregates, since the structural behaviour of the conglomeration varies depending also on its geometrical configuration. The geometrical characteristics of the theoretical *structural unit model* recall the features of the row conglomeration typology described previously (see Fig. 1).

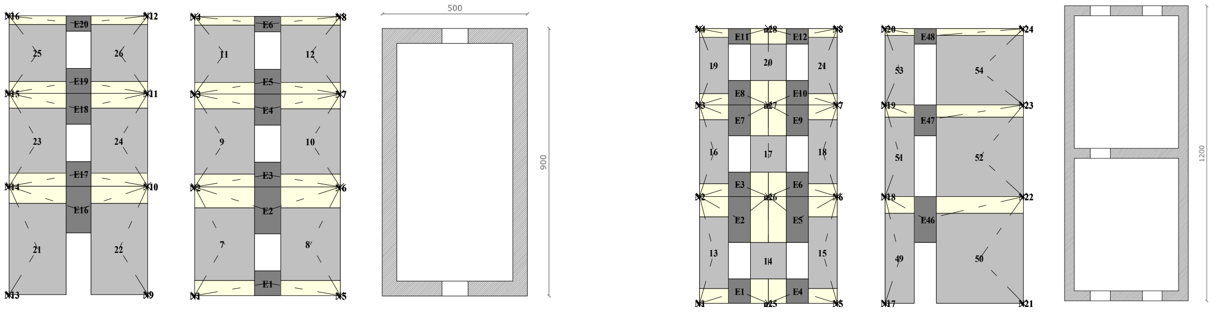

Figure 1: Structural units: front and back façades, longitudinal internal wall models and plans of both typologies

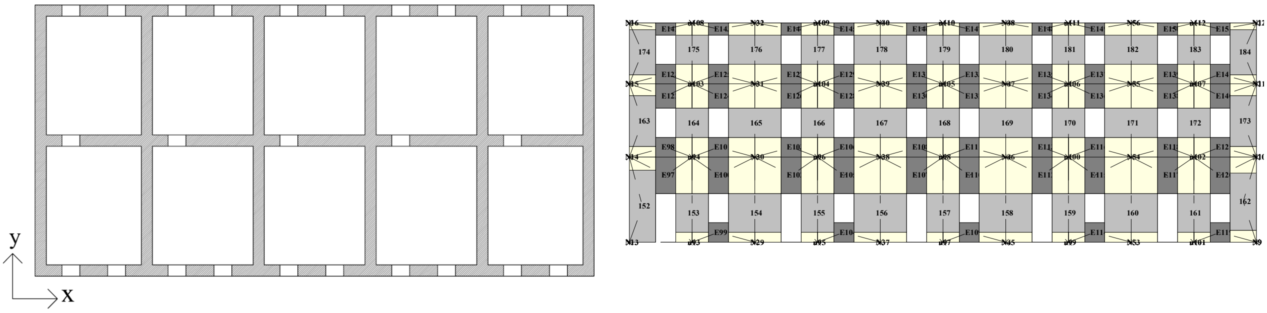

Figure 2: Model D5: 5 units two-rooms aggregate, plan and front façade

The structural unit model has been aggregated along the longitudinal axis in three different configurations: 3, 5 and 9 structural units row conglomerations. As an approximation, the aggregated structural units are fully connected; hence, the longitudinal walls are modelled as continuous.

The global system of coordinates has been identified according to the orientation of walls: the x-axis corresponds to the direction of the longitudinal walls with openings, while the y-axis to that of the transverse walls (as seen in Fig.2).

To compare the global behaviour of the different buildings, the same masonry type has been used for all. The material is characterized by properties typical of undressed stone masonry with facing walls of limited thickness and infill core, with elastic modulus E=1450 N/mm2, shear modulus G=108 N/mm2, specific weight ρ=23 kN/m3, compressive strength fm=3.2 N/mm2, shear strength τm=0.05 N/mm2. Floors are modelled as orthotropic membrane elements, with wooden joist and floorboards so that the roof framework is parallel to the main façades. They share loads to the vertical structure walls, without being significant stiffening elements, particularly for in-plane shear (G=10 N/mm2).

Assessment Procedure The nonlinear behaviour of masonry building aggregates was studied through the use of modelling techniques based on the effective macro-modelling approach, as implemented in the program TREMURI (Galasco et al. 2006).

