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META-FORMA: an automated procedure for urban scale seismic vulnerability assessment of masonry aggregates

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Abstract

The paper presents *META-FORMA* (MEchanical-Typological Approach FOR Masonry Aggregates), an automated procedure for the seismic vulnerability assessment of masonry aggregates at urban scale. The study addresses the issue of performing seismic analysis in presence of a limited knowledge framework, typical of masonry buildings at this scale of analysis, proposing an automated algorithm able to generate and analyze a large set of numerical models, as representative of recurrent aggregate configurations in a certain urban sector. Exploiting the interoperability between the programming software MATLAB and the structural analysis and design software POR2000, a large set of numerical models have been generated, as combination of few input parameters on recurrent geometrical and mechanical typological features of structural units, derived from multi-source data. After, nonlinear static analyses have been performed on each model, obtaining the bilinear curves and the capacity demand ratios as output. The proposed approach has been developed for a row aggregate configuration, typical of the historical centers of the Puglia Region, and the application has allowed to obtain with a low computational burden, a proper database of input and output parameters for a wide set of models, useful for a rapid and simplified estimate of the seismic behavior of masonry aggregates.

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Keywords: Historical Centres; Masonry Aggregates; Vulnerability Analysis.

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1. Introduction

The disastrous consequences of the recent earthquakes have led to the shared awareness of the urgency to deploy suitable strategies for seismic risk mitigation (Casolo et al., 2000; Sferrazza Papa et al, 2021; Uva et al., 2016). In the Italian context, about 70% of existing building stock was realized in total absence of any seismic standards (ISTAT, 2011), mostly located in areas with a relevant seismic hazard (Dolce et al., 2020). This means that it is necessary to assess actual performance levels, potential damages, socioeconomic losses and to provide retrofitting actions for a huge number of buildings for reducing their seismic vulnerability. Within this process, a preliminary screening at territorial scale is a key step for the prioritization and planning of further detailed analyses optimizing the necessary resources in term of time and costs. At this scale of analysis, the use of traditional building-level methods is unfeasible, since it requires very detailed data and high computational efforts, and attention should be shifted to simplified procedures, easily implementable using limited information, and able to provide results with acceptable reliability and accuracy (Pelà, 2018). Despite several studies and applications proposed in the last years, the availability and accessibility of data sources together with the computational burden required by the structural modelling and analysis at large scale remain an open issue. These problems are even more significant in historical centres, where almost all the building stock is composed by very old masonry constructions generally grouped into aggregate with heterogeneous morphology and with a seismic behavior heavily influenced by the “aggregate effect”. As a matter of fact, for structural analysis of masonry aggregate it needs sophisticated numerical methods that entail a very detailed knowledge and high time-consuming computational burden (Casolo et al., 2017; Casolo 2021; Grillanda et al., 2020; Ramos and Lourenço, 2004; Senaldi et al., 2010) unfeasible for large-scale analysis applications. To overcome this hurdle, it is necessary to manage uncertainty related to a low reliability or absence of information, opting for rational simplifications. In this context, in the last years, a number of simplified methods has been developed by performing a rapid but extensive estimate of the seismic vulnerability within historical centres (Battaglia et al., 2021; Chiumiento and Formisano, 2019; Cocco et al., 2019; Leggieri et al., 2021; Pagnini et al., 2011). Regarding large-scale data collection, many procedures have been proposed with the common aim to define homogeneous typological-structural categories representative of the existing building stock in an area under investigation (Polese et al., 2019). Among these, interview-based and form survey procedures are the main approaches able to rapidly collect extensive data, by exploiting expert judgments from specialised technicians (Baggio et al., 2007; GNDT, 1994; Uva et al., 2016, 2019). In this framework, the Italian Civil Protection Department within the ReLUIS project, has developed CARTIS procedure (Zuccaro et al., 2016), a data collection method at large-scale characterized by a peculiar approach, which provides for the definition of homogeneous urban sectors in a municipality and recurrent typological-structural features of related building classes, by interviewing one or more practitioners or local expert technicians. At large scale, other fundamental information sources are represented by digital georeferenced datasets, generally freely available in different types of formats and directly implementable and manipulable in Georeferenced Information System (GIS). This allows to manage, overlay, process and display in the same environment large sets of different typologies of information derived from multiple types of data sources (Jena et al., 2020). Therefore, it is possible to extrapolate important building parameters by integrating in GIS environment all the above-mentioned multi-source data, obtaining an overall knowledge framework about the existing building stock (Leggieri et al., 2022).

