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SEISMIC FRAGILITY EVALUATION OF TYPOLOGICAL MASONRY AGGREGATES ACCOUNTING FOR LOCAL COLLAPSE MECHANISMS

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Abstract

The paper presents a study on the seismic fragility of masonry aggregates by considering both global and local collapse mechanisms. Within the framework of urban-scale vulnerability analyses, studying the seismic behavior of the building stock of historical centers represents an intricate challenge, in which the complexity of the urban fabric and the heterogeneity of the structural systems converge. When come to aggregate buildings, additional complications arise, mainly related to the identification of a reliable structural model. An acceptable compromise for the seismic fragility evaluations and damage predictions can be performed through simplified approaches, accounting for several uncertainty sources (e.g., geometrical and mechanical parameters). Within this context, a methodology aimed at estimating the seismic fragility of masonry aggregates is proposed, based on the combination of multi-source data and mechanical analyses. First, an exposure analysis is conducted to collect typological features characterizing existing structural configurations, by exploiting data from freely accessible databases (e.g., census, regional technical cartographies) and information given by typical building inventory collection forms. Afterwards, mechanical models are generated and analyzed, accounting for different uncertainty sources. Finally, fragility curves are computed considering the possible occurrence of local collapse mechanisms. The method is tested on a case from the municipality of Foggia, in Southern Italy showing interesting results for a row masonry aggregate.

Keywords: Seismic Fragility; Masonry Aggregates; Local Collapse Mechanisms; Global Collapse Mechanisms.

1 INTRODUCTION

Over the last 50 years, the Mediterranean area was subjected to several high-intensity earthquake events, which have shown from one hand, the evolution of the seismicity level in this area and on the other hand, the objective difficulty of the existing building stock to face increasingly strong and unpredictable hazardous actions. The elevated losses observed in consequence of different earthquakes events occurred in various zones, such as Italy, Greece, and Turkey, highlight the disastrous effects on existing buildings and their users, especially on the ones designed for supporting only gravity loads and without any seismic detail. Therefore, seismic risk mitigation plans are urgent and necessary, with the aim of limiting economic, social, and cultural losses by quantifying seismic vulnerability and suggesting improvement and prevention measures. To drive public institutions and management companies to employ risk mitigation measures on the most vulnerable part of the existing building stock, large-scale analyses are required, which consist in a preliminary screening of the building typologies in a given area and their current health state. This phase is extremely complex, considering a certain number of variables that play a fundamental role in the overall vulnerability evaluation. First of all, the area of interest should be defined, and different zooms can be performed, going from the national-scale to the regional- and urban-scale. Still, according to the size of the area of interest, different quality and quantity of data are usually available, which characterize the main source of uncertainty in the ongoing evaluation. In particular, the vulnerability quantification can be performed according to different approaches, where for large areas of interest only expeditious estimates can be processed due to lower quality and quantity of data (e.g., [1-2]), while reducing the observation area, some improvements can be achieved through the use of more high-quality data and by opting for more refined simulation techniques (e.g., [3-4]). Obviously, the main discriminant governing the vulnerability estimate success is the initial database at disposal, which can be more or less consistent. Especially when comes to urban-scale and looking at the Italian experience, during the last years a methodology of urban-scale data collection was implemented, which is named CARTIS and it was developed under the framework of RELUIS Project (promoted by the Italian Department of Civil Protection) [5]. The method consists in a specific form that allows to collect typological data for masonry and reinforced concrete (RC) buildings within a municipality. These data, if adequately elaborated, allow to identify homogeneous urban areas, named urban compartments or sectors, which are characterized by buildings that, under a certain taxonomy, present similar geometrical and mechanical features. Several CARTIS-based approaches were proposed by the scientific literature, where the common output is represented by the vulnerability evaluation of building typologies through the development of fragility functions (e.g., [6-7]). These results are usually validated with similar outcomes deriving from observational data of damages provoked by earthquakes, which are statistically elaborated to empirically describe the behaviour of homogeneous classes of buildings (e.g., [8-9]). In addition to empirical approaches, simplified or elaborated mechanical methods could be used, aimed to simulate the behaviour of the building stock through numerical tricks. Other approaches can be also mentioned for estimating existing buildings vulnerability, such as hybrid [10] and heuristic [11] approaches. Although the abovementioned seismic large-scale analyses are diffused and consolidated, there are some cases in which existing methodologies could not provide accurate results, such as occurs for buildings in the historical centres. In these cases, the use of one or few index buildings, typologically determined, cannot accurately predict the seismic behaviour of masonry buildings, especially accounting for the complex morphology of the historical centre fabrics. As a matter of fact, these buildings are organized in clusters (due to urbanization effects over the years, such as expansion and superfetation actions) and then, a right definition of the seismic vulnerability cannot be outlined by investigating the single structural unit, but it should be treated accounting for the aggregation effects.