An accurate tool to evaluate internal deformation and forces of structures subjected to strong ground motion is the nonlinear dynamic analysis (incremental time history). An appropriate set of seven real spectrum-compatible accelerograms have been selected, following the procedure proposed by (Dall'Ara et al. 2006). The seven records were scaled linearly, to match their peak ground acceleration (PGA) with the target PGA of the selected response spectrum, according to (Bommer et al. 2003), in particular for values ranging between 0.05 and 0.35 g. They were then applied to the models, both in longitudinal and transverse direction with respect to the orientation of the walls.

Seismic Response Assessment

The following subsections will describe the results of the nonlinear dynamic analyses for the two types of structural unit model and for the different building aggregates models. A Rayleigh damping model is introduced to represent the contribution to the dissipation capacity of the structure which cannot be modelled through hysteretic behaviour, assuming a value of damping ratio equal to 2%.

The absolute maximum top floor displacement d_{max} of the critical wall, the level of damage at ultimate limit state, represented by the ratio of d_{max} versus the ultimate top floor displacement capacity of the critical wall d_u, (obtained as stated in the Italian seismic code (NTC08 2008)) and the in-plane angular distortion of the floors γ_{max} will be considered as representative quantities of the seismic response. The in-plane distortion of floors γ_{max} is given by the ratio of the relative displacement between opposite walls of each structural unit versus their distance.

Single Structural Unit Models The differences in slenderness between the longitudinal (parallel to the x-axis) and transverse walls, due to the presence of openings in the facades, have great influence in the displacement response of the structural units. As far as maximum absolute top-floor displacements are concerned, the structural units are subjected to a high displacement demand, reaching ultimate limit state in the longitudinal direction at relatively low values of PGA, around 0,15 g. Transverse walls of both typologies show better in-plane behaviour, reaching the ultimate limit state for values of PGA close to 0,35 g. Due to the flexibility of floors and since the transverse walls displace almost simultaneously, floors deform negligibly in plane in the transverse direction of loading, whereas the angular distortion is greater in the longitudinal direction.

Shear failure is observed at ground storey for the longitudinal wall, as well as the transverse walls subjected to the same failure mechanism both at ground and first floor and to shear cracking at the top storey.

Nonlinear Dynamic Analysis of Individual Transverse Walls The floors are assumed to consist of flexible wood diaphragms. If the simplifying assumption is made that no diaphragm action is exerted by the floors, the transverse walls could be analyzed individually, being subjected to the tributary vertical loads and corresponding actions induced by the earthquake in the direction parallel to the wall itself. Two load configurations have been applied: one corresponding to that of a transverse wall located at the extremities of the aggregate, namely the *external wall*, while the other relative to a wall with an internal position within the aggregate (the *internal wall*). Since sections of the walls are the same, the results of the nonlinear dynamic analyses follow the same proportion of the tributary loads of the walls. By making the hypothesis that these two different walls are those defining a structural unit located at the extremities of an aggregate, it could be possible to evaluate the angular top floor in-plane deformation $\gamma_y\,max$ in the y direction and then compare the results with those obtained from the global analyses of the aggregate models.

Structural Unit Aggregate Models

Displacement Response The displacement response of structural unit aggregates models refers, in the longitudinal direction, to the front façade with both doors and windows as openings, for the *single-room* aggregates, and to the internal wall, for the *two-rooms* ones. Because of the stiffening effect determined by the increasing length of the walls, the absolute d_{max} at the top-floor is decreasing in terms of mean value as a general trend.

In the transverse direction, maxima were exhibited at the central transverse walls. The values of displacement response are comparable to those obtained for a single wall subjected to the same amount of vertical loads and to the corresponding seismic forces acting parallel to the wall.

Limit States and Damage Distribution The ratio of d_{max} versus the ultimate top floor displacement capacity of the critical wall d_u has been considered as an indicator of the ultimate limit state of the different aggregates. The damage undergone by the *single-room* conglomerations is similar: the longitudinal walls reach collapse at relatively low-medium values of PGA, i.e. above 0.15 g, while the transverse walls reach their maximum capacity only at 0.35 g, as an average. The damage distribution in the longitudinal walls is almost symmetric with respect to the vertical axis, with damage level increasing from bottom sections to top ones: shear failure mechanisms occur at ground storey in all the aggregates and significant to moderate damage is observed at the upper floors.