Within this broad framework, the availability of suitable simplified methods of analysis is necessary, easily implementable using few general data about morphological, geometrical and structural features of the buildings. In this paper, a procedure named *META-FORMA* (MEchanical-Typological Approach FOR Masonry Aggregates) is presented, as an automated tool for urban scale seismic vulnerability assessment of masonry aggregates, able to exploit multi-source data for deriving fundamental morpho-typological parameters of the structural unit (SU) and aggregate configuration (AC), and to automatically generate and perform structural analysis for sets of single SUs and ACs representative of building stock investigated with a low computational burden. The procedure is implemented by means of a MATLAB code (Matlab, 2022) able to directly interact with the structural analysis and design software POR2000 (Newsoft POR2000, 2020). More in detail, a preliminary investigation of the urban fabric of a certain municipal area is performed, based on available multi-source data implemented into GIS databases and used to define the representative typological building classes and recurrent aggregate configurations. Therefore, a minimum set of geometrical and mechanical information are selected as input parameters to automatically generate sets of numerical models of the single SU and row ACs. All the generated models are then processed into POR2000 software by nonlinear static analyses, providing as output the bilinear curves of the single-degree-of-freedom (SDOF) model and the capacity/demand (C/D) ratios for each model.

META-FORMA has been tested on an urban sector of the municipality of Foggia, Puglia, Southern Italy, performing modelling and analysis for large samples of masonry building aggregates in a simple way and with low time effort. The application shows that *META-FORMA* is capable to overcome the limit connected to the poor level of knowledge, typical of the large-scale applications, by implementing a mechanical-based approach by means of few input parameters about some recurrent features of single US and able to characterize the seismic behavior and vulnerability of masonry aggregates with reduced computational effort.

2. General framework of META-FORMA

META-FORMA procedure (MEchanical-Typological Approach FOR Masonry Aggregates) is an automated tool organized in different parts (Fig. 1). Firstly, the input parameters are derived by multiple sources of information, freely available online or gathered by means of rapid collection data methodologies. Then, the sample of structural models of SUs and masonry ACs are generated as all possible numerical combinations of the values assumed for each input parameter in a plain text format (according to the I/O policy of POR 2000) through an automated procedure in MATLAB. Successively, all generated *input* files are sent sequentially to the structural analysis software using the console application (without GUI), which runs pushover analyses through a *batch procedure* in eight different horizontal directions identified through planar angles of rotation than the main reference system (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) and for two vertical load patterns: uniform and inverse triangular. Two output files for each model are obtained, respectively containing parameters of the bilinear pushover curves of equivalent SDOF models and the C/D ratios for all limit-states.

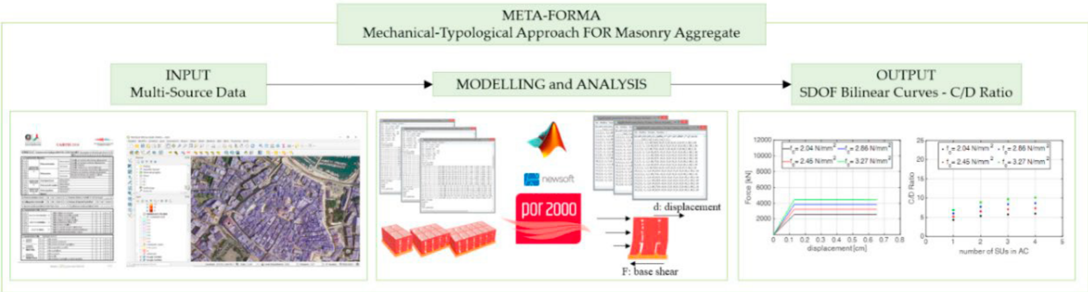


Fig. 1. General framework of *META-FORMA*.

