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Assessment of Local Collapse in Masonry Walls through Visual Programming: A Full-Scale Benchmark in the Historical Center of Bova, Italy

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Abstract. This paper addresses the challenge of assessing and preserving the structural safety of traditional masonry constructions by testing a simplified numerical method for masonry walls collapse prediction, proposed by the authors in the previous paper in Part. 1 of this volume. The method, developed in a visual scripting environment, incorporates linear programming optimization within a CAD-integrated platform, Grasshopper with Python, enabling the modeling of geometry, load definition and collapse load multiplier calculation. Through a real masonry building located in Bova, the proposed tool is evaluated for its practicality and effectiveness in facilitating fast and intuitive structural assessments, particularly in post-earthquake scenarios or severe damaged urban contexts. The results demonstrate the efficiency of the proposed approach to support rapid decision-making while ensuring the reliability of safety evaluations in masonry structures.

Keywords: masonry wall collapse · limit load prediction · visual programming · full-scale benchmark

1 Introduction

The preservation of Italian cultural heritage, particularly its masonry constructions, involves different factors that affect structural integrity. Material properties, construction methods and external forces, like seismic activity and environmental conditions, all contribute to the durability of masonry buildings. Understanding the interaction of these factors is essential for assessing vulnerability and developing strategies to preserve these historic structures (Giuffrè, 1996).

In recent years, among many structural analysis approaches of the relevant literature, limit analysis has gained popularity in professional practice through its integration into visual scripting environments, enabling efficient safety assessments of masonry

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structures. Early work (Block, 2009) introduced Thrust Network Analysis in CAD, later refined by Rippmann et al. (2012) for free-form vault design. In Funari et al. (2020) and Funari et al. (2021) a Grasshopper tool in Rhinoceros is developed for real-time collapse mechanism exploration. In Mousavian et al. (2021) a Grasshopper plugin for out-of-plane collapse in multi-story walls is proposed. A recent and interesting study on this topic is also proposed by Massafra et al. (2025), where a reverse engineering-based method is introduced for analyzing displacements and deformations in historical masonry buildings using terrestrial laser scanning and visual programming. These advancements highlighted the effectiveness of limit analysis in visual scripting environments for both design and heritage conservation.

This work, coupling limit analysis with CAD tools, using Grasshopper for real-time safety evaluations of masonry walls, presents a validation of a visual programming tool for limit analysis of masonry walls proposed in a previous paper by the authors in Part 1 of this volume. The promoted tool combines limit analysis with linear programming to identify collapse mechanisms and load multipliers. The parametric inputs, carried on within a visual scripting environment, allow users to quickly assess how changes in material, geometry and loading affect structural behavior, so testing numerically restoration or emergency strategies.

A full-scale benchmark is analyzed, precisely a masonry structure building located in the small village of Bova in Calabria. The surveyed structure, modeled in a CAD environment, is analyzed to assess the potential collapse mechanisms and the structural vulnerability. The obtained results seem to validate the practical applicability of the tested visual programming tool.

2 Visual Programming for Limit Analysis

2.1 Main Assumptions

By hypothesis, the crack pattern of the main walls constituting the examined building is not known a priori. Such circumstance is very common when facing real problems in which the geometry and paths of the cracks are not clear or they are not conducible to a fixed categorized collapse mechanism. This happens also after a detailed survey such as the one carried out in the present study where the benchmark building was surveyed using a drone and a laser scanner.

In such cases the promoted visual scripting results very effective as, in fact, it allows to analyze very quickly different possible collapse mechanisms.

In particular, by adopting a structural model based on rigid blocks and following Heyman's assumption, two collapse scenarios are considered for a masonry wall macro-element with fixed hinge A and roller B (Fig. 1(a,b)), reflecting crack patterns observed in situ.