In this view, this paper proposes a methodology tailored for masonry aggregates and aimed at investigating large-scale seismic vulnerability of masonry buildings in historical centres. In detail, the first phase of the proposed procedure consists in the exposure analysis, which allows to perform data collection from freely available databases in conjunction with output given by CARTIS form application. After, a classification under a certain taxonomy can be carried out, in order to identify the most representative structural typologies characterizing the area under investigation. Once information is available, the proposed mechanical approach is a two-steps procedure. The first step consists in the identification of the global behaviour of the entire aggregate (as proposed in [12]), while the second step consists in the definition of the seismic capacity accounting for local mechanisms. In both steps, geometrical and mechanical uncertainties are accounted for, by using the extreme flexibility and celerity provided by the structural software and analysis solver POR2000 [13]. As the output of the analysis, fragility curves can be computed from both abovementioned steps and a comparison between the ones derived from local and global mechanisms can be provided. The entire procedure was tested on a specific typology of masonry aggregate in the municipality of Foggia, Southern Italy.

2 SEISMIC BEHAVIOUR OF MASONRY AGGREGATES: STATE-OF-THE-ART

The seismic behaviour of existing masonry buildings has been always a topic of great interest, considering that masonry is the most diffused construction material in historical centres, which assume a key social and cultural role within the cities. At the same time, masonry represents a material with low seismic performance, as observed after the occurrence of seismic events. To this scope, several analytical, experimental, and numerical studies were proposed by the scientific literature and, referring to numerical ones, different techniques were developed, going from micro-models (e.g., [14-15]) to macro-models (e.g., [16]).

When talking about historical centres, the aggregate effect should be always accounted for, considering that the interaction with other buildings can strongly modify the seismic behaviour of the structural unit under investigation [17]. In general, two main approaches can be considered for investigating the seismic behaviour of masonry aggregates: (a) to investigate the single structural unit and simulate structural interaction by means of proper boundary conditions (e.g., applying external forces); (b) to simulate the entire aggregate through an overall model and study its global and local behaviour [18]. One of the first significant studies was the work proposed by Ramos and Lourenço [17], which investigated the seismic vulnerability of an entire masonry aggregate, and they focused on the aggregation effect for some structural units. The obtained results showed that the effects on the single building were identified in a lower flexibility and a higher safety factor. In Senaldi et al. [19], authors investigated the parameters of aggregation length and slab deformability for row masonry aggregates, showing difference in terms of seismic behaviour among single buildings and different configuration of aggregates. Similarly, Fagundes et al. [20] investigated the seismic behaviour of two masonry buildings from Azores, showing similar outputs to the above studies, when comparing single units and aggregate. Recently, Grillanda et al. [21-22] proposed an automated procedure to investigate local failures on masonry aggregates, by using the NURBS method [23]. The main advantage of the method was the identification of local mechanisms in complex buildings based on the limit-analysis. Angiolilli et al. [24] derived fragility curves for a masonry aggregate having an L-shape, by focusing on the corner structural unit and by analysing the possible differences with different connection types among the buildings. Still, Angiolilli et al. [25] proposed a procedure to investigate pounding effect among buildings composing a masonry aggregates, accounting for different soil conditions and in-plane and out-of-plane effects.