2.1. Input parameters for META-FORMA

The preliminary phase consists in the characterization of the SUs and in the identification of the typical ACs in a specific homogeneous urban sector (USec), which is a part of a municipality characterized by uniformity of the urban fabric and year of construction defined according to the CARTIS procedure.

The SU has been characterized by using typological structural information about the building classes of a specific USec extrapolated from the CARTIS form, such us general information related to the geographic localization and year of construction; geometric information, defined through ranges of values about the total number of storeys, the average span between walls, the average floor area, the inter-storey height, the average thickness of walls, the percentage of openings at the ground floor and at the upper floor; structural and typological information, e.g., masonry and mortar type, slab type and its deformability degree, presence and type of vaults, roof type, regularity in-plan and regularity in-height. The identification of the most recurrent ACs is performed by means of rapid visual survey using aerial photos or georeferenced cartographies. In particular, Technical Regional Cartography (CTR) allows to obtain the geometric dimensions of the polygons which represent the masonry aggregates.

Therefore, it needs to identify a minimum set of input geometrical, typological and mechanical parameters (P_i) with related range of n values (v_j, …, v_n) to generate a set of models sufficiently representative of the USec under investigation, also considering that the outputs of numerical analyses are strongly dependent on modelling assumptions and their related uncertainty (Gino et al, 2021). Seven parameters have been selected as the input for the present procedure. The geometric parameter P_1 represents the shorter dimension of the aggregate and it is equal to the length of one side of the SUs as derived by the CTR; P_2, P_3, P_4, P_5 and P_6 are geometrical parameters extracted from the CARTIS form with related ranges of values defined in terms of minimum and maximum values. Finally, being in absence of detailed information, the mechanical characterization of the masonry is performed by means of the parameter P_7, assuming from the Annex of the Italian Building Code (Circolare NTC18, 2019) pairs of minimum and maximum values for the masonry compressive strength (f_c) and the masonry tensile strength (f_v), coherently with the type of masonry reported in CARTIS catalogue. The masonry young modulus (E) and shear modulus (G) are then computed as prescribed the Italian Building Code (Aggiornamento Delle "Norme Tecniche per Le Costruzioni", 2018). The n values of v_j of each P_i are obtained through a proper discretization of the range identified by a minimum and maximum values. In the specific case, 1 or 2 more plausible values between the range extremes have been taken into account. Selecting the P_i and the related v_j for each CARTIS typological class of a certain US, it is possible to obtain a total number of models N_{model} as the product of the number of values v_j defined for each P_i ($v_j(P_i)$):

$$N_{model} = \prod_{j=1}^{n} \prod_{i=1}^{7} v_j(P_i) \cdot P_i \tag{1}$$

Consequently, considering that in a certain USec there are different typological classes (n_{class}) and in the hypothesis of different row ACs obtained as repetition of an increasing number of equal USs, n_{SU}, the total number of models, N_{TOT}, is defined as following:

