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A digital tool based on code indicators to assess the seismic behaviour of existing masonry structures: Application to Croatian residential buildings

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ABSTRACT

This paper proposes a methodology to define code-based indicators of the seismic behaviour of existing masonry structures. Given the geometrical information about the structure under investigation, the proposed method performs real-time structural checks according to the EN 1998–1 – "General rules, seismic actions and rules for buildings". Then, modal analysis is performed to assess the structure's dynamic behaviour under investigation and to assist the user in defining retrofit measures. In this study, 103 masonry buildings located in Zagreb are analysed, accounting for the cross-sectional area of load-bearing walls, geometric requirements for shear walls, regularity of plan configuration and its symmetry, torsional effects induced by the distance of the centres of mass and stiffnesses, and modal analysis. The workflow is implemented into the environment offered by Rhino3D and Grasshopper, which allows for the parametric handle of a large set of information through object-oriented scripts, and it can be valuable for both pre-earthquake and post-earthquake assessments of masonry buildings.

1. Introduction

Field surveys after earthquake events demonstrated how masonry structures are prone to experience localised failure mechanisms, producing some severe social and economic consequences, such as i) physical loss of artistic and historical materials, ii) an immaterial loss of memory and cultural identity for the people to whom that legacy "belongs", and iii) difficulties in the action of the Civil Protection in assisting the population affected by the disaster [1].

Therefore, in order to minimise losses arising from disasters, several researchers focused on implementing advancements for performing vulnerability analyses, simulating scenarios, reducing vulnerability, carrying out a cost-benefit analysis, and developing emergency plans. Regarding structural analysis, it might be performed at several scales involving different pieces of knowledge and state-of-the-art numerical or analytical tools [2,3,12–14,4–11].

For example, at the urban scale, Ferreira et al. [15,16] performed the seismic vulnerability assessment of the old city centres of Faro and Sixal in Portugal. They adopted a methodology based on the vulnerability index, which is used to evaluate structural behaviour at a regional scale. Hundreds of buildings were assessed using this methodology, and the results were post-processed using an integrated Geographical Information System tool. Vicente et al. [17] stated that studies of urban centres should be developed to identify building fragilities and reduce seismic risk. As part of the rehabilitation of the historic city centre of Coimbra, they completed the identification and inspection survey of old masonry buildings.

Even deserving some practical utility, particularly regarding the civil protection point of view, urban scale methodologies fail to assess the actual behaviour of the specific building under seismic loads. In fact, state-of-the-art recommendations underline the need for more refined simulations at the structural level that require the use of sophisticated advanced analysis methods, classified as numerical or analytical approaches [18]. Numerical approaches are typically implemented in the Finite Element Method (FEM) [19–28] or Discrete Element Method (DEM) [29–35] frameworks. FEM allows a more versatile application as masonry can be represented either through a homogeneous equivalent media (designated macro-modelling) or by a discrete representation of

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units and joints (designated as simplified micro-modelling). On the other hand, DEM is well suited for masonries with both dry and mortared joints [36–40].

However, such numerical schemes can be time-consuming and computationally expensive, and in order to be adequately implemented and achieve reliable results, a significant amount of data is needed to characterise the non-linear response material constituents [41]. To cover this issue, several research groups developed alternative modelling approaches and practical tools to decrease both the computational time and the cost related to the material characterisation [22,42–45]. In this framework, analytical approaches based on limit analysis represent a valid alternative, having the great advantage of being independent of many material properties but inevitably relying on a very simplified material model [46–49]. However, limit analysis-based tools typically neglect the structure's global behaviour, only focusing on assessing a set of local failure mechanisms [50,51].

The earthquakes in Croatia in 2020 demonstrated the need for rapid and reliable structural assessment tools for existing masonry structures. Three years after the Zagreb earthquake, the research community and structural engineers must ponder the question: Do numerical and analytical state-of-the-art methods provide reliable and fast structural assessments of existing structures?

To cover the identified research gap, a digital tool is developed here for rapid seismic assessment of masonry buildings. The proposed tools allow architects and structural engineers to achieve rapid and high-quality feedback in terms of structural performance, adopting as criteria the requirements set by EN 1998–1 [52,53]. Such a tool might play a ground-breaking role in defining a proper strategy for i) pre and post-earthquake assessment of masonry structures, ii) identifying potential retrofitting interventions, and iii) providing an estimation of the costs for achieving a desired level of safety. To accomplish the objectives, the framework described next has been followed:

- Identification of the requirements defined by the EN 1998–1 [52,53].
- Develop a visual program within a Rhino 3D + Grasshopper [54,55] plugin able to perform a rapid check and assessment of the geometrical requirements that influence the global behaviour of the structure under investigation.

To enhance future processes, it will be incorporate an advanced optimisation algorithm to effectively improve the floor plan, taking into account the identified geometrical requirements and optimising the global behaviour of the structure under investigation.

This paper is divided as follows. Section 2 presents the proposed methodology and its implementation into a visual-based program. Section 3 is devoted to validating the formulation through real case studies. Finally, relevant conclusions are drawn in Section 4.

2. Description of the proposed algorithm

A current focus of the software industry is on defining parametric-based methods to perform preliminary structural designs for new optimised buildings with complex volumes and shells. However, a limited number of studies in the literature have applied these methods to assess the structural integrity of masonry structures [56]. Therefore, the main challenge is to provide structural engineers and architects with easy-to-use tools for evaluating the structural performance of buildings for pre- and post-earthquake assessment. In this context, Generative Programming (GP) appears as a reliable and efficient solution, being a programming paradigm based on the code-reuse concepts, which implies using the coding knowledge following the reusability principles.

In the following subsections, a GP paradigm is adopted for developing a Grasshopper [55] component for the rapid seismic assessment of masonry buildings. Fig. 1 schematises the workflow of the proposed methodology. Once the structural survey is performed, namely plan layout, floor numbers and their inter-story height, the requirements set by EN 1998–1 [52] are checked. Furthermore, as an output, the developed code provides the computational mesh to be used in Karamba 3D [57], which allows for employing eigenfrequency analysis. The motivation for performing eigenfrequency analysis is to visualise the building's mode shapes and verify if the predominate modes have torsional shapes (a complementary possibility is to estimate seismic spectral demand, not considered at this stage). Finally, the user may perform a preliminary definition of a possible retrofitting intervention defining an optimisation problem that aims at minimising the distance between the centre of mass and the centre of the stiffness to reduce torsional effects. It should be noted that the latter is part of the proposed workflow, but it is not considered in this research paper since it addresses only the assessment stage.

The proposed workflow cannot be regarded as a detailed safety assessment, though it provides an estimation of the building's seismic performance. Structural engineers and architects involved in pre- or post-earthquake assessments can use the numerical outcomes of the proposed procedure as a valuable starting point for making preliminary recommendations to stakeholders or local authorities with regard to the structural integrity of masonry buildings. One can note that simplified methods require specific conditions, as discussed earlier, and should end up with a conservative assessment since they are typically performed without physically inspecting the buildings or with limited knowledge of the investigated object, resulting in poor accurate evaluations. However, the proposal tool can still identify highly vulnerable cases and prioritise further studies in earthquake-prone regions.