When going to large-scale analysis, the accurate study of a specific masonry aggregate could be not representative of the overall situation in the focused urban area (besides to be time consuming) and then, simplified approaches are preferable. With this regard, Formisano [26] proposed a procedure based on the methodology suggested by the Italian Guidelines on Cultural Heritage to predict the seismic behaviour of different masonry aggregates. Later, Formisano et al. [27] proposed a procedure to derive a synthetic index to quantify seismic vulnerability of masonry aggregates, basing on a new survey form elaborated according to the GNDT approach [28] and introducing new parameters for the overall evaluation (e.g., position and interaction of the structural units). In Maio et al. [29], authors proposed a hybrid method to evaluate seismic vulnerability of a masonry aggregates, by combining the results of nonlinear static analysis and the output of two methods providing different vulnerability indexes. Cocco et al. [30] employed two different methodologies to estimate the vulnerability of masonry aggregates in a historical centre, which were based on the empirical results obtained from previous studies and on the results provided by Vulnus software [31]. Results showed a comparison in terms of fragility curves and pros and cons of the approach with application to different scales of analysis. Leggieri et al. [12] proposed META-FORMA, an automated procedure to investigate the global seismic behaviour of row masonry aggregates, on the base of the simplified approach incorporated in the structural software POR2000. Although the proposed procedure was efficient and flexible from different points of view (e.g., computational effort, uncertainty consideration), the main issue resided in the not consideration of local mechanisms, which are of fundamental importance in the vulnerability definition of a typologically defined masonry aggregate. On this base, the present paper aims to improve a procedure like META-FORMA, by considering the local mechanisms and by providing global and local fragility curves, do not reducing the declared advantages.

3 A TWO-STEPS PROCEDURE TO CHARACTERIZE MECHANICAL-BASED SEISMIC FRAGILITY OF MASONRY AGGREGATES

The proposed framework is summarized in Figure 1 and consists in some consecutive steps that are described in the following subsections.

3.1 Data collection and identification of structural typologies

The first step of the proposed framework consists in the definition of the structural typologies of masonry aggregates, which are representative of the building stock in the area under investigation. To this scope, the main reference is the output provided by the application of the CARTIS form, which allows to characterize typological geometrical and mechanical features in sub-urban areas of the investigated municipality, named urban sectors (US). Using the above procedure, existing buildings are classified according to: (a) geometric information, such as number of storeys, average floor area, interstorey height, thickness of walls and percentage of openings; (b) structural information, such as the types of masonry, slab, roof, presence of irregularities (in-plan and in-height). The obtained information can also be integrated with other freely available database, which can improve the final database, such as technical regional cartographies or census information. Once the input database is ready, the distribution of the main parameters influencing structural and seismic performance can be computed, to account for geometrical and mechanical uncertainties characterizing the typologies. With this regard, several approaches can be employed for each parameter, playing from a uniform to a normal or lognormal distribution and assuming discrete or continuous variables. On the base of the analyst's preference, mechanical modelling can be performed, by discretely combining input parameters (e.g., [12]) or by employing intensive simulation approaches, such as Monte Carlo methods (e.g., [4]). In both cases, a large and consistent number of simulations is performed, from which extract useful outputs for the next steps.