$$N_{TOT} = n_{class} \cdot n_{SU} \cdot N_{model} \tag{2}$$

2.2. Generation of numerical model and seismic analysis

The numerical modelling of the SUs and ACs is performed by using the structural software POR2000 (Newsoft POR2000, 2020), which is based on a simplified fully 3D model of the building that implements the hypotheses of box-like behavior of the masonry structure and implying two fundamental assumptions: (a) shear-type scheme, with constrained rotations at the base and the top sections of masonry piers; (b) in-plan rigid roto-translation motions for the storey slab, with the advantage to provide a good compromise between a simple modelling and an accurate result. A bilinear perfectly elasto-plastic behavior is assumed for the masonry piers and a proper mechanism of damage suitable to obtain a mechanical coherent collapse limit state. Hence, the second step of *META-FORMA* consists in the modelling of all N_{TOT} models obtained through the procedure described in Section 2.1. The huge number of structural models which can be generated, requires to automatize the numerical modelling procedure. With this aim, a proper algorithm has been elaborated using the programming software MATLAB (Matlab, 2022), able to automatically generate numerical models compiling a *.txt* file according to the I/O policy by POR2000 in order to executed trough a console application in a batch procedure. For this step, a second part of the algorithm is elaborated that is able to select a model, to run the pushover analyses and to switch on the next model. For each analysis, POR2000 provides two different outputs *.txt* file: (a) the bilinear curves of the equivalent SDOF, defined trough the values of the yielding force (F_y), the yielding displacement (d_y) and the ultimate displacement (d_u), with reference to eight directions and two distributions, for a total of sixteen bilinear curves; (b) the C/D ratios, expressed in terms of peak ground accelerations (*PGAs*) for four limit-states accounted in the Italian building code. It is worth pointing out that each model analysis, as implemented using interoperability between MATLAB and POR2000, requires a time of about 3 seconds, which means that to obtain output files for a set of 1000 models, it needs only 50 minutes.

2.3. Post-processing of data: preliminary result for a case study

The last phase regards the post-processing of the input and output data. All numerical combination of the input parameters related to each structural model are stored and indexed in a 7-by-N_{TOT} matrix; similarly, the output parameters of each analysis have been allocated in two matrices of 3-by-N_{TOT} and 4-by-N_{TOT} dimensions: the first contains the values of F_y, d_y and d_u of the bilinear curves; the second contains the values of the C/D ratios for the four limit-states, assuming the same index of the corresponding model. This data structure, in which input parameters are univocally related with output parameters, allows to implement several queries to provide in easily and rapid way different results of the seismic behavior for a large set of masonry aggregates without going through the structural modelling and analyses, but only starting from the knowledge of few geometrical and mechanical parameters about the SU.

3. Application of *META-FORMA*: the case study of the historical center of Foggia, Southern Italy

The proposed procedure has been applied to a pilot case of the municipality of Foggia, a city located in the north of Puglia, Southern Italy, characterized by a PGA ranging from 0,131g to 0,176g, with a probability of exceeding (P_{VR}) equal to 10% in a reference period (V_R) of 50 years (Aggiornamento Delle "Norme Tecniche per Le Costruzioni", 2018). For this municipality, the CARTIS form has been already compiled. Among the 12 different USecs identified, *META-FORMA* has been applied for C02 (Fig. 2), being one of the oldest parts of the city and containing 47% of all the masonry buildings of the municipality. Buildings are organized in aggregates with rectangular shape in plan and usually made up of a single row of SUs, varying in number from 2 to 4, as schematized in Fig. 2, with similar height and base area and with a shorter side ranging between 10 and 15 m.

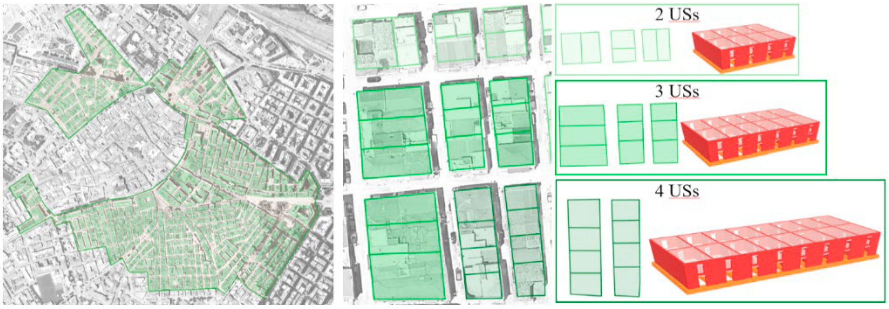


Fig. 2. From left to right, aerial view of C02 urban sector in the historical centre of Foggia: identification of the ACs typology, example of the modelling process of the ACs.