As explained in the above quoted paper by the authors, in the first scenario (Fig. 1(a)), the macro-block rotates about hinge A and the collapse load multiplier, say α, can be obtained directly from the virtual-work balance equation, as demonstrated for the simple overturning mechanism of a masonry macro-element (Cifani, et al., 2006). In the second scenario (Fig. 1(b)), an internal hinge C appears at an undetermined height, dividing the macro-element into two sub-elements. Because the location of hinge C is unknown, the

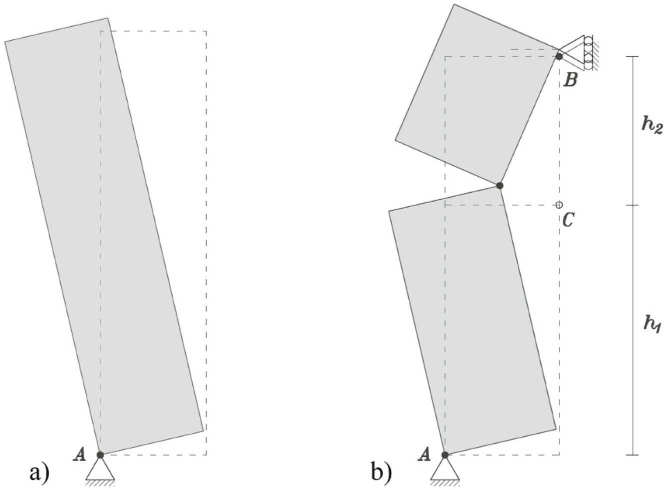


Fig. 1. Schematic representation of a masonry macro-element collapse mechanism: (a) a single macro-element rotating around the external hinge A; (b) two interconnected macro-elements rotating around the internal hinge C, whose position is unknown

virtual-work balance equation alone is not sufficient and must be supplemented by an optimization algorithm to identify the most critical collapse configuration. The resolutive optimization problem seeks the minimum collapse multiplier α under a constraint equation guaranteeing that the internal hinge lies within the block rather than at its extremity. The resulting linear-programming formulation is solved in Python using the linprog function.

2.2 Visual Programming Framework

The limit analysis optimization is implemented within Grasshopper, the visual scripting environment of Rhinoceros, enabling direct import of CAD geometries for masonry walls. This integration delivers an interactive workflow in which the kinematic limit analysis automatically identifies the most probable collapse mechanism and computes the corresponding load multiplier in real time. Figure 2 outlines the process illustrated using one possible case with the corresponding collapse mechanism identified as the vertical bending of one main wall.

The process can be divided into three main sections and begins by defining the geometry of the macro-elements by importing the CAD model into Grasshopper (left sketch in Fig. 2). The user selects the relevant wall cross-section and specifies boundary conditions, applied loads, and material properties. In the second section (central sketch of Fig. 2), the script automatically detects the wall cross-section and extracts all necessary geometric information, including centroid locations, self-weight distributions, and dimensions. Then, the Python script joins all inputs and executes the limit-analysis optimization. In the third final section (right sketch of Fig. 2), the tool outputs the collapse-load multiplier and the related collapse mechanism. It is worth noting that, users can adjust inputs

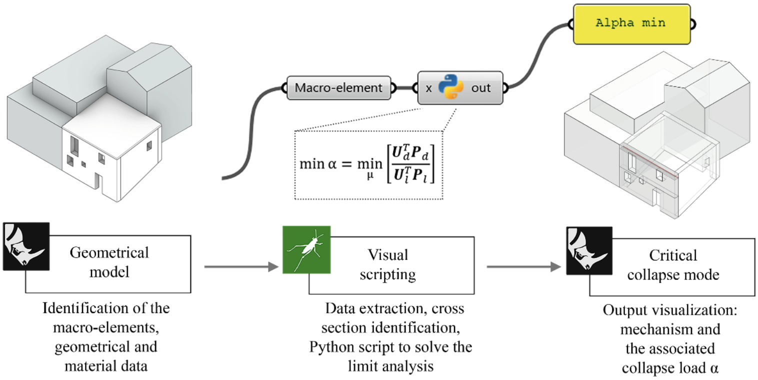


Fig. 2. Workflow of the visual scripting approach for performing limit analysis on a double-story masonry façade with a vertical bending mechanism

interactively and observe real-time updates, enabling rapid assessment of how changes in geometry, material properties, or load conditions influence collapse risk.

The mechanisms considered in the implementation of the visual scripting tool include the most common out-of-plane collapse mechanisms for masonry walls. Such mechanisms arise when external actions, most notably seismic forces, overcome the equilibrium of an entire wall or of a large wall segment. Their activation depends on factors governing out-of-plane response, including the quality of orthogonal wall connections, wall-to-wall interactions, roof configuration, opening layout, loads from upper stories, and even the position of the building within the urban fabric.

