SEISMIC VULNERABILITY ANALYSIS OF MASONRY AGGREGATES USING AN AUTOMATED ARCHETYPE-BASED PROCEDURE

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Abstract: *The development of reliable methods for assessing the seismic vulnerability at the urban scale of masonry aggregates could provide helpful guidance for reducing the expected damage and losses. However, the lack of structural data and the presence of many sources of uncertainty complicate the vulnerability analyses and reduce the effectiveness of numerical approaches. In this work, a mechanical-based procedure for the seismic vulnerability assessment, named META-FORMA-XL (MEchanical-Typological Approach FOR Masonry Aggregates – X Local), is proposed. It is based on the automated construction of archetype buildings that are ideal representations of the actual buildings accounting for all the possible uncertainties by exploiting exposure data collected in inventory forms available on urban or sub-urban scales. The method is applied to a case study concerning the fragility analysis of low-rise masonry aggregates located in Southern Italy. Finally, the procedure is validated by comparing the fragility curves obtained using the archetype-based approach and those evaluated on a real building for which a complete knowledge of the geometrical and mechanical features is available.*

1. Introduction

The high level of complexity that frequently characterises the historical centres represents a serious obstacle in the evaluation of their seismic vulnerability. However, many recent earthquakes occurred in the Mediterranean area have produced disastrous effects and highlighted the elevated vulnerability of the existing building stock. As such, a fine-tuning of reliable and robust procedures for the seismic vulnerability assessment of masonry aggregates represents an urgent task, aimed at developing appropriate risk mitigation plans capable of predicting the effects of seismic events and reducing the expected losses. Then, over the last 20 years, several methodologies have been developed to quantify the vulnerability of the existing buildings. In particular, the reliability of these methods strongly depends on the size of the analysed area. In fact, for large areas expeditious estimates are preferred due to lower quality and quantity of data (Frassine and Giovinazzi (2004), Formisano (2017), Formisano et al (2015), Leggieri et al (2022)), while when the size reduces, some improvements can be achieved with more high-quality data and more refined simulation techniques (Ruggieri et al (2022), Liguori et al (2023a)). Obviously, the main discriminant governing the vulnerability estimate is the initial database at disposal. In this regard, in Italy during the last years a methodology of urban-scale data collection was implemented, named CARTIS and developed under the framework of RELUIS Project (promoted by the Italian Department of Civil Protection) (Zuccaro et al (2015)). CARTIS consists in a specific form that allows to collect typological data for masonry and reinforced concrete 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 (Brando et al (2021), Sandoli et al (2022), Liguori et al (2023b)). These results are usually validated using empirical data as baseline (Rosti et al (2021a, 2021b)). Other approaches for estimating the seismic vulnerability can be also mentioned, such as hybrid (Maio et al (2015), Sandoli et al (2021)) and heuristic (Lagomarsino et al (2021)) 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 and then, a proper definition of the seismic vulnerability cannot be outlined by investigating the single structural unit, but it should be treated accounting for the aggregation effects (Ramos and Lourenço (2004)).

Based on these premises, this work proposes a methodology tailored for masonry aggregates and aimed at investigating the large-scale seismic vulnerability of masonry buildings in historical centres and named META-FORMA-XL (MEchanical-Typological Approach FOR Masonry Aggregates – X Local) (Ruggieri et al (2023)). 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 the output given by the CARTIS form application. Afterward, a classification under a certain taxonomy can be carried out, in order to identify the most representative structural typologies characterizing the area under investigation and defined as archetype buildings. On the basis of these mechanical representation of the masonry aggregate, a two-step numerical analysis is conducted. The first step consists in the identification of the global behaviour of the entire aggregate, as proposed by Leggieri et al (2021), while the second step consists in the definition of the seismic capacity accounting for local mechanisms, whose relevance in masonry building aggregates is well known (Grillanda et al (2020), Angiolilli et al (2023)). In both steps, geometrical and mechanical uncertainties are accounted for. Many advanced numerical approaches for the analysis of masonry buildings are available in literature (Casolo and Milani (2013), Uva et al (2020)). However, simpler approaches are best suited for large-scale vulnerability assessment (Shabani et al (2021)). Therefore, the global analysis is performed using the software POR2000 by Newsoft (2021), which is characterised by high efficiency, making it possible to analyse many structures in a small timeframe. Therefore, the uncertainty propagation can be carried out by analysing all the possible archetypes obtained as a combination of the uncertain data, as well as applying Monte Carlo simulations to reduce the number of simulations. Finally, fragility curves can be computed from both steps and a comparison between the ones derived from local and global mechanisms can be provided. The proposed procedure is tested on a specific typology of masonry aggregate in the municipality of Foggia, Southern Italy, and a validation process is performed to compare the mechanical-based fragility curves for the archetype buildings with those evaluated on an actual geometry.