2.1. Input data

As shown in Fig. 1, the first step is to analyse the floor plan of the building. In the Croatian context, walls with a thickness smaller than 0.29 m are usually not considered able to carry loads as they just act as vertical partitions. This is also the average minimum thickness value recommended by EN 1998–1 [52] for masonry shear walls, which indicates a value of 0.35 m for stone masonry and 0.24 m for other types of unreinforced masonry [58]. For the sake of clarity, walls thicker than 0.29 m, i.e. load-bearing walls, are categorised into walls with horizontal bearing capacity along the x-axis or y-axis. Such a stage is synoptically represented in Fig. 2, where walls are grouped parallel to the x-axis (blue) and y-axis (green), respectively. The walls respecting such

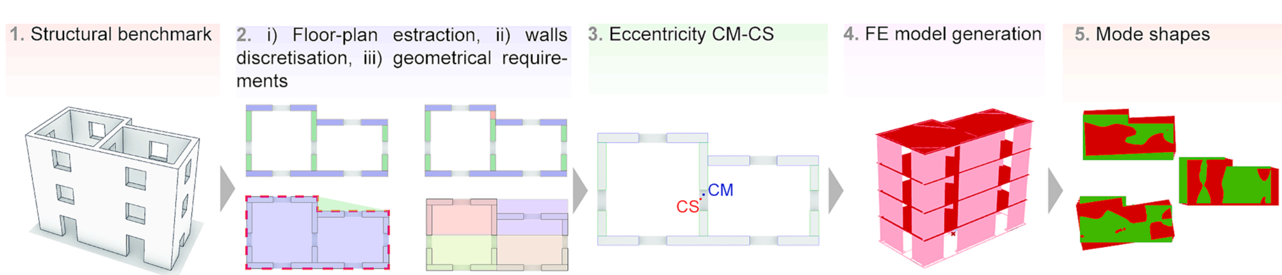

Fig. 1. Flowchart for a case study building.

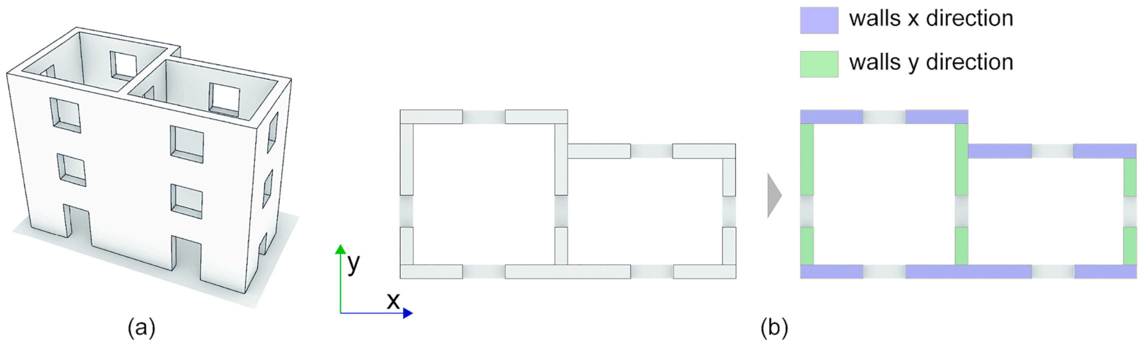

Fig. 2. (a) Structural benchmark, (b) Walls' in-plane direction identification.

minimum thickness conditions are listed and classified as having seismic resistance.

2.2. EN 1998–1 requirements

The driven concept of the proposed procedure is the verification of some of the rules set by the EN 1998–1 [52]. The fundamental idea behind this choice is based on the concept that if an existing masonry building respects such "basic principles of conceptual design" plus "rules simple for masonry structures", it will, most likely, inherently exhibit good seismic behaviour.

As detailed next, the following requirements are considered: i) minimum cross-sectional area of load-bearing walls; ii) geometric requirements for shear walls; iii) regularity of the plan configuration; iv) asymmetry; v) torsional resistance and stiffness.

2.2.1. Minimum cross-sectional area of load-bearing walls

The first geometric requirement considered is the minimum cross-sectional area of load-bearing walls for simple masonry buildings depending on the location and type of construction [52].

Depending on the product $a_g \cdot S$ at the site, the type of construction, and the number of storeys above ground, it is possible to determine the minimum total cross-sectional area in two orthogonal directions.

Table 1 reports the information provided by EN 1998–1. From the structural engineering point of view, when a building under investigation fails to adhere to this threshold limit, its seismic resistance performance is probably compromised.

According to the EN 1998–1 [52], for buildings where at least 70 % of the shear walls under consideration are longer than 2 m, the k factor is given by $k = 1 + (l_{av} - 2)/4 < 2$, where l_{av} is the average length expressed in meters, of the considered shear walls, in all other cases $k = 1$.

Table 1
The recommended allowable number of storeys above ground and minimum area of shear walls for "simple masonry buildings" [52].

Acceleration at site $a_g \cdot S$		$< 0.07 \cdot k \cdot g$	$< 0.10 \cdot k \cdot g$	$< 0.15 \cdot k \cdot g$	$< 0.20 \cdot k \cdot g$
Type of construction	Number of storeys (n)	Minimum sum of cross-sectional areas of horizontal shear walls in each direction, as a percentage of the total floor area per storey ($p_{A,\min}$)			
Unreinforced masonry	1	2.0 %	2.0 %	3.5 %	n/a
	2	2.0 %	2.5 %	5.0 %	n/a
	3	3.0 %	5.0 %	n/a	n/a
	4	5.0 %	n/a*	n/a	n/a

** Roof space above full storeys is not included in the number of storeys.

Fig. 3 reports how to calculate $p_{A,\min}$ once the cross-sectional area of the shear wall for each direction is known.

2.2.2. Geometric requirements for shear walls

The proposed algorithm checks the geometric requirements, namely the wall thickness, the ratio of wall height (assumed conservatively as the inter-storey height) and thickness, and the ratio between wall height and thickness. Table 2 reports the EN 1998–1 [52] recommended geometric requirements for masonry shear walls, which have been implemented into the Grasshopper [55] component. The proposed method compares the value of the geometric requirements for each wall belonging to the floor plan and provides a list of walls that do not meet the requirements. Thus, each wall that does not respect even only one of the three requirements is classified as unsafe.

2.2.3. Regularity of plan configuration and compact shape

Plan configurations characterised by a regular layout typically exhibit better seismic behaviour. According to EN 1998–1 [52], further rules for simple masonry buildings aim to define the plan configuration's regularity and have been implemented in the proposed workflow. As suggested by EN 1998–1 [47], in order to consider the plan configuration as regular, the shape should be approximately rectangular, and the ratio between the length of the smaller side and the larger side should not be smaller than a minimum value $\lambda_{\min} = 0.25$.

A further check regards the control of whether the plan shape may be considered compact or not. If the ratio between the green and blue areas, represented in Fig. 4, is smaller than 15 %, the plan configuration can be considered compact, which indicates good seismic behaviour.

2.2.4. Asymmetry

Some of the basic principles of conceptual design are not precisely defined in EN 1998–1 [52]; hence, the Asymmetry index has been defined for the sake of the proposed methodology, as shown in Fig. 5. Namely, the floor plan is divided into four parts (Fig. 5a), and for each quadrant, the area of the wall within that quadrant indicated as subscript ($A_{qn,wall}$) is calculated (Fig. 5b). Then, the structure under investigation is considered asymmetric if the following inequalities are satisfied:

$$\frac{\left|\left(A_{q1,wall} + A_{q2,wall}\right) - \left(A_{q3,wall} + A_{q4,wall}\right)\right|}{\max\left\{\left(A_{q1,wall} + A_{q2,wall}\right), \left(A_{q3,wall} + A_{q4,wall}\right)\right\}} \geqslant 0.1 \text{ along } x \text{ direction} \quad (1)$$

$$\frac{\left|\left(A_{q1,wall} + A_{q3,wall}\right) - \left(A_{q2,wall2} + A_{q4,wall}\right)\right|}{\max\left\{\left(A_{q1,wall} + A_{q3,wall}\right), \left(A_{q2,wall} + A_{q4,wall}\right)\right\}} \geqslant 0.1 \text{ along } y \text{ direction} \quad (2)$$

2.2.5. Torsional resistance and stiffness

The seismic torsional response can lead to unfavourable behaviour, i.