These mechanisms are here divided into *overturning mechanisms* and *bending mechanisms*. Overturning mechanisms may be *simple*, involving rotation of a single wall segment, or *composed*, in which adjacent orthogonal wall portions are also dragged into motion; each can occur at one story or span multiple stories. Bending mechanisms are categorized by the orientation of the bending plane, *vertical* or *horizontal* and likewise may affect a single level or multiple levels of the structure.

The study by Lasorella et al. (2025) schematically illustrates the eight out-of-plane collapse mechanisms, based on the classification of Milano et al. (2009): simple overturning of a single-story wall; simple overturning of a multi-story wall; composed overturning of a single-story wall; composed overturning of a multi-story wall; composed overturning of a corner wall; vertical bending of a single-story wall; vertical bending of a multi-story wall; horizontal bending of a single-story wall.

3 The Benchmark Building of Bova

The analyzed building is located in Bova a small village belonging to the so-called Grecanic area of Calabria at 820 m above sea level, (Fig. 3(a)). The benchmark building is the one evidenced in Fig. 3(b), precisely, a masonry structure located in one of the most critical areas of Bova. Following an initial inspection and degradation analysis, the building has been identified as deteriorated; it is a two-stories masonry structure that has been abandoned and in a state of evident decay.

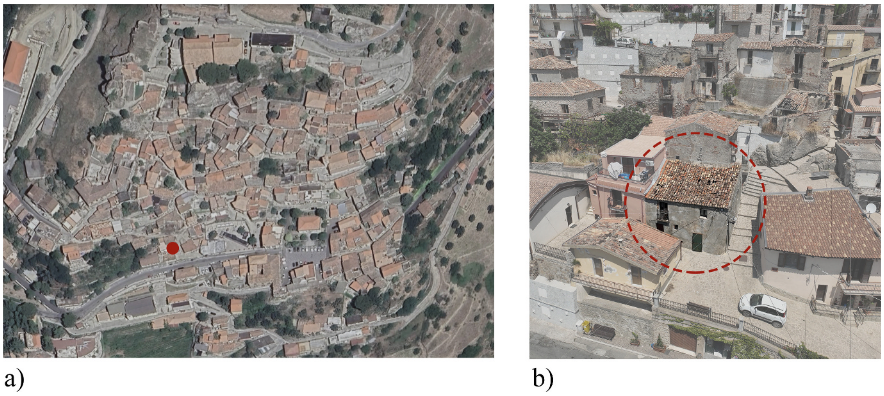


Fig. 3. a) municipality of Bova, with the red dot indicating the location of the case study building; b) a closer view of the case study is provided, highlighting the building's structural surrounding context.

The survey was conducted using a drone and a laser scanner, which generated a point cloud from which the 3D model was derived in a CAD environment. The macro-elements potentially involved in local collapse mechanisms were then identified looking at few visible cracks in the main walls. Regarding the material and geometric parameters; the assumed masonry specific weight is 18 kN/m^3; the wall thickness is 0.5 m. These values were estimated due to limited internal access, at only certain points, such as windows and doors, being there measurable. The building has a façade height of 5 m and a length of 7.5 m, with a lateral wall length of 6.1 m.

As shown in the following analyses, two macro-elements were identified involving the main façade and the sidewall, as they are the most exposed to possible collapse. For each macro-element, the geometric parameters and self-weights W were automatically extracted from the CAD input. The weight P_s from the roof and the second-floor slab are considered. The weights were estimated taking into account of a wooden floor with a thickness of 0.30 m, supported by the front wall. Ten collapse mechanisms have been considered. They are described hereafter with the aid of Figs. 4–13.