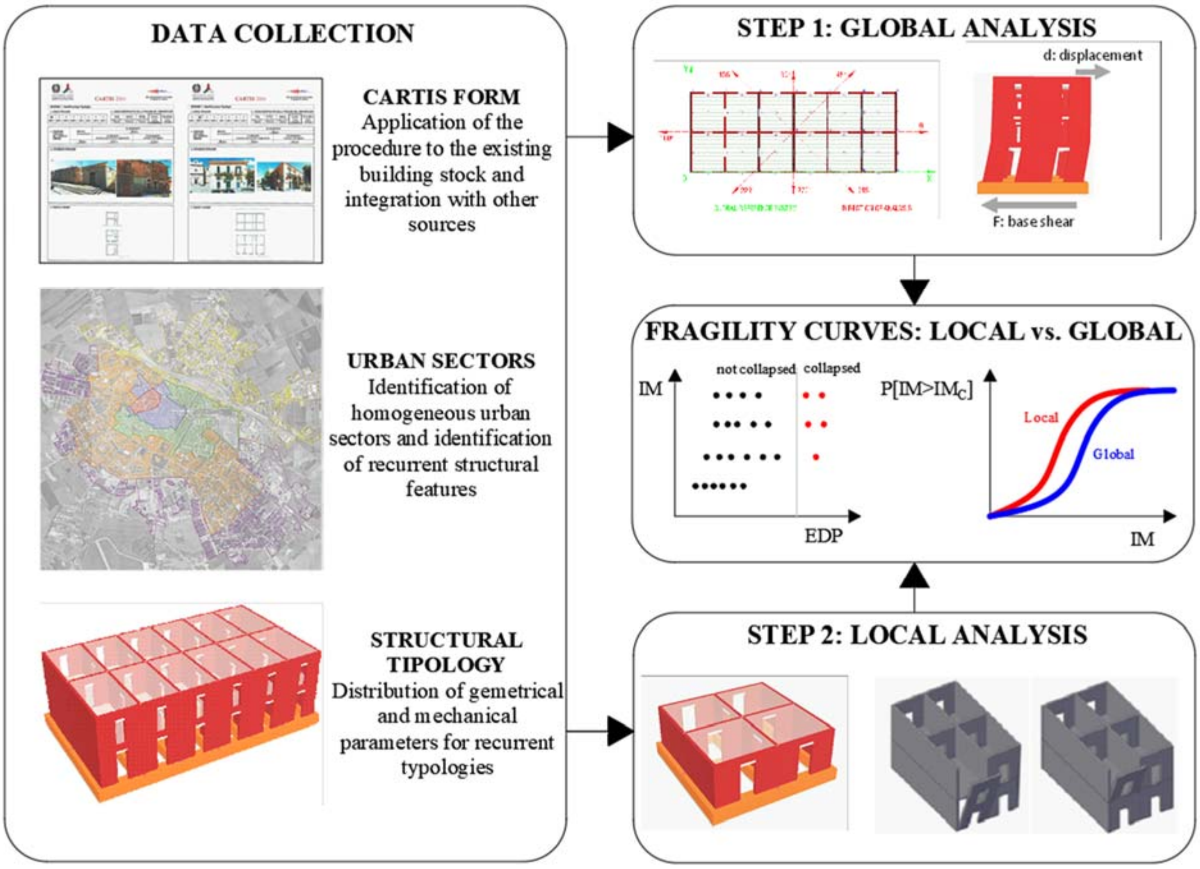

Figure 1: Graphical framework of the proposed two-steps procedure.

3.2 Step 1: global analysis and fragility curve

The first step of the proposed two-steps procedure consists in the evaluation of the seismic fragility of the typologically defined masonry aggregate, accounting for global capacity. For the case at hand, the adopted structural software is the POR2000, which implements the POR method that schematize masonry buildings through an approach where the only resistant elements are the piers while the behavior of the spandrels (linked to the piers through rigid nodes) is neglected. This approach implies a box-like behavior of the structure with the slab that assume a secondary role in the overall seismic behavior. On this basis, numerical models can be generated according to the parameters definition mentioned in Section 3.1. All models can be automatically generated, and analyses can be run through the automated tool proposed in [12]. The employed method of analysis is the pushover, which is executed by the software accounting for 2 load profiles (uniform and inverse triangular) and 8 directions (2 main axes, 2 diagonal directions and 2 verses). From the results of nonlinear static analyses, the capacity/demand (C/D) ratios can be extracted, according to the framework proposed by the Italian Building Code (NTC18, [18]). In this step, different limit-states can be considered. Nevertheless, for the scope of this work, only life-safety (LS) limit-state is accounted for. According to [18], for masonry buildings, LS limit state is exceeded when the first pier achieves a displacement equal to 75% of near-collapse displacement ($d_{NC,D}$), accounting for ductile mechanisms and computed as

$$d_{NC,D} = 0.01\ H \quad (1)$$

where H is the height of the masonry pier. Thus, fragility curves can be estimated. In fact, combining geometrical and mechanical parameters, a set of models is generated, and the entire sample can be analyzed with increasing seismic intensity. For the case at hand, peak ground acceleration (PGA) is considered as intensity measure (IM). Thus, for each value of the IM, ratios C/D for each load profile are estimated and, assuming that the LS is exceeded when C/D is lower than 1, fragility curve can be determined according to the method proposed by Baker [32]. Among the obtained curves, the global fragility curve is represented for the sake of simplicity from the one having the lower value of the median (among the 16 estimated), accounting for each main direction (named X and Y).