2. META-FORMA-XL

In this Section, the proposed procedure is described. Further details can be found in Ruggieri et al (2023).

2.1 Data collection

The first phase 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. Thus, mechanical modelling can be performed, by discretely combining input parameters or by employing intensive simulation approaches, such as Monte Carlo methods. In both cases, a large and consistent number of simulations is performed, from which extract useful outputs for the next steps.

2.2 Archetype definition

Using the data at disposal, the archetype model can be defined. The archetype is a simplified mechanical model that the analyst adopts to represent the behaviour of a class of buildings, for which some information is uncertain. Obviously, to be faithful to reality, the archetype shall account for all existing geometrical and mechanical uncertainties. In this view, our archetype is a simplified model of a masonry aggregate, which is defined starting from a parametrically defined single building that is replicated according to the desired aggregation form (e.g., row, courtyard).

The proposed archetype model is conceived to account for all uncertainty sources in terms of geometrical and mechanical parameters. For the variation of the couple parameter-value and of the masonry aggregate modelling (i.e., replication of structural units according to a predefined form), it is possible to exploit the same principles provided in the original version of META-FORMA (Leggieri et al. (2021)), in which a fully automated procedure is proposed.

2.3 Global analysis

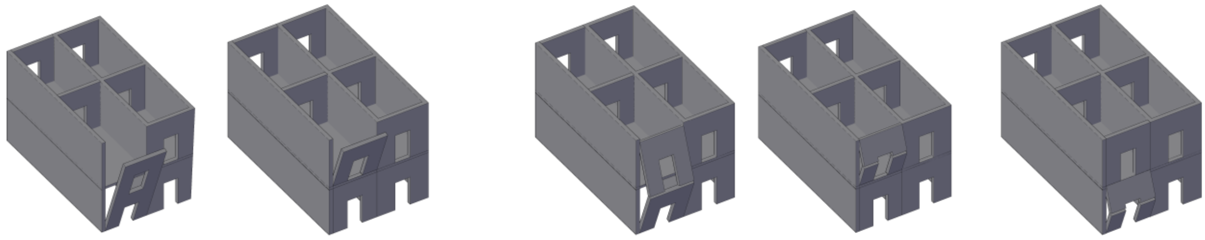
Concerning the global analysis, the seismic behaviour of archetype models is investigated accounting for the in-plane behaviour of the masonry walls. Regarding the modelling of the single structural unit, the software used is POR2000 (Newsoft (2021)) that adopts an equivalent frame approach in which the only resistant elements are represented by the masonry piers and the contribute of the masonry spandrels is neglected. The zones where the failure modes occur are localized in the piers that are connected to the spandrels through rigid nodes. Following the concepts in the original method, a box-like behaviour is accounted in the archetype model, which implies two main assumptions: (a) shear-type behaviour, with constrained rotations at the top and at the bottom of the masonry piers; (b) the floors are subjected only to in-plan rigid roto-translations. The above hypotheses are reliable if good connections exist among masonry piers, which implies a good torsional behaviour of the building. This could represent a limit for the use of the method, especially for those buildings without presenting good connections among masonry panels. Nevertheless, for purpose of aggregates, the absence of wall connections could be overcome by the group effect given by the clustering of structural units (especially in the central units). The assumptions at the base of the models provide a high efficiency in the analysis resolution, which makes the software very fast, as an important skill in large-scale analysis. Another aspect to highlight about the selected modelling method is the consideration of the openings, which are taken into account with some modifications, by employing a reduction of the effective height of the masonry piers by means of a specific diffusion angle of stress in the near of openings and by introducing a stiffness modification in the spandrel located above and under the openings. Regarding the nonlinear behaviour of the structural elements, each masonry pier is modelled through a specific behaviour, for which a bilinear perfectly elasto-plastic constitutive law is usually assigned, defined in terms of strength and ductility.