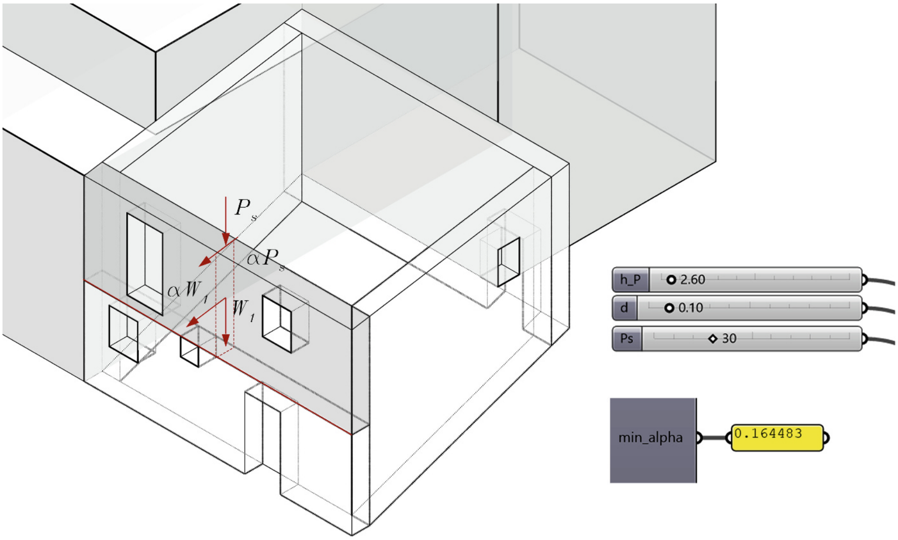
Figure 4 shows the *simple overturning* case involving the *front wall of the upper floor*. In this scenario, the acting loads include the self-weight of the wall, its horizontal component proportional to the collapse multiplier, and the weight of the single-pitched roof. The collapse multiplier in this case has a value of 0.16. While, Fig. 5 shows the *simple overturning* mechanism involving the *entire front façade*. In this case, the self-weight of the lower floor wall and the interfloor slab are also considered. The collapse multiplier for this scenario is 0.06.

In Fig. 6 and Fig. 7, the *composed overturning* mechanisms for the *upper floor and* the *entire façade* are analyzed. The geometry of the involved sidewall portion is assumed. The obtained collapse multipliers are 0.17 and 0.15, respectively, higher than those of the corresponding simple overturning cases.

In Fig. 8, the *overturning* mechanism *at the corner* between the walls converging from the front façade and the sidewall is analyzed, with a collapse multiplier value of 0.22. Finally, the *vertical bending* mechanism involving the *main façade* was examined

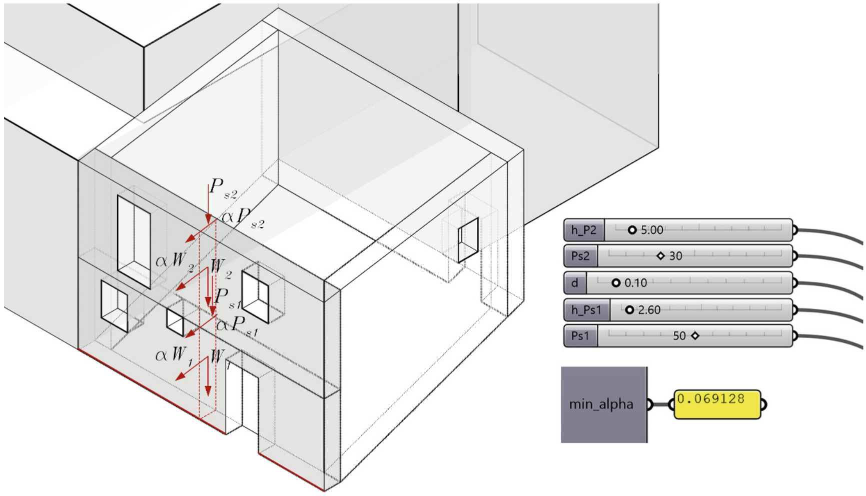
(Fig. 9). The hinge formed at the upper floor, and in this case, the collapse multiplier is 0.24.

Moreover, other analyzed mechanisms are those involving the *sidewall of the building*. As before, in Fig. 10, the *simple overturning* case is analyzed with a collapse multiplier of 0.10, and the *composed overturning* case (Fig. 11) with a multiplier of 0.12. The *corner overturning* in Fig. 12 between the sidewall and the facade wall is then examined, yielding a collapse multiplier of 0.36. The final analyzed case in Fig. 13 is the *vertical bending* that furnishes a collapse multiplier of 0.37, with the hinge forming near the top of the wall.