Two different masonry classes have been detected according to CARTIS form: MUR01 and MUR02 with the related specific general, geometrical, structural and typological features. The set of the 7 input parameters P_i has been fixed with the corresponding range of values v_j, obtained by subdividing in equal parts the ranges of each P_i. Table 1 reports the arrays constituting the input variables defined for each of P_i and containing the related values of v_j. Once the input parameters have been fixed, the algorithm of *META-FORMA* is applied. All SUs have been considered regular in plan and regular in elevation, with a square or rectangular shape and with an inter-storey height of 3,5 m for the ground floor and 3 m for upper floors. Three different ACs have been modelled by replicating 2, 3 and 4 SUs. For each of the typology classes MUR01 and MUR02 the set of models was built, also considering the case of single SU as an isolated configuration (AC_1) and other 3 sets of models obtained with 2, 3 and 4 SUs (respectively AC_2, AC_3 and AC_4). According to Equation 1, 3240 models have been generated for each of the ACs. By employing Equation 2 and considering the four ACs for each of the two classes, the total number of generated numerical models amounted to 25920. Coming back to the total number of models, the input matrix is a 7-by-25920, dimensions that will be useful for the subsequent elaborations. Once all models are available, all the *.txt* files have been automatically imported in POR2000 (one-by-one and sequentially), and nonlinear static analyses have been run obtaining a set of 25920 output *.txt* files containing sixteen bilinear curves of the equivalent SDOFs and a set of 25920 output *.txt* files containing the C/D ratios for the four limit-states. From the output files, the values of F_y, d_y and d_u have been extracted for each SDOF capacity curve and allocated in 3-by-25920 matrices, considering each direction and load distribution. The values of C/D ratios, related to the analyses in direction 0°, for the four limit-states have been stored in a 4-by-25920 matrix. Using the matrices of the input and output parameters, it becomes easy to quickly link the bilinear curves of the SDOF systems and the corresponding C/D ratio to a specific US and to a specific AC. Indeed, by fixing the seven

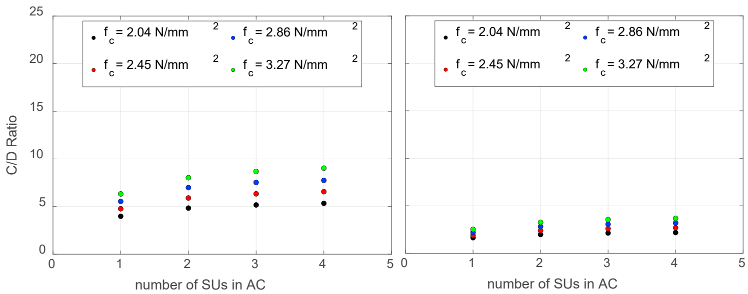
$v_j(P_i)$, it is possible to rapidly obtain the outputs for a specific model and to easily compare the seismic performance of models by varying one or more parameters.

Table 1. Input parameters (P_i) and relative values (v_j) for each structural-typological class.

Parameter	Variable (P_i)	Source	Values (v_j) MUR01	Values (v_j) MUR02
Side of the SU [m]	P_1	CTR	[10 12 15]	
Base area [m^2]	P_2	CARTIS	[70 85 100]	[130 150 170]
Number of storeys	P_3	CARTIS	[2 3]	[3 4]
Thickness of walls [m]	P_4	CARTIS	[0,25 0,30 0,50 0,70 1]	
Percentage of openings in upper floors [%]	P_5	CARTIS	[10 15 20]	
Percentage of openings in the ground floor [%]	P_6	CARTIS	[20 25 30]	
Average compressive (f_c) and tensile (f_y) strengths [MPa]	P_7	Italian Building Code	[2,04 2,45 2,86 3,27] [0,10 0,13 0,16 0,19]	

Some examples of preliminary results are reported in Fig. 3 and Fig. 4 (more details are available in Leggieri et al., 2021).