Once defined the modelling assumptions, the employed structural software allows to perform nonlinear static analyses along multiple directions by defining an angle of incidence of the seismic action measured with respect to the global reference system (i.e., from 0° to 360°, with an incremental step of 45°). For the case at hand, of interest are the two main directions (defined as X and Y) and both verses, corresponding to 0° and 180° for X direction and 90° and 270° for Y direction. For each analysis, according to the prescriptions provided by the Italian Building Code (NTC,2018), nonlinear static analyses are performed through two load profiles, that is, the uniform (proportional to the mass of the storeys) and the inverse triangular (proportional to the height of the storeys) ones. As results of the analyses, the relationship between the global capacity and the demand of each archetype is provided. Finally, capacity-demand ratios are available for the entire sample of archetype buildings, assuming as value of the seismic demand a representative one of the area under investigation.

2.4 Local analysis

Concerning local analyses, the seismic behaviour of archetype models is investigated in order to take into account the occurrence of damages related to out-of-plane mechanisms in masonry walls. For purpose of automatization, the local analysis module extracts from the input files generated through the global analysis modules the useful features to perform a specific investigation on the out-of-plane behaviour of masonry panels.

To this scope, a macro-block model is considered which is based on the hypothesis that, when the mechanism activates, the structure separates into rigid blocks thanks to the development of macro cracks along which all the deformation is concentrated. Each block is assumed to be infinitely rigid and resistant. This approach is frequently adopted for modelling out-of-plane collapse and it is based on the assumption of a bad connection between orthogonal walls, which implies the occurrence of simple rocking and vertical flexure mechanisms, as shown in Figure 1. For the case at hand, each archetype can be subjected to both mechanism types involving one or more storeys. While for the simple rocking case the positions of the macro crack are assigned at the bottom of each storey, for the vertical flexure the macro crack is positioned in order to device the worst case.



(a) Simple rocking (b) Vertical flexure

Figure 1 Local mechanisms considered in the analysis: (a) simple rocking; (b) vertical flexure.

For each mechanism, the nonlinear kinematic approach is adopted to obtain a capacity curve in terms of the applied seismic force and the displacement of a reference point.

For a given direction of the seismic action, the capacity-demand ratio for local mechanisms is obtained as the minimum value evaluated by applying this procedure to each façade and each local mechanism. As a final consideration, it is worth mentioning that the local nature of this analysis implies that the results do not depend on the number of cells of the aggregate. In addition, as further assessment of the proposed local analysis, all evaluations are made by considering the possible presence or absence of the ring beam.

2.5 Fragility curves

The obtained results can be processed to derive global and local fragility curves. In general, fragility curves express the probability that the structure (or a part of it) exhibits to exceed a specific deformation condition, i.e., limit-state. From the mathematical point of view, a fragility curve is described by a cumulative distribution function (CDF) reporting the relation between a selected seismic intensity (defined through an intensity measure, IM) and the related probability of failure, Pf. Hence, the fragility function can be expressed as

$$P(failure|IM = x) = \Phi\left(\frac{ln(x/\mu)}{\beta}\right) \tag{1}$$

where Φ(·) is the standard normal CDF, x is a value of IM and assume increasing values, μ and β are the median and the dispersion of the CDF, respectively, the failure identifies the condition beyond which the limit-state is exceeded.

3. Case study

The proposed procedure was applied to the row masonry aggregates in the historical centre of Foggia, Puglia, Southern Italy. Details on the area under consideration can be found in Ruggieri et al (2023). The application of META-FORMA-XL provides the fragility curves given in Fig. 3 and Fig. 4. The analysis of the curves gives room for some considerations. In fact, it is worth noting that, comparing global and local fragility curves and assuming a value of IM, in X direction the local curves present a higher $P_{f,L}$ (probability of failure for local mechanisms) than $P_{f,G}$ (probability of failure for global mechanisms) when the ring beam is not considered, while the reverse occurrence is observed when the ring beam is accounted for. Instead, in Y direction, $P_{f,L}$ considering or not the ring beam is always higher than $P_{f,G}$. Observing global fragility curves of models made by 1 cell, it is worth observing that in our archetypes, the openings are placed in the masonry panels oriented in X direction, which provokes a higher $P_{f,G}$ than the one obtained in Y direction. Hence, by varying the number of cells, an evident trend can be observed in global mechanisms. As a matter of fact, in X direction the $P_{f,G}$ decreases as the number of cells increases, while in Y direction the $P_{f,G}$ increases as the number of cells increases. Note that the increment of fragility in Y direction is faster than the decrement of fragility in Y direction.