3.3 Step 2: local analysis and fragility curve

In the second step, the local capacity of the typologically defined masonry aggregate is investigated. The adopted approach is based on a kinematical description of the local collapse, being based on the formation of a series of cylindrical hinges where all the deformation is concentrated. In particular, the analysis is performed on the basis of two types of locale mechanisms. The first type is given by all the rocking modes that can be activated by a rigid rotation at each floor base, while a second type consists in the formation of three aligned hinges on the building façade. These mechanisms can interest the entire building façade or a portion of it. For the second type mechanism, the position of the intermediate hinge is determined by minimizing the IM required for the activation of the mechanism. Figure 2 shows the considered local mechanisms for a single wall of a simple two-storeys masonry structure.

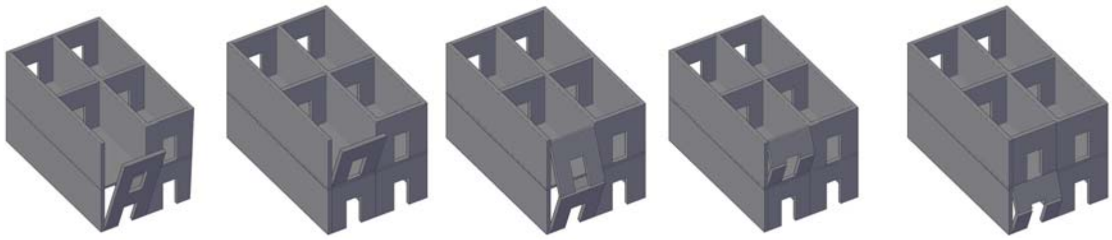

Figure 2: Local mechanisms considered in the analysis.

A nonlinear kinematic approach is adopted to trace the capacity curve of each mechanism. In particular, the geometrically nonlinear behavior is obtained by a Taylor expansion up to the second order of all the nonlinear terms present in the work of all the applied loads. The latter ones include the dead loads, the seismic force assumed proportional to the masses, the thrust of slabs or arches and the effect of ring beam. In this way one obtains a nonlinear relation between the seismic force and the horizontal displacement of a control point. Each LS is identified along the capacity curve in terms of displacement limit. According to NTC 2018 [29], LS limit displacement is evaluated as

$$d_{LS,l} = 0.4\ d_0 \quad (2)$$

where d_0 is the displacement related to the zeroing of the seismic action. In order to construct fragility curves, for each analyzed building, it is necessary to obtain the PGA that produces the displacement limit $d_{LS,l}$ and, to this end, the inelastic spectrum method is adopted [31]. For each considered structure, this PGA value is evaluated as the minimum among the values given by all the local mechanisms. Also in this case, fragility curves can be provided for each main direction (X and Y), considering that the results obtained for X direction accounting for local mechanisms should be compared with the ones in Y direction accounting for global mechanisms (and vice versa).

4 APPLICATION OF THE PROPOSED PROCEDURE: THE CASE STUDY OF MASONRY AGGREGATE OF FOGGIA, SOUTHERN ITALY

4.1 Overview on the investigated area and application of the CARTIS form procedure

The proposed procedure was applied on the pilot case of the municipality of Foggia, Puglia Region, Southern Italy. The city is located in the North of the Region, and it presents values of the PGA around 0.25g. According to the preliminary analysis reported in [12], the entire existing building stock is constituted by around 7000 buildings, for which the 45% is characterized by masonry buildings. For the observed municipality, the CARTIS form procedure was applied, and 12 USs were identified, as shown in Figure 3a. Within each US, different typological classes were detected, which are identified with the acronyms MUR and CAR, referred to masonry and RC buildings, respectively. Focusing on the areas fully characterized by masonry buildings, the oldest part of the city was considered, which is subdivided between the USs named C01 and C02. This latter contains about the 50% of the masonry buildings in the city and it can be displayed in Figure 2b.

Figure 3: (a) Output of CARTIS for procedure in the municipality of Foggia; (b) detailed map of C02.

Looking at the buildings in C02, two specific typologies were identified according to CARTIS procedure, that is, MUR01 and MUR02 (each one is characterized by different features form the geometrical and mechanical points of view). For most of the cases, masonry buildings results to be in aggregate and belonging to MUR01, as well as characterized by a similar base area (from 70 to 100 m^2), similar number of storeys (from 1 to 2) and a rectangular shape with shorter side ranging from 10 to 15 m. Another specific aspect is related to the number of structural units composing the masonry aggregates, which varies from 2 to 4 buildings, and they are usually disposed in row. Other parameters were typologically defined, such as the masonry typology (square stone block), the floor type (rigid slab), and the roof type (flat); while for other ones, ranges of values were established, such as for the thickness of the walls and the percentage of openings. Obviously, at the urban scale of analysis, all structural and geometrical parameters are characterized by uncertainty, and then plausible values were taken into account, according to the methodology in [12].