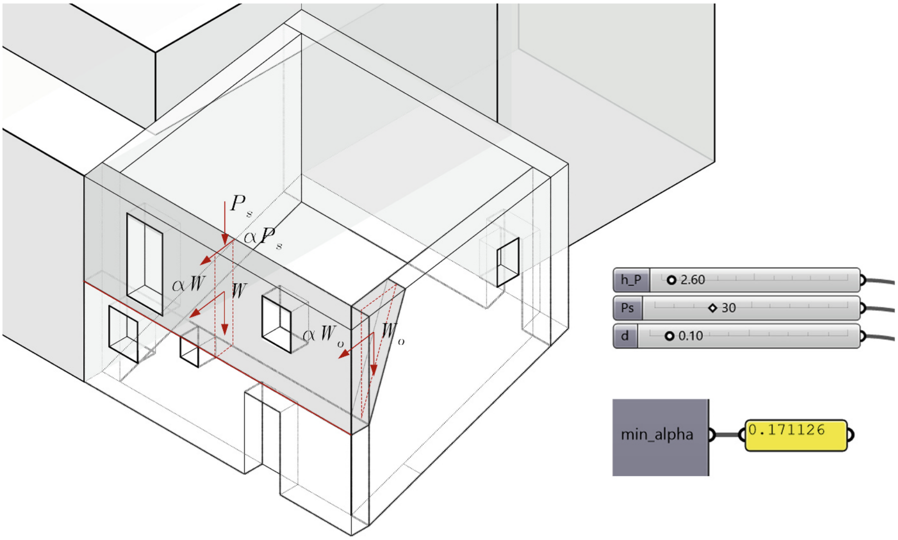
h_P 2.60
d 0.10
Ps 30
min_alpha 0.164483

Fig. 4. Output of the visual scripting tool, showing the collapse load multiplier value for the single-story simple overturning mechanism under the loading conditions: W (self-weight) and P_s (load exerted by the roof)



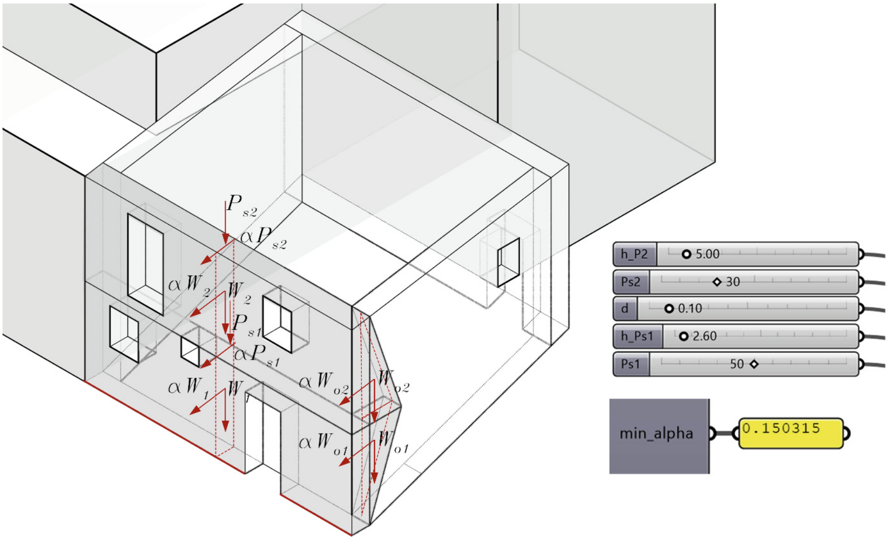
h_P2 5.00
Ps2 30
d 0.10
h_Ps1 2.60
Ps1 50
min_alpha 0.069128

Fig. 5. Output of the visual scripting tool, showing the collapse load multiplier value for the two-story simple overturning mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof and floor)