Fig. 3. Bilinear curves for the class MUR01 obtained by uniform load pattern, $v_j(P_1)$ equal to 10 m; $v_j(P_2)$ equal to 70 m^2; $v_j(P_3)$ equal to 1; $v_j(P_4)$ equal to 0.25 m; $v_j(P_5)$ equal to 10%; $v_j(P_6)$ equal to 20% and by varying f_c. In order from left to right respectively AC_1, AC_2, AC_3 and AC_4.



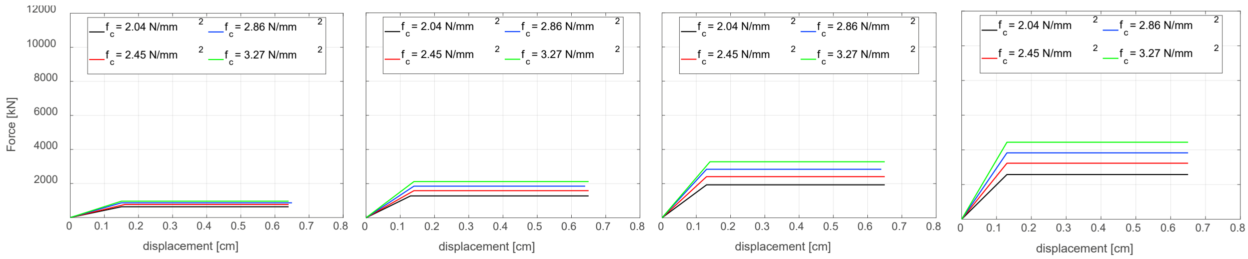


Fig. 4. C/D ratios for the models MUR01 for the IO limit-state, uniform load pattern and 0° direction, obtained by $v_j(P_1)$ equal to 15 m; $v_j(P_2)$ equal to 100 m^2; $v_j(P_4)$ equal to 0.25 m; $v_j(P_5)$ equal to 20%; $v_j(P_6)$ equal to 30% and by varying f_c. In order from left to right respectively the models with 1 and 2 number of storeys.

4. Conclusion and future development

The aim of the paper is to present an automated tool, named *META-FORMA* (MEchanical-Typological Approach FOR Masonry Aggregates), for large-scale seismic vulnerability assessment of masonry aggregates, starting from few input parameters about typological-structural building classes and involving low computational effort. The development of such procedure has been possible exploiting the interoperability between the programming software MATLAB and the structural software POR2000. The application to the case study of Foggia municipality have shown the potentials of the proposed automated procedure. Indeed, *META-FORMA* allows to overcome the difficulty to determine a nearly full knowledge about the structural and typological features of individual structural units, requiring few information about the US for the implementation. Moreover, it is a fully automated but simplified procedure, allows to investigate the seismic behaviour of a myriads of numerical models by optimizing the low computational time, which is usually the burdensome aspect in the analysis of masonry aggregates. Finally, the inputs and outputs are properly stored and indexed into data structures (ie. SQL DATA BASE), always available and easily searchable in order to extrapolate different types of results. Such a data structure can be employed for several scopes: (a) in large-scale approaches and risk mitigation strategies, *META-FORMA* allows to define the vulnerability of a masonry aggregate, located in a certain area and for which some data are available; (b) in single building-level approaches, *META-FORMA* provides a screening of the preliminary results about a specific masonry aggregate and the SUs that compose it. Obviously, if a detailed analysis is desired, further investigations are necessary from more accurate survey, but the obtained result can represent the base for initial observations and for a final comparison.

Nevertheless, remains some limitations due to a strong simplifying hypothesis assumed, such as equal SUs in the same AC, and application only to row AC. However, this issue can be easily overcome in the future by making adjustment to the code, to make it applicable also to different aggregate typologies composed by SUs characterized by different geometrical and mechanical parameters. The huge number of results and the simplicity of the data structure allows a rapid post-processing, which can be aimed to an extensive sensitivity analysis for studying the influence of the different input parameters on the seismic performance of masonry aggregates, according to the proposed approach. Finally, further important developments will regard the realization of a graphical user interface, in which the user will set the input parameters to directly extract the output parameters and the possibility to execute simultaneously the analyses for more models significantly reducing the analysis time.

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