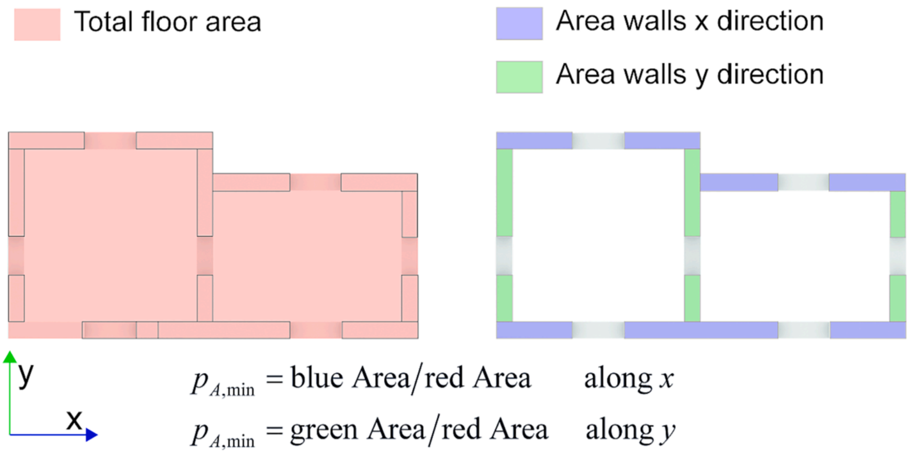

Fig. 3. Graphical interpretation of the percentage of the cross-sectional area of load-bearing walls.

Table 2
Geometric requirements for masonry shear walls by EN 1998–1 [52].

Masonry type	$t_{ef,\min}$ (mm)	h_{ef}/t_{ef} max	$(l/h)_{\min}$
Unreinforced, with natural stone units	350	9	0.50
Unreinforced, with any other type of units	240	12	0.40
Unreinforced, with any other type of units, of low seismic intensity (i.e. peak ground acceleration lower than 0.20 g).	170	15	0.35

t_{ef} is the wall thickness.
h_{ef} is the effective height of the wall.
h is the greater clear height of the openings adjacent to the wall.
l is the wall length.

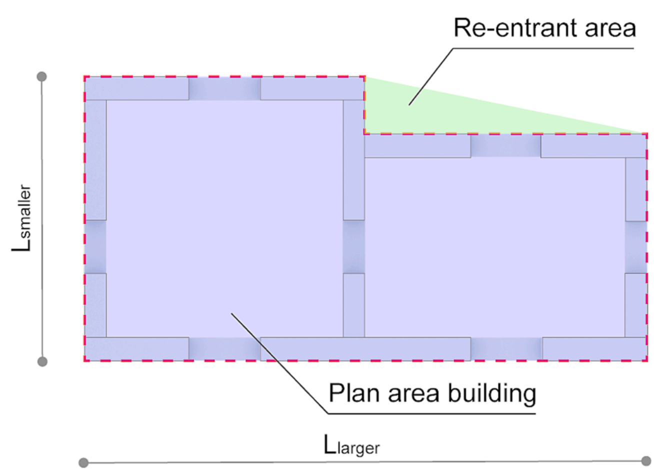

Fig. 4. The compact shape of the building.

e. generating fragile and localised failure mechanisms. The vector distance between the centres of mass and stiffness is a relevant marker to address the likelihood of a structure being affected by such torsional modes [60]. To achieve this task, the proposed method quantitively measures the vector distance between the centres of mass and stiffness. Operatively, a list of all the load-carrying walls is generated by collecting information such as mass m and centre of gravity coordinates x,y. Such data are used within equations (3) and (4) to calculate the centre of mass of the structural system:

$$x_{CM} = \frac{\sum x_i \cdot m_i}{\sum m_i} \tag{3}$$

$$y_{CM} = \frac{\sum y_i \cdot m_i}{\sum m_i} \tag{4}$$

The information contained in the list mentioned above is used to calculate the centre stiffness of the structural system by implementing the following equations:

$$x_{CS} = \frac{\sum x_i \cdot K_i}{\sum K_i} \tag{5}$$

$$y_{CS} = \frac{\sum y_i \cdot K_i}{\sum K_i} \tag{6}$$

The distance between the centre of mass and the centre of stiffness is thus calculated, and their x and y components are expressed as a percentage of the building length in x and y, respectively.

2.3. Finite element discretisation and eigenfrequency analysis

The loading bearing walls are sorted in a list, and a finite element discretisation using shell elements is performed using the Karamba 3D [57] component for Grasshopper. Since these are load-bearing walls that extend from the base to the top of the building, it is possible to raise the entire building model by defining the following input parameters: the number of storeys, the height of each floor, and slabs thickness. After selecting the input parameters, the user has to define an adequate computational mesh discretisation. As part of this paper, all primary structural elements are slabs and walls, defined as shell elements (Fig. 1). One should note how the connections between perpendicular walls have been modelled as having infinite stiffnesses, considering that the building stock under investigation in the Croatian context did not show this as a relevant issue; however, the user can set it to a finite value if an accurate assessment is performed. A similar consideration regards the floors' stiffnesses.

To solve the eigenvalue problem, the user must define each load-bearing wall's material properties and the loads. The material is chosen from a database in Karamba [45] or can be defined manually based on the masonry typology [61]. Once the numerical model is automatically generated, Karamba 3D [57] performs the eigenfrequency analysis (Fig. 1).

3. Application of the proposed methodology to Zagreb

This section demonstrates the potential of the proposed workflow through its application to real case studies and allows exploring the panorama of the existing Croatian building stock.

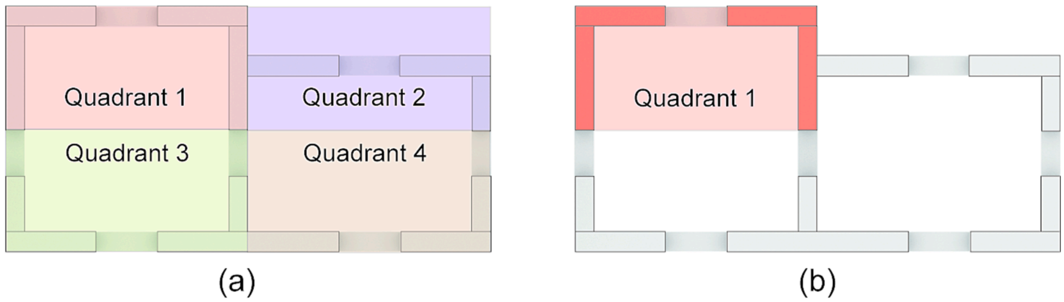

Fig. 5. Asymmetry check: (a) division of the plan into four quadrants, (b) area of the walls for Quadrant 1.

3.1. Case studies and building typology

The 1880 earthquake with M_w of 6.3 struck Zagreb, also known as The Great Zagreb earthquake, and caused significant damage to the city's building stock (over 1700 buildings were damaged). Architects and builders from all over the Austro-Hungarian Empire were called upon to help with the reconstruction process. Their actions significantly changed the city's appearance, with many of the old, narrow streets and buildings being completely re-designed. Reconstruction took several years, and some buildings were not fully restored until the early 1900s. Such a long period for the reconstruction included various architectural styles across this historical period to reconstruct Zagreb. Specifically, during the renovation and reconstruction after the earthquake, there was a shift toward a more uniform and standardised architectural style known as Historicism, followed by Secession and Modern movements in subsequent years.

- Historicism (1880–1914) was characterised by the use of traditional materials such as brick, stone, and stucco, as well as a preference for ornate facades, columns, and pediments. Buildings from this period often have asymmetrical facades and variable rooflines, reflecting a departure from the strict symmetry of earlier architectural styles. In addition, many buildings from this period have large windows and high ceilings.
- Secession (1895–1918), also known as Art Nouveau, was a popular style in Zagreb during the turn of the 20th century. The facades of Secession buildings are often asymmetrical and feature decorative elements such as wrought-iron balconies, floral patterns, and sculptural details. Structurally, the Secession in Zagreb was characterised by the introduction of reinforced concrete and steel materials, which created more complex forms and structures. The use of large windows, open floor plans and natural lighting was also common. Brick walls with wooden floors and roofs still predominated in residential buildings.
- In the interwar period, Modernism (1918–1940) became the predominant architectural style in Zagreb. It is characterised by using simple forms, clean lines and emphasis on functionality over ornamentation. In the residential sector, the load-bearing walls are still made of brick masonry, but the floor structures are increasingly built of concrete. The influence of Modernism in Zagreb continued well into the second half of the century.