4.2 Application of the proposed two-steps procedure for a masonry aggregate typology and fragility curves definition

On the base of the typological definition of masonry aggregates in the historical centre of Foggia, the proposed procedure was applied to a specific case. Observing the map in Figure 3b, most of the row masonry aggregates present from 2 to 3 structural units. Hence, the analysis was oriented on aggregates with 3 buildings, which present similar geometrical and mechanical features. The scheme of the considered structural typology can be observed in Figure 4, in which it is shown the disposition of the masonry units in the urban fabric, the in-plan shape of the row aggregates, and the numerical model performed in the structural software POR2000.

Varied Parameters	Values
Thickness of internal and external walls (m)	0.25/0.30/0.35/0.40/0.45/0.50
Percentage of openings - ground floor (%)	20/25/30
Percentage of openings – upper floors (%)	10/15/20
Average compression strength (MPa)	2.04/2.65/3.26
Average tensile strength (MPa)	0.10/0.145/0.19
Height of ground floor (m)	3.5/3.6/3.7/3.8/3.9/4.0
Height of upper floors (m)	3.0/3.1/3.2/3.3/3.4/3.5
Ring beam	yes/no

Table 1: Summary of the varied parameters and related values

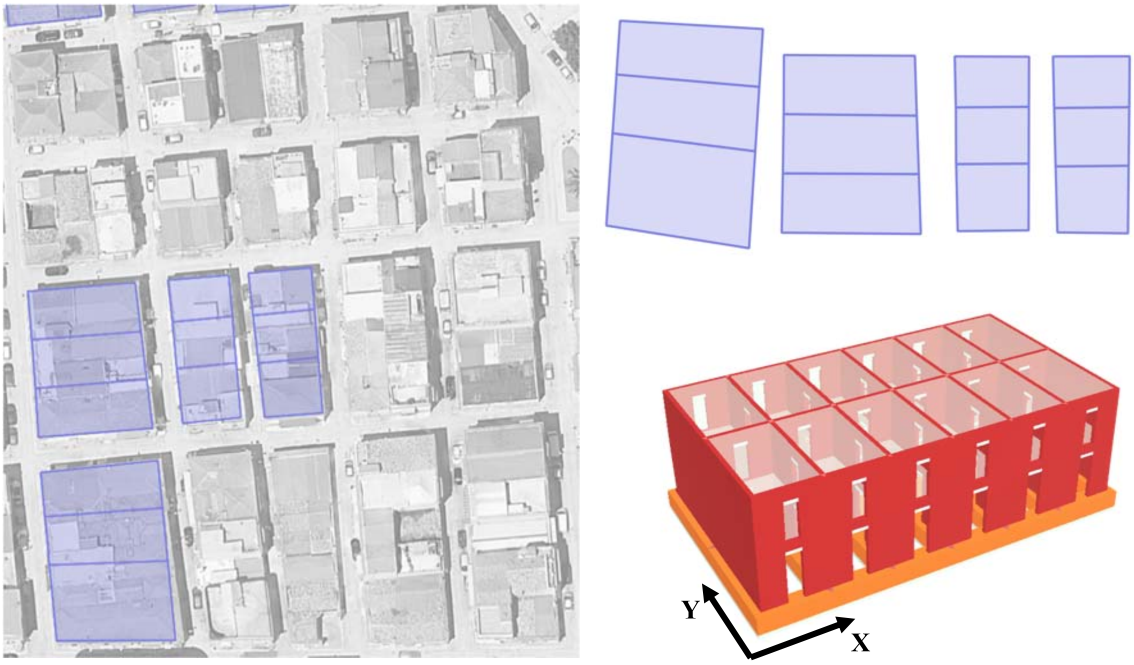

Figure 4: Geometrical definition of row masonry aggregate in Foggia with 3 structural units.