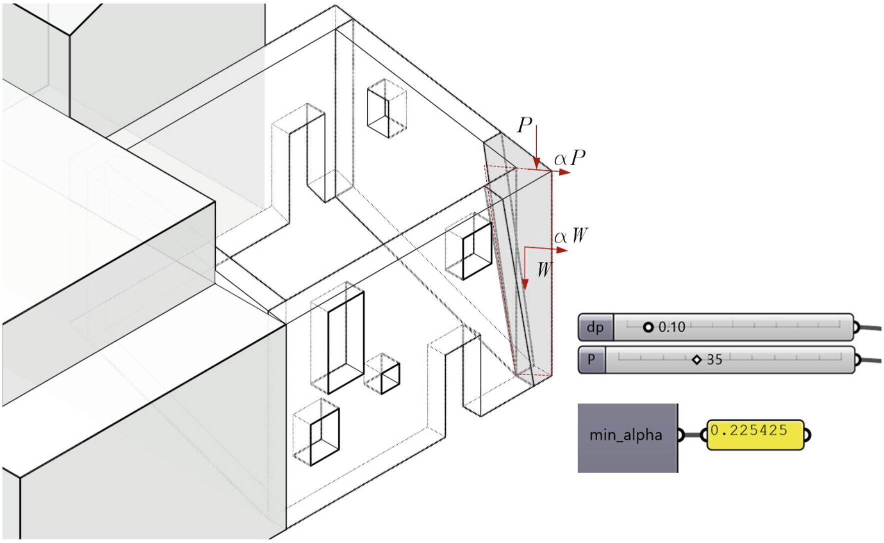
h_P 2.60
Ps 30
d 0.10
min_alpha 0.171126

Fig. 6. . Output of the visual scripting tool, showing the collapse load multiplier value for the single-story composed overturning mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof)



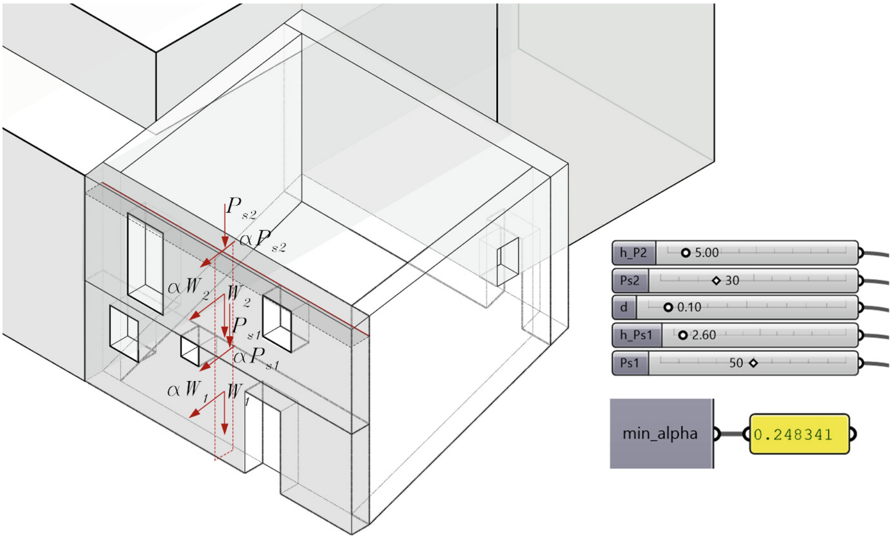
h_P2 5.00
Ps2 30
d 0.10
h_Ps1 2.60
Ps1 50
min_alpha 0.150315

Fig. 7. Output of the visual scripting tool, showing the collapse load multiplier value for the two-story composed overturning mechanism under the loading conditions: W (self-weight) and P_s (load exerted by the roof and floor)



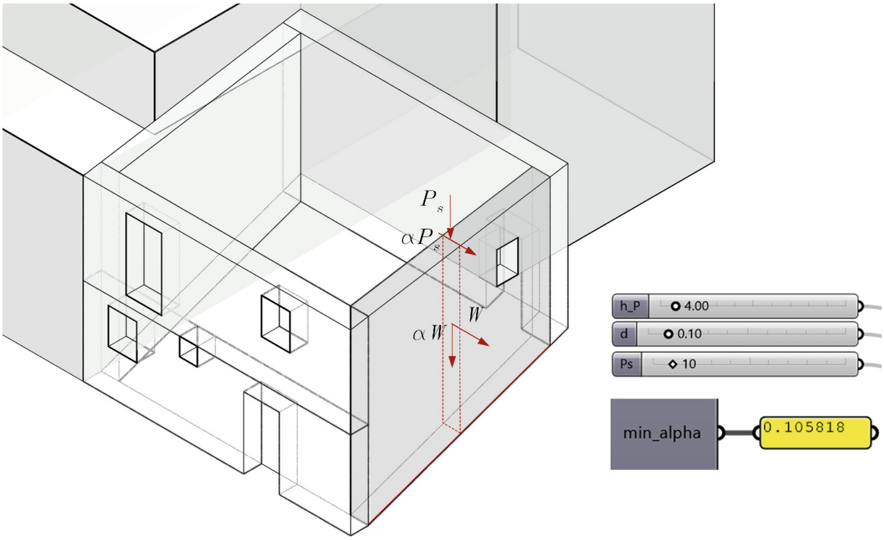
dp 0.10
P 35
min_alpha 0.225425

Fig. 8. Output of the visual scripting tool, showing the collapse load multiplier value for the corner overturning mechanism under the loading conditions: W (self-weight) and P_s (load exerted by the roof)