While Historicism, Secessionism, and Modernism are perhaps the most known, several other architectural styles were prominent in the city until the 1940s. Indeed, different styles, such as Art Deco, National style, Neo-Baroque and Neo-Renaissance, also significantly influenced the city's architecture during this period. Moreover, many of these styles were sometimes applied simultaneously, resulting in buildings with a mixture of architectural elements.

It is worth clarifying that classifying buildings into distinct architectural styles allows exploring whether style changes correspond to new structural concepts, such as an increased percentage of walls or other design elements. For this work, the data on buildings and building typologies were obtained through archival blueprints and actual renovation projects of earthquake-damaged buildings, which were provided to the authors by structural engineering companies located in Zagreb.

3.2. Results from 103 buildings

The procedure described in Section 2 is tested on a total of 103 masonry buildings. These case studies encompass structures constructed during the period from 1864 to 1940, representing three distinct architectural styles, namely Historicism, Secession, and Modernism.

Each building under investigation features unreinforced masonry and timber floors/roofs, spanning 3 to 4 stories. The prevailing construction material utilised was brick masonry walls, units bonded with lime mortar, with varying thicknesses ranging from 0.75 m to 0.30 m. Notably, the thickness of these walls decreases as one ascends the height of the building. Regarding the reference coordinate system, the adopted assumption is that the *x*-direction is always parallel to the neighbouring street, as shown in Fig. 6.

The proposed tool offers rapid processing, enabling almost real-time results once the input parameters are precisely defined. The outcomes are presented through diagrams, effectively sorting buildings based on their construction year and grouping them according to distinct architectural styles.

Fig. 7a shows the results for the in-plan wall area. One should note that the PGA at the site is 0.26 g, which is higher than the maximum PGA shown in Table 1. In this case, for the sake of safety check, the minimum value of $p_{A,\min} = 5\%$ has been considered. In fact, during rapid post-earthquake assessments conducted in Croatia, the 5 % threshold was adopted as a reference value for a preliminary evaluation of the cross-sectional area as a percentage of the total floor area in order to categorise those buildings as unsafe. However, such a threshold could be modified based on the different structural engineering assumptions or interpretations that could change based on the boundary condition in which the buildings are being investigated.

The value of $p_{A,\min} = 5\%$ has not been respected for 12 % of the buildings in the *x*-direction and 16 % in the *y*-direction. It is worth noting that by changing the limit value of 10 % of the in-plane wall area, it has not been respected for about 75 % of the buildings in the *x*-direction and in the *y*-direction.

Fig. 7b presents the cumulative frequency analysis for the data obtained solely along the *x*-direction. It is evident that both the total curve (i.e. 'Global') and the individual curves, where buildings from different architectural periods are grouped into separate bins, clearly follow the same trend. This demonstrates that the architectural styles did not significantly affect this particular indicator.

Fig. 8a measures the percentage of shear walls that do not respect the rules outlined in Table 2. Specifically, the analysis examined minimum wall thickness (t_{ef}) and ratios (h_{ef}/t_{ef}) and (l/h). The suggested approach involves evaluating the geometric criteria for each wall in the floor plan and generating a list of walls that fail to meet these requirements. Consequently, any wall that does not meet even a single one of the three

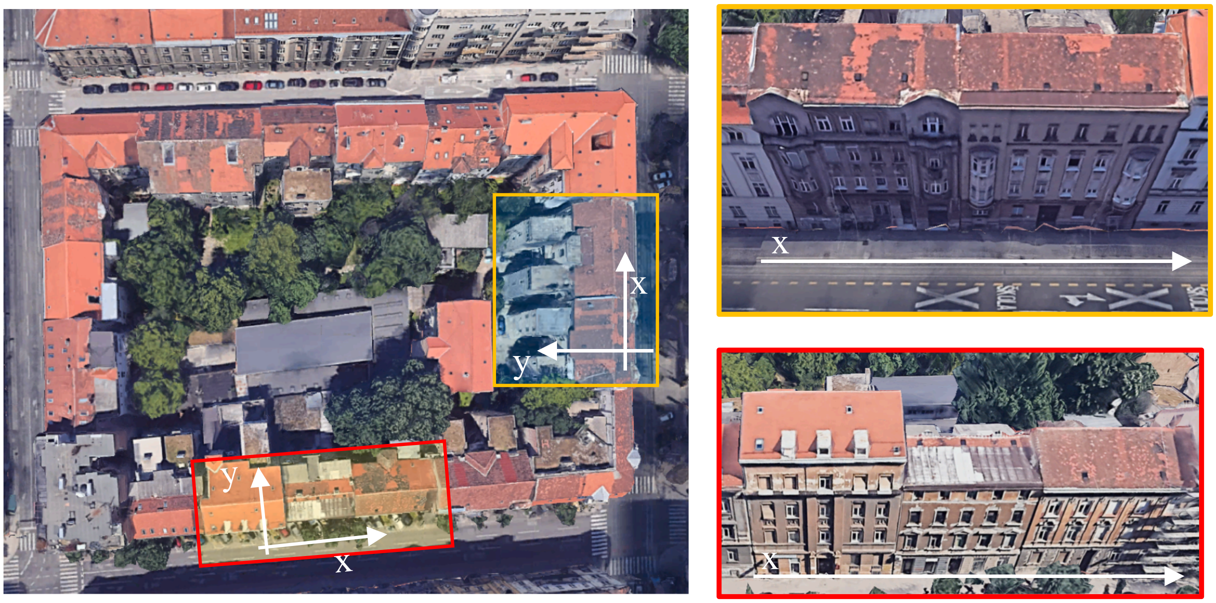

Fig. 6. Typical building block in Zagreb, the *x* axis is assumed parallel to the street.

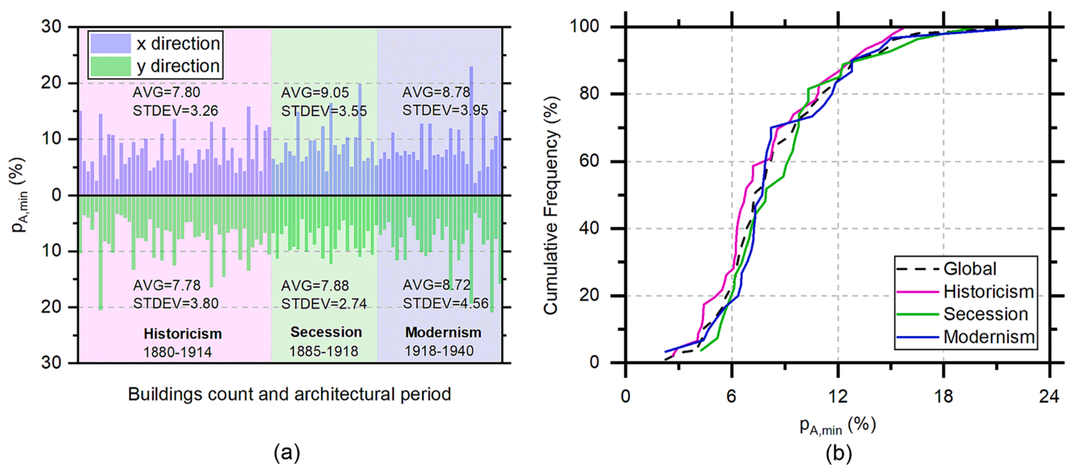

Fig. 7. Cross-sectional area as a percentage of the total floor area: (a) value for each building, (b) Cumulative frequency analysis.