As previously stated, uncertainties were accounted for in the models as discrete variables on the base of CARTIS definition and a summary of the varied mechanical and geometrical features is reported in Table 1. Some parameters were kept as fixed, that is, the base area of the structural units (equal to 85 m^2), the shorter side of the aggregate (equal to 12 m) and the number of storeys (equal to 2).

It is worth nothing that the varied parameters were selected according to the twofold aim of the analysis. For the global analysis, very important are the percentage of openings, the thickness of walls and the tension and compression strengths of masonry. Instead, for the local analysis, the thickness of walls, the height of ground and upper floors, and the presence of the ring beam assume higher importance. Combining all parameters in Table 1, a total of 5382 models were generated and analyzed through the two-steps procedure (from the global and local point of view). The outputs of global and local analyses were processed, and fragility curves were estimated for each main direction. The results are shown in Figures 5 and 6 for X and Y directions (as indicated in Figure 4), respectively, and obtained values of medians and dispersions are reported in Table 2. For local mechanisms, two fragility curves were computed, namely with and without ring beam. From the obtained results, several achievements can be observed. First, observing the fragility curves accounting for local mechanisms, it is evident the significant role of ring beam, which reduce the vulnerability of masonry buildings. On the other hand, for the global capacity, the presence or absence of the ring beam is pointless. After, looking results in X and Y directions, as expected the fragility curves obtained accounting for local mechanisms and without considering the ring beam are the more vulnerable, which implies that the local behavior of masonry panels drives the fragility on the entire aggregate. Instead, observing the fragility curve obtained by considering the global behavior, it results to be more vulnerable in X direction and less vulnerable in Y direction then the fragility curves obtained by considering local mechanisms and ring beam. This result is explainable by considering that in X direction the high quantity of openings assumes an important role in the global fragility definition, while in Y direction, the openings are lower and then, the fragility curve presents a higher median value. Still, regarding to the results obtained accounting for local mechanisms and the presence of ring beams, in X direction the out-of-plane failures occur with high seismic action, considering the absence of openings, while in Y direction (with openings) the required load for the collapse is lower.

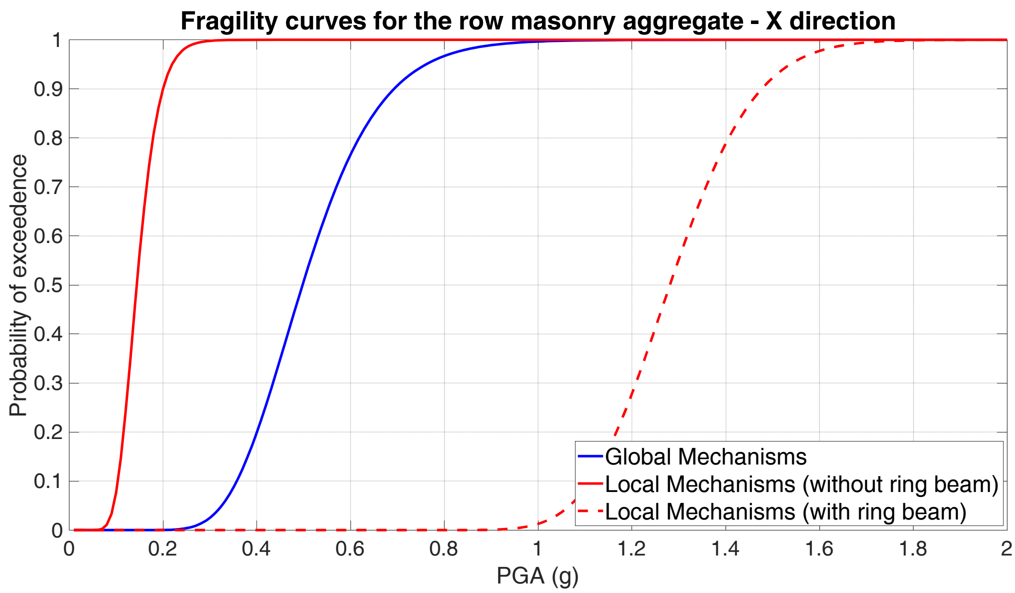

Figure 5: Fragility curves of typological masonry aggregate, accounting for local and global mechanisms – X direction