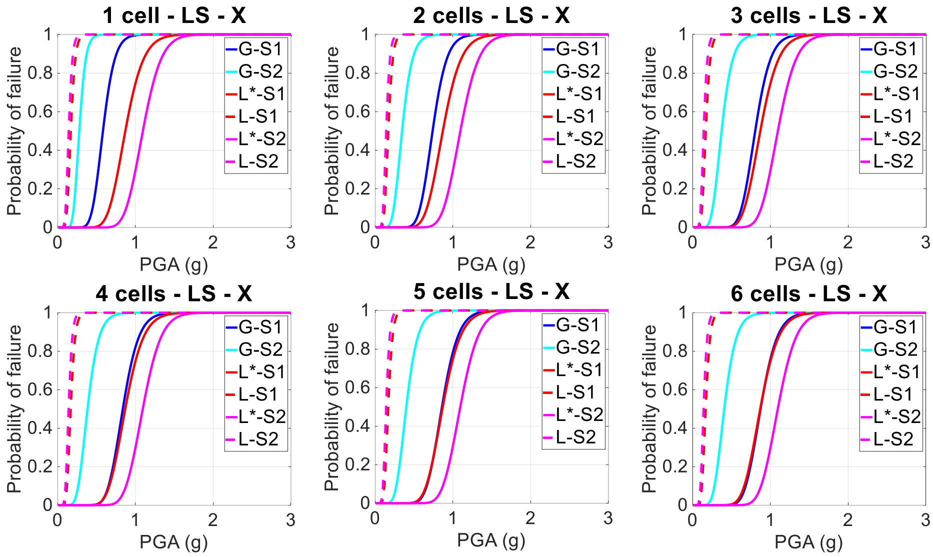


Figure 3 – Fragility curves in X direction, accounting for local and global mechanisms (with and without ring beam), reported for varying the number of storeys and number of cells. G stands for global, L stands for local without ring beam, L stands for local with ring beam. 1S and 2S indicate 1 storey and 2 storeys, respectively.*

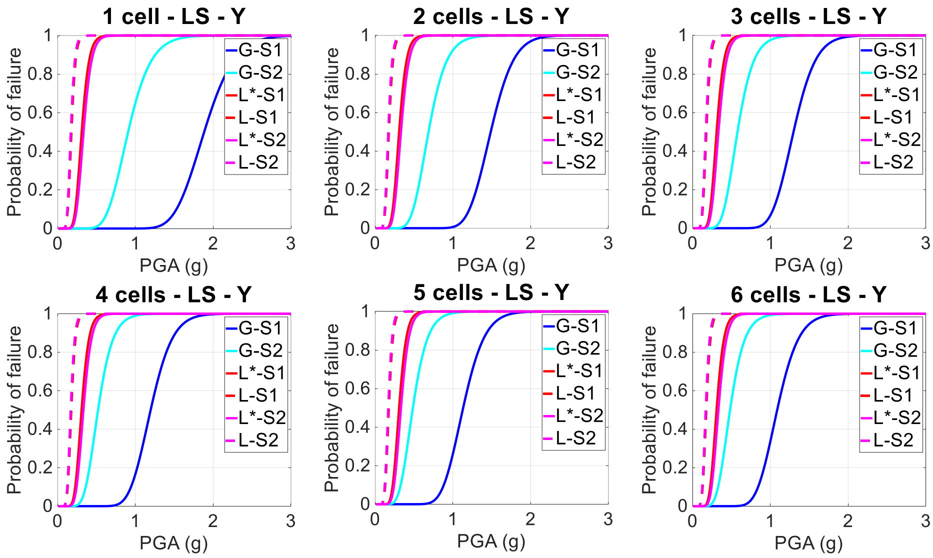


Figure 4 – Fragility curves in Y direction, accounting for local and global mechanisms (with and without ring beam), reported for varying the number of storeys and number of cells. G stands for global, L stands for local without ring beam, L stands for local with ring beam. 1S and 2S indicate 1 storey and 2 storeys, respectively.*

Concerning local fragility curves, the variation of the number of cells in archetypes does not influence results, considering that the analysis was performed panel-by-panel. In the end, within each graph, as the number of storeys varies, the fragility for global mechanisms changes, having a higher $P_{f,G}$ for archetypes with 2 levels. Instead, for local mechanisms, the differences are not that obvious, having that, without considering ring beam the fragility is almost same for both main directions, while when considering ring beam, the fragility presents a higher $P_{f,L}$ for archetypes with 1-story in X direction and an almost same result in Y direction.