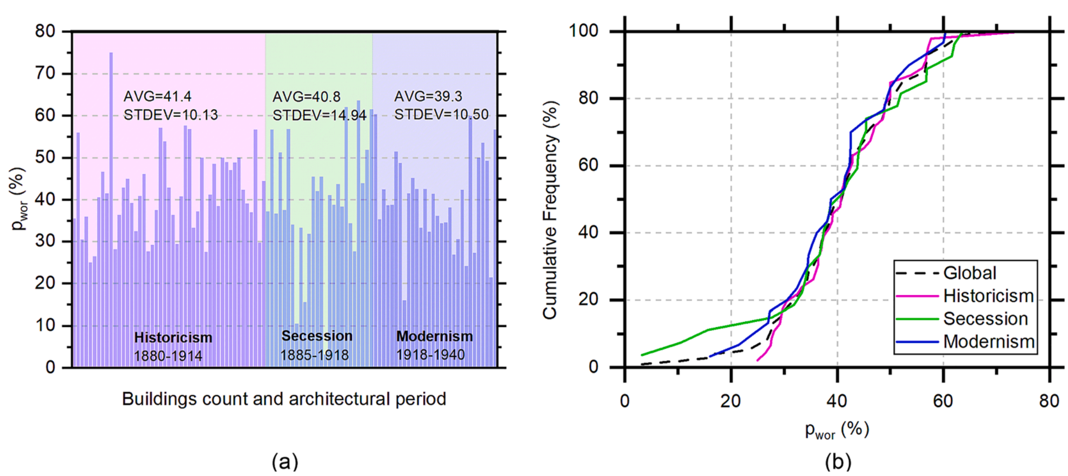

Fig. 8. Percentage of shear walls not complying with all three geometric requirements reported in Section 2.2.2: (a) value for each building, (b) Cumulative frequency analysis.

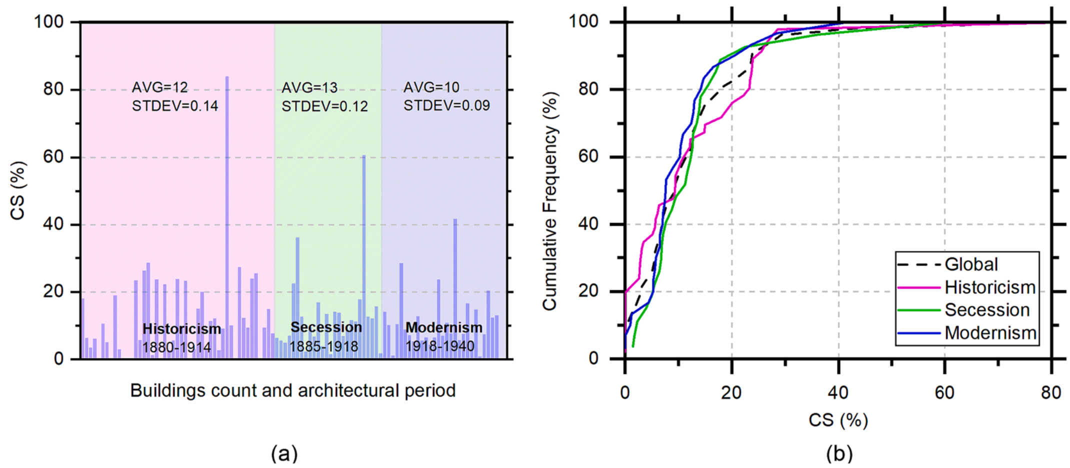

Fig. 9. Compact shape index as defined in Section 2.2.3: (a) value for each building, (b) Cumulative frequency analysis.

requirements is categorised as unsatisfactory.

For the majority of the cases, the minimum wall thickness criterion is the primary factor out of the three mentioned ones. This underscores the crucial role that wall thickness plays in ensuring the structural integrity of masonry buildings during earthquake events. In all case studies, more than 20 % of walls are thinner than they should be. Overall, 40 % of the walls do not meet the geometric requirements. It should also be noted that shear walls not conforming to the geometric requirements from Table 2 may be considered secondary seismic elements for an eventual FE structural analysis.

As demonstrated by the previous indicators, the cumulative frequency analysis in this case also reveals a distinct homogeneity among the samples, despite belonging to different architectural periods (Fig. 8b).

As illustrated in Fig. 9a, the buildings' compact shape analysis revealed that 24 % of the case studies do not satisfy the criterion described in Section 2.2.3.

Regarding the cumulative frequency analysis, Fig. 9b illustrates that during the Historicism period, the sample of buildings exhibits a lower level of homogeneity. This is evident from the curve having a slightly smaller slope compared to the other two architectural periods. The findings imply that architects during the Secession and Modernism periods exhibited a heightened awareness of the compact shape characteristics in residential buildings, resulting in a more standardised sample distribution within those specific periods.

Fig. 10a shows the buildings' plan aspect ratio, defined as a non-dimensional coefficient calculated as the ratio between the shorter and longer sides of the building. According to EN 1998–1, the minimum value allowable is $\lambda_{\min} = 0.25$, and it is satisfied the criterion that all buildings satisfy. Fig. 10b, demonstrates how the sample distribution is quite homogeneous across the three considered architectural periods.

Fig. 11a represents the results regarding the analysed buildings' uniformity in both directions. Even though EN 1998–1 [52] does not prescribe this requirement, such a check has been implemented in the proposed digital tool since asymmetric systems typically do not behave satisfactorily. As shown in Fig. 11a, the buildings under consideration exhibit a significant lack of symmetry in at least one direction, having an asymmetry index as defined in Section 2.2.4 greater than 0.1. Such a trend indicates possible large torsional effects due to the geometry irregularities. On the other hand, the cumulative frequency analysis underlines how the Modernism sample has overall smaller asymmetry index value, demonstrating how passing the years, designers were more concerned regarding this important structural indicator (Fig. 11b).

In this regard, Fig. 12a shows the distance vector between the centre of mass and the centre of stiffness of the buildings under consideration, expressed as a percentage of the building length in the *x* and *y* directions, respectively. Results are in agreement with those related to the asymmetry index since the eccentricity tends to be slightly reduced between the Historicism and the Modernism samples.

Finally, Fig. 13a shows the fundamental period, computed via the modal analysis for each building, expressed in seconds. A noticeable trend emerges, wherein the fundamental period tends to increase as

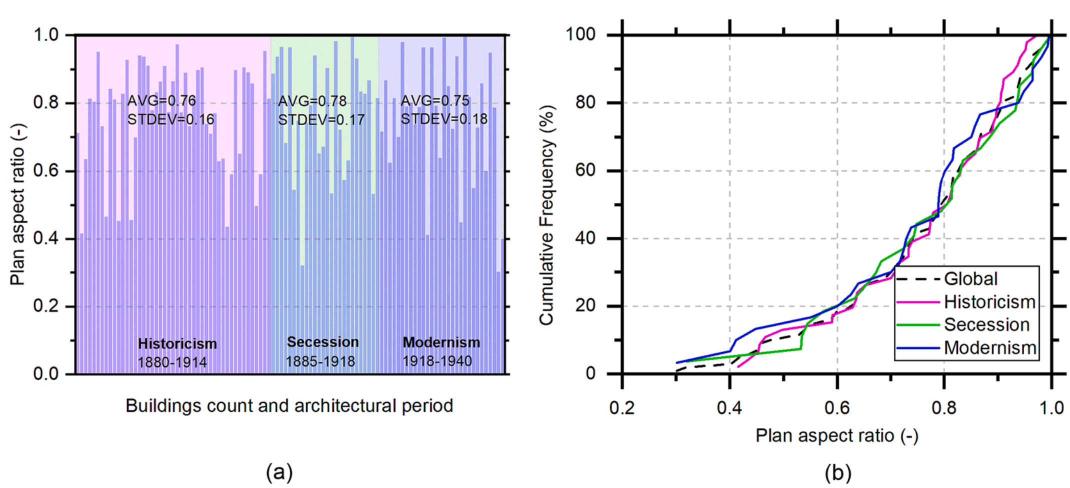

Fig. 10. Plan aspect ratio as defined in Section 2.2.3: (a) Plan aspect ratio value for each building, (b) Cumulative frequency analysis.