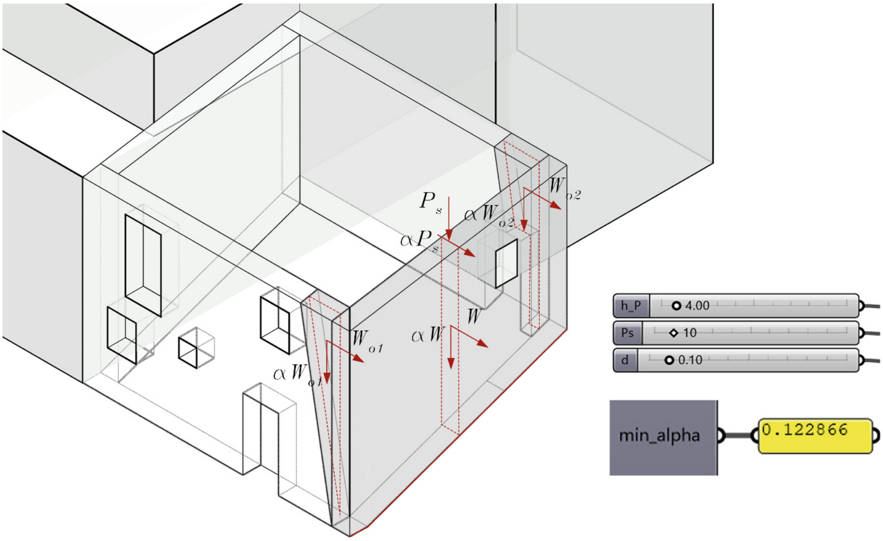
h_P2 5.00
Ps2 30
d 0.10
h_Ps1 2.60
Ps1 50
min_alpha 0.248341

Fig. 9. Output of the visual scripting tool, showing the collapse load multiplier value for the vertical bending mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof)



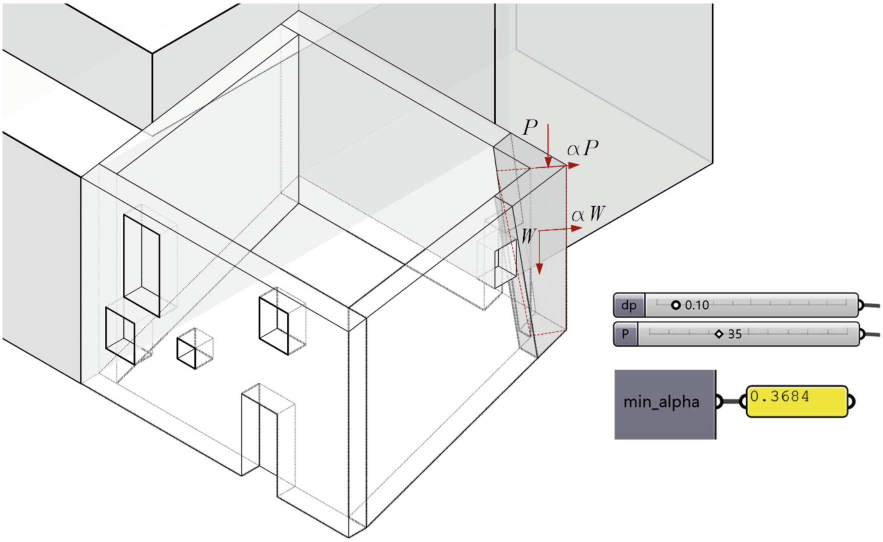
h_P 4.00
d 0.10
Ps 10
min_alpha 0.105818