4. Validation

With the aim of validating the obtained output from META-FORMA-XL, a real-life case study of masonry aggregate was investigated. In detail, the surveyed structures are located always in the historical centre of Foggia, and it is composed by 5 buildings (cells) disposed in row. All buildings present 1 storey with the same height, but the in-plan dimensions vary. The photo of the entire aggregate is reported in Fig. 5, while in Fig. 6 the drawings of the elevation view and of the planimetric distribution of panels are depicted. The detailed geometrical survey allows to categorize this case study under the ranges above identified to generate the analysed archetypes. It is worth noting that, at disposal of the authors, most of the geometrical features are available, while only the mechanical properties are unknown (i.e., $f_{c,m}$ and $f_{v,m}$). On the other hand, some geometrical features here accounted could be affected by uncertainty, such as the thickness of the walls. For this latter parameter, the external walls vary from 40 to 50 cm, while the internal walls vary from 25 to 30 cm. Hence, the fragility analysis of the real row masonry aggregate can be processed, accounting in the numerical model for the variation of the mechanical properties and of the wall thickness. Analogously to the established criteria to investigate typological aggregates, the study of the real cases study was carried out by considering each main direction and both global and local mechanisms. No visual information was detected for the presence or absence of the ring beam, and for this reason, the analysis was performed with and without this structural detail.

Figure 5. Picture of the real row masonry aggregate used for purpose of validation.

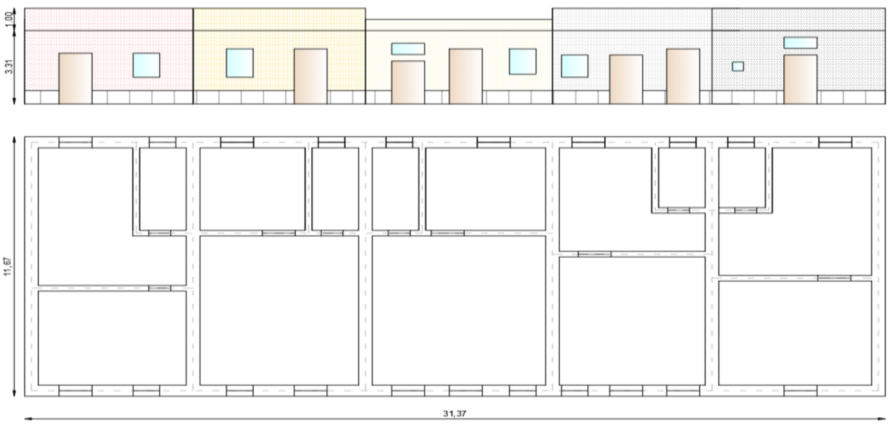


Figure 6. Drawings of the surveyed row masonry aggregate. From the top to the bottom, elevation view of the buildings and planimetric distribution of masonry panels. Reported measures are expressed in meters limited to the base area sides and height of the focused masonry aggregate.

Thus, if the output of META-FORMA-XL is reliable, the local and global fragility curves should represent the seismic behaviour of the real masonry aggregate. On the other hand, it is almost impossible to derive the same result from the typological and the detailed analysis, that is, it is impossible that a specific fragility curve perfectly matches the same output for the real masonry aggregate. To overcome this limit, a spindle of typological fragility curves can be derived, which represents, on one hand, the minimum and the maximum limits for each typological fragility curve and, on the other hand, encloses the output provided by the detailed analysis on the real case study. To define the minimum fragility curves, the assumed parameters are the minimum values for thickness of walls and for mechanical parameters of masonry, and the maximum values for the percentage of openings at ground and upper floors. Instead, to define the maximum fragility curves, the assumed parameters are the maximum values for thickness of walls and for mechanical parameters of masonry, and the minimum values for the percentage of openings at ground and upper floors.

The procedure in META-FORMA-XL can be repeated, evaluating fragility curves by using a lower number of models (324 models for each subsample). At the same time, the numerical model of the real masonry aggregate was carried out and the fragility curves were obtained by varying the uncertain parameters (12 models).