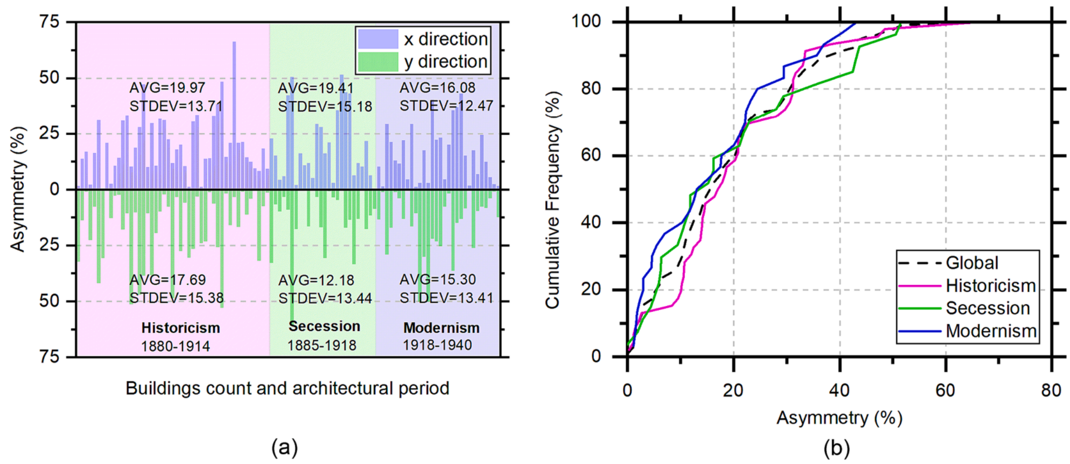

Fig. 11. Asymmetry index as defined in Section 2.2.4: (a) Asymmetry value for each building, (b) Cumulative frequency analysis.

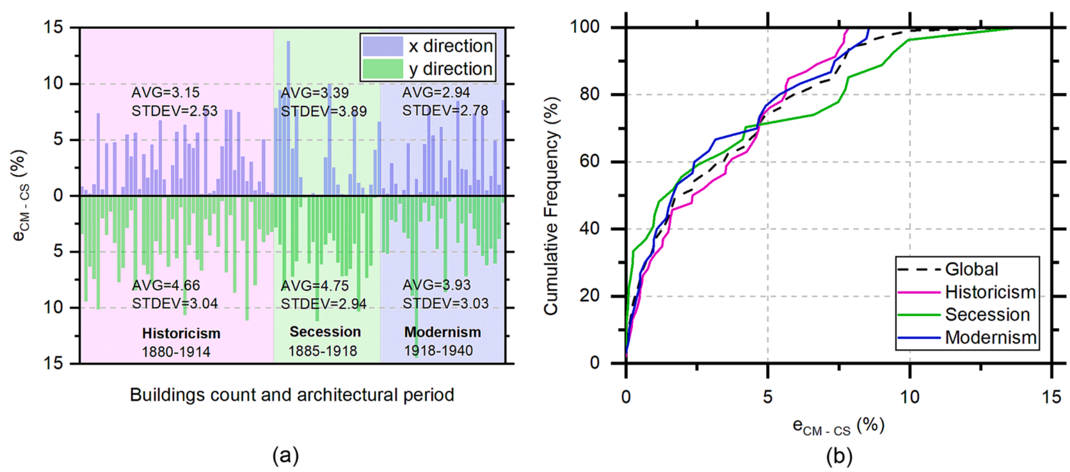

Fig. 12. Eccentricity centre of mass centre of stiffness: (a) value for each building, (b) Cumulative frequency analysis.

passing from Historicism to Secession to Modernism (Fig. 13a and b). This trend is attributed to the advancements in construction techniques seen during these architectural eras. Over time, better engineering practices have been adopted, resulting in improved connections between structural elements and enhanced material strength. As a result, architects have been able to construct resilient buildings, even if more slender, and thus capable of withstanding various dynamic forces and seismic events more effectively.

Overall, the sample of buildings analysed appears quite consistent in terms of indicators adopted to measure their seismic performance. In fact, buildings belonging samples of buildings belonging to different architectural period behaves similarly. Table 3 summarises the results, where the mean value and the standard deviation are reported for each indicator investigated.

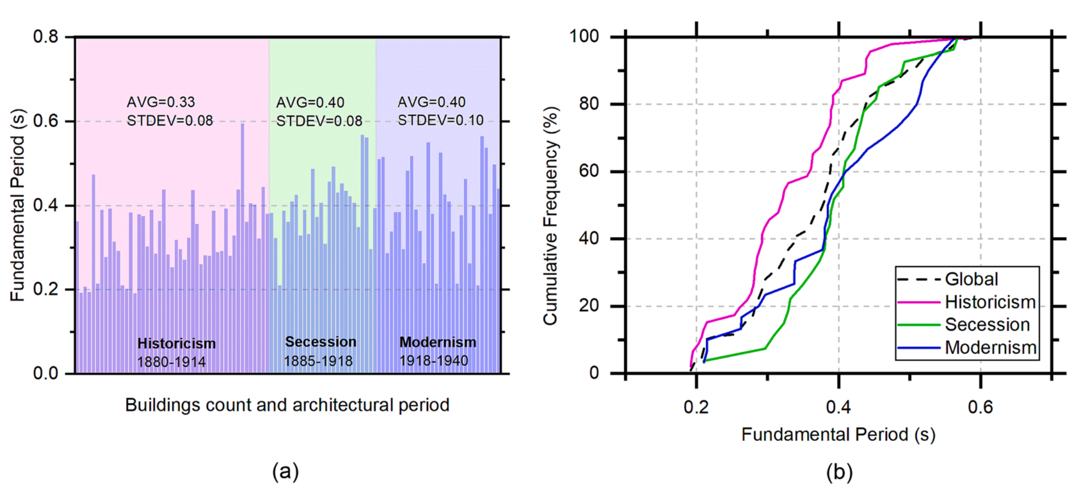

Fig. 13. Fundamental period: (a) Fundamental period value for each building, (b) Cumulative frequency analysis.

Table 3
Summarised results from 103 buildings.

Architectural period		In-plan wall area (%)		Asymmetry (%)		Eccentricity (%)		Plan aspect ratio (-)	Compact shape (%)	Walls do not meet the requirements (%)
		x	y	x	y	x	y			
Historicism	Avg	7.78	7.78	19.97	17.69	3.15	4.66	1.37	12	41.4
	StDev	3.26	3.80	13.71	15.38	2.53	3.04	0.36	0.14	10.13
Secession	Avg	9.05	7.88	19.41	12.18	3.39	4.75	1.39	13	40.8
	StDev	3.55	2.74	15.18	13.44	3.89	2.94	0.34	0.12	14.94
Modernism	Avg	8.78	8.72	16.08	15.30	2.94	3.93	1.46	10	39.3
	StDev	2.74	4.56	12.47	13.41	2.78	3.03	0.53	0.09	10.50

4. Conclusions

Digital processes and analytical methodologies, such as parametric design and visual programming, have great potential in the construction sector and structural design. This is because the methods are easy to apply, user-friendly, and efficient. Parametric design tools have proven useful in high-rise buildings' architectural and structural design but can also be used in various fields of structural engineering, such as the seismic assessment of existing masonry structures.

The recent earthquakes in Croatia have highlighted the need for efficient post-earthquake assessment tools. Therefore, this paper presents an easy-to-use approach to check seismic safety requirements and indicators set by EN 1998–1 [52]. The proposed method enables efficient assessment of the buildings' geometric characteristics and gives an overview to a designer if the existing masonry building is safe according to the adopted standards. One can note that a significant advantage of the proposed methodology for assessing masonry buildings' seismic vulnerability is its flexibility and adaptability to different norms and standards. The procedure is integrated into an easy-to-use digital tool through a visual program implemented in Grasshopper [55]. In order to perform the assessments, the user needs to define, along the floor layout, only a few additional pieces of information, such as the number of storeys, slab and wall thicknesses. Once the knowledge of some data for a certain problem is achieved, the analysis and printing of the results are almost instantaneous. The main automated outputs are symmetry check, compactness, percentage of the walls in two directions, building slenderness, vector of eccentricity between the centre of mass and stiffness and wall thicknesses. Furthermore, global dynamic behaviour is identified through modal analysis. Depending on the model's degree of detail, the assessment can be more accurate and upgrading the model is a continuous research goal.