Fig. 10. Output of the visual scripting tool, showing the collapse load multiplier value for the single-story simple overturning mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof)



h_P 4.00
Ps 10
d 0.10
min_alpha 0.122866

Fig. 11. Output of the visual scripting tool, showing the collapse load multiplier value for the single-story composed overturning mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof)



dp 0.10
P 35
min_alpha 0.3684

Fig. 12. Output of the visual scripting tool, showing the collapse load multiplier value for the corner overturning mechanism under the loading conditions: *W* (self-weight) and P_s (load exerted by the roof)

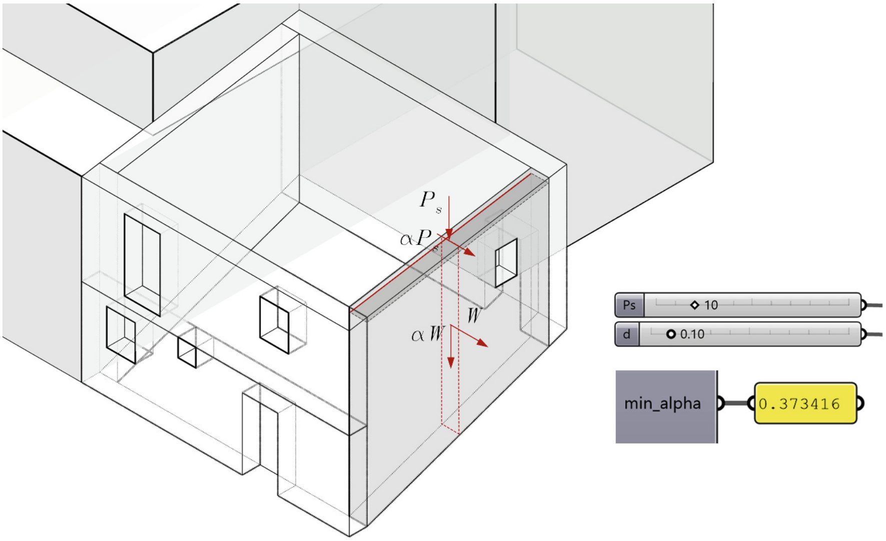


Fig. 13. Output of the visual scripting tool, showing the collapse load multiplier value for the vertical bending mechanism under the loading conditions: W (self-weight) and P_S (load exerted by the roof)

At the conclusion of the analyses in the spirit of kinematic limit analysis theory, it is possible to identify the most probable collapse mechanisms, particularly those with the lowest values of collapse multipliers, and this again through the use of the visual scripting tool. It is worth to remark that the analyzed benchmark is a masonry structure in a seismic-prone area and served as a practical example to demonstrate the method's effectiveness in evaluating possible collapse mechanisms so assessing the structural vulnerability of masonry buildings. The results highlight how the proposed approach can accurately predict failure modes and assist in determining structural weaknesses that require attention, not only to face seismic loads but also looking at actions due, for example, to climate change coupled with an actual state of severe degradation due to the lack of any restoration action.

Furthermore, the study confirms the effectiveness of the approach in providing reliable and computationally efficient evaluations of collapse mechanisms. Beyond the specific benchmark, the methodology shows potential for application to a wide range of masonry case studies, as it can be adapted to different geometries, bound-ary conditions and degradation scenarios. In addition, by exploiting the flexibility of the visual scripting environment, the approach opens the way to multidisciplinary applications, allowing different analyses to be performed and combined within the same framework. This general applicability reinforces its role as a versatile tool for both academic investigations and professional practice.

4 Concluding Remarks

A visual scripting tool for kinematic limit analysis of masonry walls subjected to out-of-plane loads has been tested on a real masonry building assumed as benchmark. The walls have been modeled using a rigid-block-based approach, with limit analysis applied in its standard kinematic form to predict collapse mechanisms and related load multipliers through an optimization process.

This interactive tool allows quick identification of key factors, such as geometry, material properties and applied load intensity and direction that influence the activation or prevention of collapse mechanisms in cracked walls. The tool also enables real-time evaluation of how adjustments, corresponding to structural restoration interventions, can improve safety, especially in post-seismic scenarios and/or within degraded areas.

The obtained results on a real-scale masonry building seem to validate the effectiveness of the promoted approach to be viewed as a predictive tool oriented to structural safety assessment.

An ongoing research is focusing on more complex masonry structural systems, also investigating on sliding rigid-block mechanisms to refine the modeling to better reflect real masonry behavior.

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