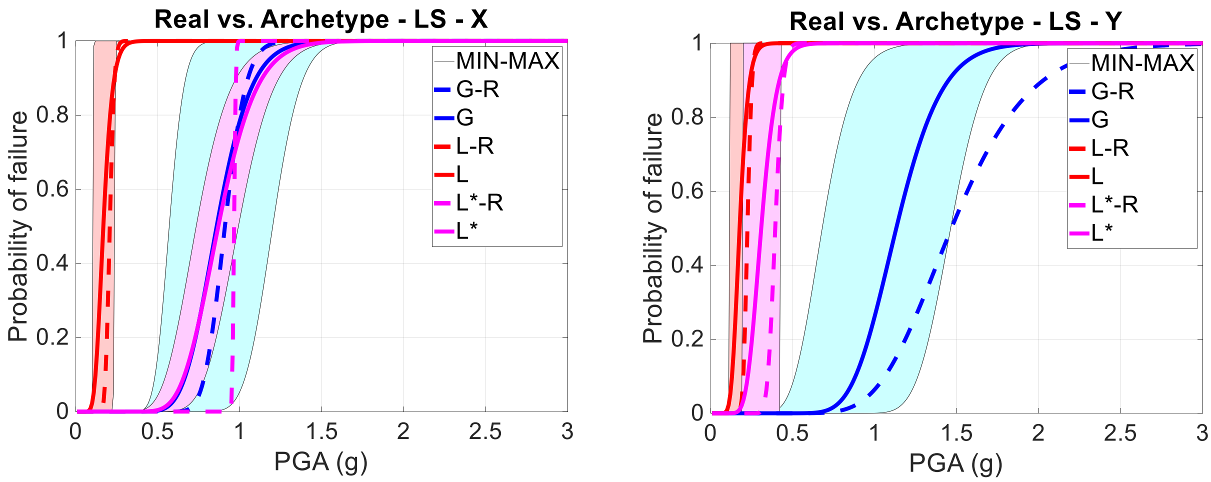


Figure 7. Comparison of fragility curves between real (dashed line) and archetype (continuous line) buildings in X (left-hand side) and Y direction (right-hand side), accounting for local and global mechanisms (with and without ring beam). G stands for global, L stands for local without ring beam, L stands for local with ring beam, and R stands for real, respectively. Min-Max indicates the minimum and maximum fragilities for identifying the spindles curves for all failure mechanisms.*

The comparison between the fragility curves of real and archetype masonry aggregates and the assessment of fragility curves of the real masonry aggregate within the minimum-maximum spindles are reported in Fig. 7, subdividing results in X and Y directions, and investigating each failure mechanism (fragility for local mechanisms were evaluated with and without ring beams).

Looking in detail the obtained results, some aspects can be highlighted. First, the fragility curves evaluated on the real aggregate present the same trends of the archetype results, with higher P_f in X direction (due to the openings) and lower P_f in Y directions. Observing the local fragility curves for all directions and considering or not the presence of the ring beam, the value of the dispersion β is extremely lower than the one derived for the archetypes, and this is mainly due to a lighter variation of the uncertainties and, above all, to a variation of parameters do not strongly affecting the local behaviour (only the thickness of the walls). Instead, the important role of the varied mechanical parameters in global mechanisms provides a comparable dispersion between real and archetype aggregates for global fragility curves. Comparing the fragility curves of real and archetype buildings, in X direction results are in good agreement, especially for global mechanisms and local mechanisms without ring beam. Lower accuracy is observed for local mechanisms with ring beams, mainly caused by the obtained different dispersions (medians are not extremely different). Instead, in Y direction, a good agreement of results can be observed for local mechanisms (both for cases with and without ring beams), while for global mechanisms, the fragility of the real building tends to present a lower $P_{f,G}$, which suggests a certain conservativism. Assessing the position of fragility curves for the real masonry aggregate within the minimum-maximum spindles, despite the inaccuracy in terms of dispersion, most of the curves presents medians within limits, which suggest good potentialities in prediction. Overall, META-FORMA-XL provides near good predictions for large-scale seismic analysis of masonry aggregates for both global and local mechanisms. In the end, it is worth nothing that, looking at the mechanisms having the higher Pf, the output of META-FORMA-XL perfectly fits with the fragility curve of the real masonry.

5. Conclusions

The paper presents an approach, named META-FORMA-XL, to derive fragility curves of typologically defined masonry aggregates, accounting for global and local mechanisms. The starting point is represented by an exposure analysis providing typological data from freely available databases (e.g., Census, Regional Technical Cartography) and from the CARTIS form. Structural models are generated using an archetype-based philosophy. In the model generation, uncertainties are taken into account by systematically varying modelling features and accounting for the influence of parameters on the seismic behaviour. Afterwards, numerical analyses are performed to derive the structural capacity for the global behaviour and for local collapse mechanisms. The output of the procedure consists in global and local fragility curves for each main direction of analysis.

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 the historical centre. 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. Finally, the fragility curves provided by the method have been compared with those obtained by considering an actual geometry. The good agreement between the two results validates the proposed approach. Further developments of the work will aim to extend the proposed procedure by accounting for more complex structural typologies.

6. Acknowledgements

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