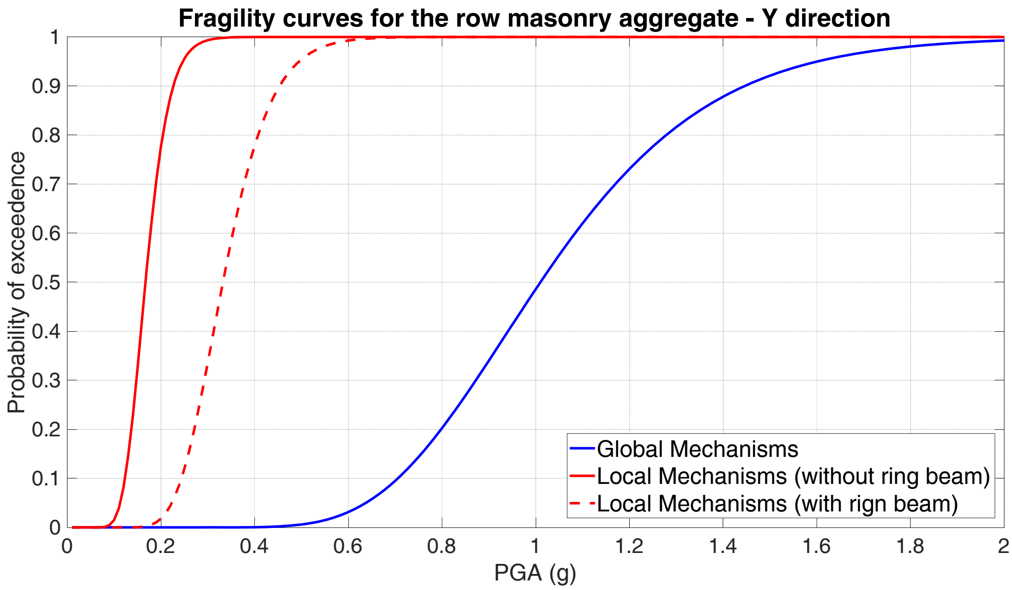

Figure 6: Fragility curves of typological masonry aggregate, accounting for local and global mechanisms – Y direction

Type of mechanism	Direction	Median (g)	Dispersion
Global	X	0.497	0.26
Global	Y	1.010	0.26
Local (without ring beam)	X	0.144	0.26
Local (without ring beam)	Y	0.167	0.24
Local (with ring beam)	X	1.281	0.11
Local (with ring beam)	Y	0.332	0.24

Table 2: Summary of median and dispersion for the fragility curves, accounting for local and global mechanisms and analysis direction

5 CONCLUSIONS

The paper presents an approach to investigate the fragility curve of typologically defined masonry aggregates, accounting for global and local mechanisms. In detail, the proposed procedure starts from an exposure analysis, where typological data are collected from freely available databases (e.g., Census, Regional Technical Cartography) and from the well-known CARTIS form. Once data are available and the structural and geometrical features of typical masonry aggregates within the investigated area are known, structural models are generated by using POR2000 software. In the model generation, uncertainty is taken into account, systematically varying modelling features and accounting for the influence of parameters on seismic behavior. After the two-steps procedure is performed. The first one consists in the definition of seismic fragility of masonry aggregate looking at the global behavior (e.g., horizontal displacement expressed as a percentage of the pier height) for a predefined limit-state. The second step consists in the definition of seismic fragility of masonry aggregate, looking at the possible occurrence of local mechanisms, which are defined through a nonlinear kinematic approach. The output of the procedure consists in the comparison among global and local fragility curves (for the case at hand, two case are considered, accounting for and not ring beam) for each main direction of analysis, where the most vulnerable represent the overall behavior of the masonry aggregate.

The procedure was tested on the case study of Foggia, Southern Italy, for which a near-full typological information was available on the masonry aggregate of historical centre. Thus, a row masonry aggregate with 3 structural units was considered and typologically defined. Modelling and analysis campaigns were performed, and fragility curves were provided for both main directions. The output of the procedure application suggested the importance of the proposed application, showing for each analysis direction the most probable failure mechanisms in case of seismic actions.

Further developments of the work will aim to extend the proposed procedure to different typologies of masonry aggregates, i.e., row masonry aggregates with more structural units, and to fully automatize the approach for purpose of large-scale assessment of these kinds of structures. In addition, more aspects could be considered in the overall fragility evaluation of masonry aggregates, such as the whip effect or the load increment obtained for the header structural units.

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