The proposed procedure has been tested by assessing 103 residential buildings located in Zagreb. Analysing the structural indicators allows practitioners to identify the similarities and differences in structural design across the three different periods and calibrate appropriate retrofitting solutions to improve seismic resistance.

One should note how the proposed approach does not aim to perform an accurate seismic assessment but rather to define strategies and help stakeholders to drive the decision-making regarding investment plans. Furthermore, this tool has the advantage of giving professionals a preliminary idea regarding the structural behaviour of the structure, driving decisions regarding investment in destructive or non-destructive tests to perform a proper seismic assessment of masonry structures.

In terms of future development, a module to input the material characteristics obtained by destructive or semi-destructive methods can easily be incorporated into existing models. An exciting component of the construction profession would be upgrading the model with different ways and materials to reinforce the existing structure (e.g. fibre, fibre-reinforced polymers, etc.). On the sustainability side, an additional module that calculates the amount of CO_2 embodied (or removed) would be useful for presenting European sustainable design goals.

CRediT authorship contribution statement

Mislav Stepinac: Methodology, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Karlo Ožić:** Methodology, Validation, Writing – original draft. **Anthony Ninčević:** Methodology, Validation. **Marco Francesco Funari:** Methodology, Validation, Supervision, Writing – original draft, Writing – review & editing. **Paulo B. Lourenço:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] P. B. Lourenço, "The ICOMOS methodology for conservation of cultural heritage buildings: Concepts, research and application to case studies," in *REHAB 2014 - Proceedings of the International Conference on Preservation, Maintenance and Rehabilitation of Historical Buildings and Structures*, Green Lines Institute for Sustainable Development, Mar. 2014, pp. 945–954. doi: 10.14575/gl/rehab2014/095.

[2] Blyth A, et al. Assessment and mitigation of seismic risk at the urban scale: an application to the historic city center of Leiria, Portugal. Bulletin of Earthquake Engineering 2020;18(6):2607–34. https://doi.org/10.1007/s10518-020-00795-2.

[3] Mebarki A, Boukri M, Laribi A, Farsi M, Belazougui M, Kharchi F. Seismic vulnerability: Theory and application to Algerian buildings. Journal of Seismology 2014;18(2):331–43. https://doi.org/10.1007/s10950-013-9377-0.

[4] Simões PBLAG, Bento R, Lagomarsino S, Cattari S. Seismic assessment of nineteenth and twentieth centuries URM buildings in Lisbon: structural features and derivation of fragility curves. Bulletin of Earthquake Engineering 2019.

[5] S. B. Giorgia Predari, Lorenzo Stefanini, Marko Marinković, Mislav Stepinac, "Adriseismic Methodology for Expeditious Seismic Assessment of Unreinforced Masonry Buildings." buildings, 2023. doi: ttps://doi.org/10.3390/buildings13020344.

[6] S. R. Gonzalez-Drigo, A. Avila-Haro, A. H. Barbat, L. G. Pujades, Y. F. Vargas and S. C. Lagomarsinoc, "Modernist Unreinforced Masonry (URM) Buildings of Barcelona: Seismic Vulnerability and Risk Assessment." pp. 214–230, 2014. doi: http://dx.doi.org/10.1080/15583058.2013.766779.

[7] Marius Mosoarca AA, Onescu I, Onescu E. Seismic vulnerability assessment methodology for historic masonry buildings in the near-field areas. Engineering Failure Analysis 2020. https://doi.org/10.1016/j.engfailanal.2020.104662.

[8] Aleksandar Zlateski TMF, Lucesoli M, Bernardini G. Integrating human behaviour and building vulnerability for the assessment and mitigation of seismic risk in historic centres: Proposal of a holistic human-centred simulation-based approach. International Journal of Disaster Risk Reduction 2020.

[9] P. B. L. Federico Romis, Silvia Caprili, Walter Salvatore, Tiago M. Ferreira, "An Improved Seismic Vulnerability Assessment Approach for Historical Urban Centres: The Case Study of Campi Alto di Norcia, Italy." Applied sciences, 2021. doi: https://doi.org/10.3390/app11020849.