Instead for the *two-room* conglomeration typology, in the longitudinal direction, the ultimate limit state is reached for PGA values around 0.10 g, while in transverse direction for PGA above 0.30 g in average. In particular, in the longitudinal direction, collapse is reached for shear failure in the lintels and significant shear cracking on the piers of the internal wall, whereas the front and back façades show null to slight shear cracking.

In-plane Response of Floors As far as the in-plane deformation of floors is concerned, in the longitudinal direction the response of the aggregates is mainly determined by the presence and distribution of openings in the facades. If the *single-room* aggregate typology exhibit almost constant values of γ_{max} for PGA above 0.20 g, the *two-rooms* structural unit aggregates instead undergo greater distortions, due to the presence of the internal wall and hence to a different distribution of masses, although the values of deformation tend to decrease with increased number of aggregated units. In the transverse direction, the in-plane deformation of the aggregates is almost equal, independently of the conglomeration typology. The mean of maximum values of in-plane distortion γ_{max} reaches its maximum at the units at the extremities, but then, for units closer to the centre of the aggregate, the deformation tends to values closer to zero. This behaviour is in great part due to the different tributary masses carried by the end walls. Fig. 3 presents the mean of the maximum values of deformation characterizing each structural unit of 9-unit *two-rooms* aggregate model.

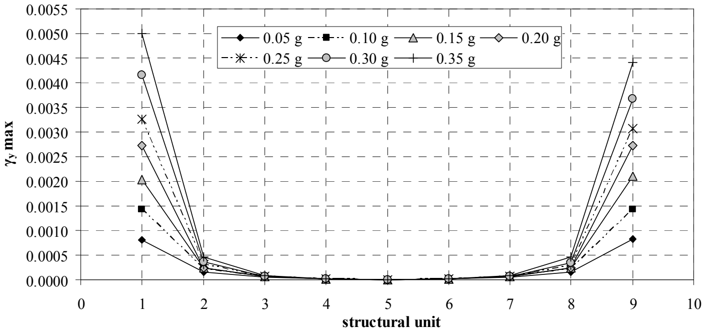

Figure 3: Model D9: average of the maximum angular in-plane deformation for each structural unit in the aggregate, in y direction

Comparison of the Seismic Response of Structural Unit Aggregate Typologies

The seismic response of the two typologies of building aggregates has been compared in terms of mean of maximum response parameters obtained by the nonlinear dynamic analyses.

Fig. 4 presents the displacement response of the different aggregate typologies in the longitudinal direction. Considering the results obtained of the single structural unit as representative of the seismic behaviour of a unit included in an aggregate would imply an overestimation of the displacement response, since the single structural unit would be subjected to a much higher demand. The displacement responses of the two conglomeration typologies are almost equal in the transverse direction, as seen in Fig.4, and well approximated by the results obtained in the analysis of the single external walls, if the proper distribution of vertical loads and seismic forces is accounted for.

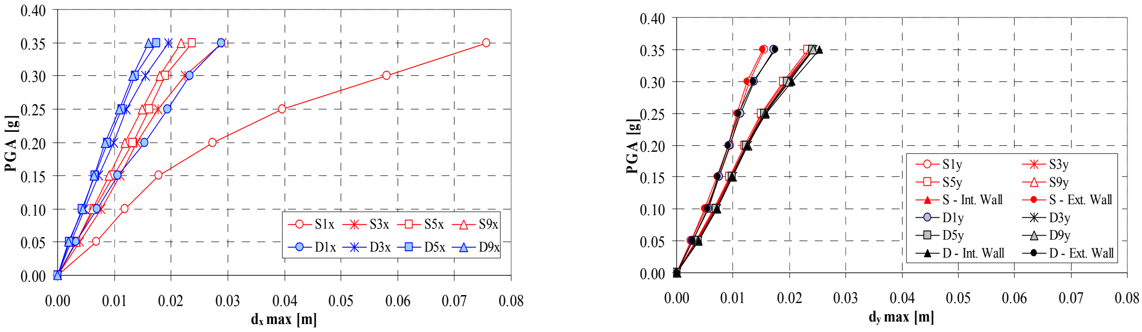

Figure 4: Comparison between single-room and two-rooms aggregate models response. Average of maximum top floor displacements in the x and y direction for front façade