[10] Wilson R, Szabó S, Funari MF, Pulatsu B, Lourenço PB. A Comparative Computational Investigation on the In-Plane Behavior and Capacity of Dry-Joint URM Walls. Int J Archit Herit 2023:1–22.
[11] Sansoni C, da Silva LCM, Marques R, Pampanin S, Lourenço PB. SLaMA-URM method for the seismic vulnerability assessment of UnReinforced Masonry structures: Formulation and validation for a substructure. J Build Eng 2023;63: 105487. https://doi.org/10.1016/j.jobe.2022.105487.
[12] Franchi A, Napoli P, Crespi P, Giordano N, Zucca M. Unloading and reloading process for the earthquake damage repair of ancient Masonry columns: The case of the Basilica di Collemaggio. Int J Archit Herit 2022;16(11):1683–98.
[13] Pulatsu B, Funari MF, Malomo D, Gonen S, Parisi F. Seismic assessment of URM pier spandrel systems via efficient computational modeling strategies. Bulletin of Earthquake Engineering 2023:1–24.
[14] Vadalà F, Cusmano V, Funari MF, Caliò I, Lourenço PB. On the use of a mesoscale masonry pattern representation in discrete macro-element approach. J Build Eng 2022;50:104182. https://doi.org/10.1016/j.jobe.2022.104182.
[15] Maio R, Ferreira TM, Vicente R, Estêvão J. Seismic vulnerability assessment of historical urban centres: Case study of the old city centre of Faro, Portugal. Journal of Risk Research 2016;19(5):551–80.
[16] Ferreira TM, Vicente R, Da Silva JARM, Varum H, Costa A. Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal. Bulletin of Earthquake Engineering 2013;11(5):1753–73.
[17] R. Vicente, S. Parodi, S. Lagomarsino, H. Varum, and J. A. R. M. Silva, "Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal," *Bull. Earthq. Eng. 2010 94*, vol. 9, no. 4, pp. 1067–1096, Dec. 2010, doi: 10.1007/S10518-010-9233-3.
[18] D'altri AM, et al. "Modeling Strategies for the Computational Analysis of Unreinforced Masonry Structures. Review and Classification,“ 2020;27:1153–85. https://doi.org/10.1007/s11831-019-09351-x.
[19] Silva LC, Lourenço PB, Milani G. Derivation of the out-of-plane behaviour of masonry through homogenisation strategies: Micro-scale level. Computers and Structures 2018;209:30–43. https://doi.org/10.1016/j.compstruc.2018.08.013.
[20] Hoveidae N, Fathi A, Karimzadeh S. Seismic damage assessment of a historic masonry building under simulated scenario earthquakes: A case study for Arge-Tabriz. Soil Dynamics and Earthquake Engineering 2021;147:106732. https://doi.org/10.1016/j.soildyn.2021.106732.
[21] Roca P, Cervera M, Pelà L, Clemente R, Chiumenti M. Continuum FE models for the analysis of Mallorca Cathedral. Engineering Structures Jan. 2013;46:653–70. https://doi.org/10.1016/j.engstruct.2012.08.005.
[22] M. F. Funari, L. C. Silva, N. Savalle, and P. B. Lourenço, "A concurrent micro/macro FE-model optimised with a limit analysis tool for the assessment of dry-joint masonry structures," *Int. J. Multiscale Comput. Eng.*, vol. In Press, 2022, doi: 10.1615/IntJMultCompEng.2021040212.
[23] da Silva LCM, Milani G, Lourenço PB. Probabilistic-based discrete model for the seismic fragility assessment of masonry structures. Structures 2023;52:506–23. https://doi.org/10.1016/j.istruc.2023.04.015.
[24] Mosoarca M, Fofiu M, Onescu I. Failure mechanism of historic churches in Gorj county for shallow seismic action. Engineering Failure Analysis 2023;152:107502.
[25] Onescu I, Onescu E, Mosoarca M. Seismic risk assessment and crisis management for historical buildings in Timisoara. J Build Eng 2023;72:106665.
[26] Mosoarca M, Onescu I, Onescu E, Anastasiadis A. Seismic vulnerability assessment methodology for historic masonry buildings in the near-field areas. Engineering Failure Analysis 2020;115:104662.
[27] Mosoarca M, Onescu I, Onescu E, Azap B, Chieffo N, Szitar-Sirbu M. Seismic vulnerability assessment for the historical areas of the Timisoara city, Romania. Engineering Failure Analysis 2019;101:86–112.
[28] Karimzadeh S, Funari MF, Szabó S, Hussaini SMS, Rezaeian S, Lourenço PB. Stochastic simulation of earthquake ground motions for the seismic assessment of monumental masonry structures: Source-based vs site-based approaches. Earthquake Engineering and Structural Dynamics 2023.
[29] Lemos JV. Discrete element modeling of masonry structures. Int J Archit Herit 2007;1(2):190–213. https://doi.org/10.1080/15583050601176868.
[30] J. V. Lemos, "Discrete element modeling of the seismic behavior of masonry construction," *Buildings*, vol. 9, no. 2, 2019, doi: 10.3390/buildings9020043.
[31] Bui TT, Limam A, Sarhosis V, Hjiaj M. Discrete element modelling of the in-plane and out-of-plane behaviour of dry-joint masonry wall constructions. Engineering Structures 2017;136(October):277–94. https://doi.org/10.1016/j.engstruct.2017.01.020.
[32] Kim J, Lorenzoni F, Salvalaggio M, Valluzzi MR. Seismic vulnerability assessment of free-standing massive masonry columns by the 3D Discrete Element Method. Engineering Structures 2021;246:113004. https://doi.org/10.1016/j.engstruct.2021.113004.
[33] S. Gonen, B. Pulatsu, E. Erdogmus, P. B. Lourenço, and S. Soyoz, "Effects of spatial variability and correlation in stochastic discontinuum analysis of unreinforced masonry walls," *Constr. Build. Mater.*, vol. 337, no. September 2021, p. 127511, Jun. 2022, doi: 10.1016/j.conbuildmat.2022.127511.
[34] Pulatsu B, et al. Probabilistic approach to assess URM walls with openings using discrete rigid block analysis (D-RBA). J Build Eng 2022;61:105269. https://doi.org/10.1016/j.jobe.2022.105269.
[35] Pulatsu B, Gonen S, Funari MF, Parisi F. Spatial stochastic D-RBA and limit equilibrium analysis of unreinforced masonry pier-spandrel structures. Engineering Structures 2023;296:116897.
[36] Gonen S, Soyoz S. Reliability-based seismic performance of masonry arch bridges. Structure and Infrastructure Engineering 2021:1–16. https://doi.org/10.1080/15732479.2021.1918726.
[37] N. Savalle, E. Vincens, and S. Hans, "Pseudo-static scaled-down experiments on dry stone retaining walls: Preliminary implications for the seismic design," *Eng. Struct.*, vol. 171, no. October 2017, pp. 336–347, 2018, doi: 10.1016/j.engstruct.2018.05.080.
[38] Malomo D, DeJong MJ, Penna A. Influence of Bond Pattern on the in-plane Behavior of URM Piers. Int J Archit Herit Dec. 2019;00(00):1–20. https://doi.org/10.1080/15583058.2019.1702738.
[39] Simon J, Bagi K. Discrete element analysis of the minimum thickness of oval masonry domes. Int J Archit Herit 2016;10(4):457–75. https://doi.org/10.1080/15583058.2014.996921.
[40] V. Sarhosis, J. V Lemos, and K. Bagi, "Chapter 13 - Discrete element modeling," in *Woodhead Publishing Series in Civil and Structural Engineering*, B. Ghiassi and G. B. T.-N. M. of M. and H. S. Milani, Eds., Woodhead Publishing, 2019, pp. 469–501. doi: https://doi.org/10.1016/B978-0-08-102439-3.00013-0.
[41] Lourenço PB, Silva LC. Computational applications in masonry structures: From the meso-scale to the super-large/super-complex. International Journal for Multiscale Computational Engineering 2020;18(1):1–30. https://doi.org/10.1615/IntJMultCompEng.2020030889.
[42] D. Malomo and M. J. DeJong, "A Macro-Distinct Element Model (M-DEM) for simulating the in-plane cyclic behavior of URM structures," *Eng. Struct.*, vol. 227, no. April 2020, p. 111428, 2021, doi: 10.1016/j.engstruct.2020.111428.
[43] A. M. D'Altri, N. Lo Presti, N. Grillanda, G. Castellazzi, S. de Miranda, and G. Milani, "A two-step automated procedure based on adaptive limit and pushover analyses for the seismic assessment of masonry structures," *Comput. Struct.*, vol. 252, p. 106561, Aug. 2021, doi: 10.1016/j.compstruc.2021.106561.
[44] D. Malomo and M. J. DeJong, "A Macro-Distinct Element Model (M-DEM) for out-of-plane analysis of unreinforced masonry structures," *Eng. Struct.*, vol. 244, no. April, p. 112754, 2021, doi: 10.1016/j.engstruct.2021.112754.
[45] M. F. Funari, L. C. Silva, E. Mousavian, and P. B. Lourenço, "Real-time Structural Stability of Domes through Limit Analysis: Application to St. Peter's Dome," *https://doi.org/10.1080/15583058.2021.1992539*, pp. 1–23, Oct. 2021, doi: 10.1080/15583058.2021.1992539.
[46] Cascini L, Gagliardo R, Portioli F. LiABlock_3D: A Software Tool for Collapse Mechanism Analysis of Historic Masonry Structures. Int J Archit Herit 2020;14(1): 75–94. https://doi.org/10.1080/15583058.2018.1509155.
[47] De Felice G, Giannini R. Out-of-plane seismic resistance of masonry walls. Journal of Earthquake Engineering 2001;5(2):253–71. https://doi.org/10.1080/13632460109350394.
[48] M. F. Funari, B. Pulatsu, S. Szabó, and P. B. Lourenço, "A Solution for the Frictional Resistance in Macro-Block Limit Analysis of Non-periodic Masonry," *STRUCTURES*, 2022.
[49] Szabó S, Funari MF, Pulatsu B, Lourenço PB. Lateral capacity of URM walls: a parametric study using macro and micro limit analysis predictions. Applied Sciences 2022;12(21):10834.
[50] Giuffré A. "A Mechanical Model for Statics and Dynamics of Historical Masonry Buildings," in *Protection of the Architectural Heritage Against Earthquakes*. Springer Vienna 1996:71–152. https://doi.org/10.1007/978-3-7091-2656-1_4.
[51] D'Ayala D, Speranza E. Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings. Earthquake Spectra 2003;19(3): 479–509. https://doi.org/10.1193/1.1599896.
[52] "EN 1998-1 (2004) Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings (EN 1998-1:2004); European Committee for Standardization (CEN): Brussels, Belgium, 2004.".
[53] "Eurocode 8: Design of Structures for Earthquake Resistance—Part 3: Assessment and Retrofitting of Buildings." European Committee for Standardization Brussels, Belgium, 2005.
[54] "Rhino - Rhinoceros 3D," 2020. https://www.rhino3d.com/(accessed Jul. 09, 2021).
[55] "Grasshopper - algorithmic modeling for Rhino," 2020. https://www.grasshopper3d.com/(accessed Jun. 15, 2021).
[56] Funari MF, Mehrotra A, Lourenço PB. A tool for the rapid seismic assessment of historic masonry structures based on limit analysis optimisation and rocking dynamics. Applied Sciences Feb. 2021;11(3):1–22. https://doi.org/10.3390/app11030942.
[57] Preisinger C, Heimrath M. Karamba—A toolkit for parametric structural design. Structural Engineering International 2014;24(2):217–21.
[58] Szabó S, Funari MF, Lourenço PB. Masonry patterns' influence on the damage assessment of URM walls: Current and future trends. Dev Built Environ 2023;13: 100119. https://doi.org/10.1016/j.dibe.2023.100119.