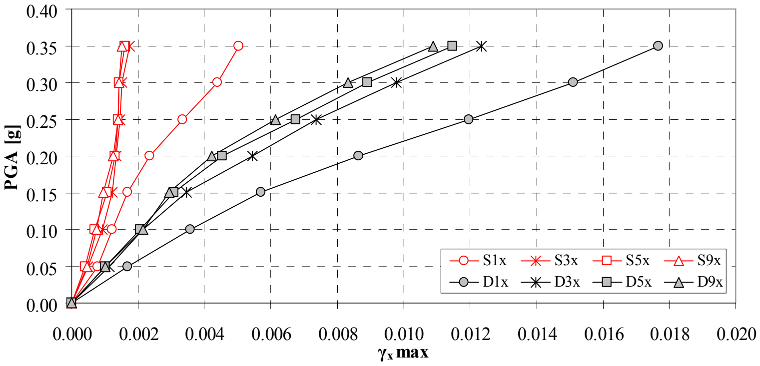

Figure 5: Comparison between single-room and two-rooms aggregate models response. Average of maximum in-plane angular deformations in the x direction

As far as the angular in-plane distortion of floors is considered, the single structural unit is subject to higher deformations in the longitudinal direction due to the asymmetric disposition of openings in the longitudinal walls, as seen in Fig. 5.

In the transverse direction, the in-plane deformation of the aggregates is almost equal, independently of the conglomeration typology.

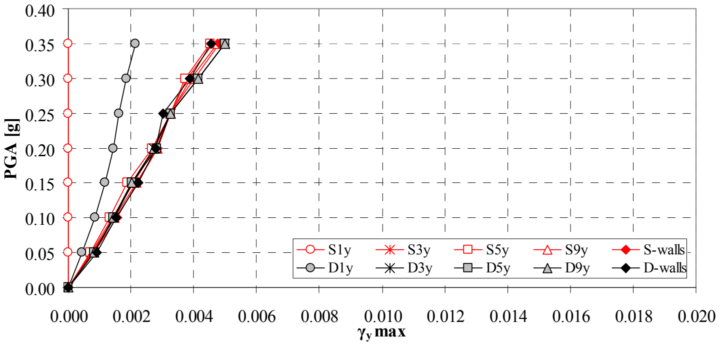

Figure 6: Comparison between single-room and two-rooms aggregate models response. Average of maximum in-plane angular deformations in the y direction

The results presented in Fig.6 refer to the mean of maxima that are obtained at the extremities of the aggregates, where the response is mostly influenced by the asymmetric distribution of masses and stiffness among the walls in the extreme units. The different response of the structural units in comparison to the aggregates is evident: extracting a single unit from the block, without taking into account its position and the appropriate tributary masses coming from the adjacent unit(s), will not capture the torsional behaviour that is characteristic of the units at the extremities of the aggregate, although this would be approximately captured by the analysis of the single walls.

Conclusions

The results presented are aiming to provide a better understanding of the seismic response of masonry building aggregates. In this work, only the presence of flexible floor diaphragms (i.e. timber floors) has been considered in all structural units. The behaviour with the presence of stiff diaphragms, as could result e.g. from renoveling/strengthening works in some units still has to be investigated.

In the idealised configurations considered herein, the results obtained confirm some theoretical considerations on the difference of structural behaviour of buildings under seismic action, when they are considered to be as part of an aggregate or as independent structural units. The in-plane floor distortion happens to be a useful parameter to highlight some aspects, showing the higher deformation undergone by the end units of the aggregate, compared to the intermediate units, when the transversal response is analyzed.

The analysis of the transverse response of the aggregate was also carried out by considering separately the single transverse walls subjected to their tributary masses and weights. The results obtained demonstrate that such approximated method would evaluate well the displacement of building aggregate modelled with flexible floors. Besides, the angular in-plane distortions of floors are almost equal in terms of mean with those obtained for the structural units at the extremities and in the central locations within the aggregate. Anyway, this procedure does not capture the in-plane distortion of floors occurring in the units that are immediately close to those at the extremities.

Further studies on seismic response of row conglomerations of buildings, taking advantage of the analytical procedure developed within this work, may be addressed to better understand the role of floor stiffness, slope of soils and synchronization of base motion. Moreover, the presented procedure may be adopted in order to assess the influence on seismic response of building aggregates of stiffening interventions on floors of single structural units and of differences in height relatively to pounding phenomena between adjacent buildings.

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