Research Article

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Visual scripting approach for structural safety assessment of masonry walls

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Abstract: A visual scripting approach for limit analysis of masonry walls subjected to out-of-plane loads is proposed. To this aim, within a visual scripting framework, an interactive CAD representation of the structure and of the acting loads, boundary conditions, and restraints is coupled with an optimization algorithm to calculate the collapse load multiplier and visualize the related predicted collapse mechanism. The proposed approach can be useful for practical purposes, indeed it allows us to quickly identify the key factors that influence the structural response and, through the tuning of some input data, can furnish some hints for design purposes. The effectiveness of the promoted tool is verified by application to eight well-known benchmark cases.

Keywords: visual scripting, optimization algorithm, Masonry macro-blocks, limit analysis

1 Introduction

The safeguard of Italian cultural heritage is undoubtedly a relevant topic, widely discussed from different points of view including those related to the preservation and safety assessment of historic buildings which, for the most part, are masonry constructions. The structural integrity of masonry buildings depends on various factors related to the acting loads, the real material conditions, the structural typology, and the state of preservation. It is well known that masonry structures, designed to mainly resist to gravitational loads, can collapse due to seismic forces, foundation failures, long-term deformations, or impacts due to extreme environmental conditions. As far as materials are concerned, the factors that can influence the strength of masonry are often due to their poor quality, as well as to their degradation caused by adverse environmental conditions or aging.

The great interest aroused by the architectural heritage, added to the increased attention and sensitivity of public opinion on the topic, has contributed to stimulating the development of various methods to evaluate the structural safety of masonry buildings. Without claiming to be exhaustive and limiting the context to that of historical masonry structures, a first rough distinction can be made looking at the *analysis method* employed for the study of the mechanical behavior of the masonry structure and at the *constitutive description* of the "masonry material." Within the analysis methods, a further distinction can be made between *nonlinear incremental methods* and direct, or *limit analysis methods*. With reference to the constitutive description, a distinction can also be done between approaches that employ a *continuum description* of the masonry material and those that treat the masonry by a *rigid-block-based description*. Each approach has its own advantages and limitations, making it often more suitable for specific types of structural problems. For further details on this issue, refer to the review paper by D'Altri *et al.* [1] and references therein.

Several nonlinear incremental methods focus on a numerical modeling of the full mechanical response of the masonry structure, including assumptions at different material scales (micro- and macro-mechanical ones or multiscale ones), taking also into account damaging effects, interface effects, and so on. Looking at some recent contributions, the analysis of masonry structures is carried out by finite element methods (FEM, see, e.g. [2] and [3] and references therein) also suggesting the use of probabilistic approaches to take into account the uncertainty of some parameters involved in the FE analysis [4]. Such numerical methods, even if are valuable research contributions in the field, lack effectiveness from a practical point of view. They indeed require very often a detailed knowledge of the masonry's mechanical, material, and geometrical parameters to be

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carefully identified, and are characterized by a great complexity of the pertinent numerical simulations being computationally demanding. Among recent studies, using nonlinear incremental methods with a block-based description, can be cited the paper by Galassi and Zampieri [5], who introduces an automated procedure for predicting failure and collapse mechanisms in masonry arch structures. The proposed incremental method leads to the evaluation of internal forces acting on the joints of blocks, under the condition that structural equilibrium and continuity are satisfied. Following the same research line, the contribution by Portioli and Lourenço [6] proposes a model employing rigid-block with an elasto-plastic softening interface for the nonlinear static analysis of masonry structures. The theoretical model is then validated through experimental tests and numerical analyses, focusing on material softening, failure mechanisms, and under the hypothesis of monotonic load and large displacements. The use of nonlinear approaches is indeed preferable for small-scale problems, such as the analysis of a single wall. In fact, these approaches require the application of a model that is generally computationally more expensive because it has to take into account the uncertainties related to the properties of the involved materials and the intrinsic heterogeneity of the masonry.

In line with Italian technical guidelines [7], many approaches are based on limit analysis theory, both *via* a static and/or a kinematic approach and this grounding on the observation that structural collapse often begins with a localized phenomenon, resulting from the instability of specific macro-elements [7]. Many of these local phenomena have been studied, identified, and classified (*e.g.*, Milano *et al.* [8]) so providing a series of case studies to which reference can be made to identify possible triggers of structural collapse. Limit analysis aims to predict the collapse load of a structure, or of a structural element, without detailing the mechanical response leading to failure. For this reason, methods based on limit analysis appear competitive not only in simplifying the safety assessment process, but also in providing an immediate understanding of potential collapse risks in masonry structures. Limit analysis kinematic approaches are proposed, for example, in the study by Casapulla *et al.* [9,10] for the assessment of seismic vulnerability of masonry walls without or with grouted anchors and in the study by Wang and Milani [11] for the analysis of damage mechanisms in masonry aggregates. Numerical methods based on this theory, which often make use of optimization algorithms, prove to be effective in the direct determination of the collapse load and the related mechanism, even with reference to structures with complex geometries. In this context, the structure is often effectively modeled through rigid blocks with the inclusion of friction effects. Among the works that can be included in this line of research can be mentioned those of Baggio and Trovalusci [12,13], which address a nonlinear programming problem with friction starting from a linearized limit analysis problem, applied to masonry structures modeled as rigid blocks with interface dilatancy. A constrained optimization problem is instead solved in Ferris and Tin-Loi [14] who propose an alternative method to calculate the collapse loads of rigid block systems with non-associative friction and tension-free contact. Gilbert *et al.* [15] proposed a linear programming formulation to address the problem of non-associative frictional joints, while Gilbert [16] developed an efficient numerical method, based on the kinematic theory, for the determination of the bearing capacity of masonry structures. Nodargi *et al.* [17] implemented a variational-based fixed-point algorithm to solve the limit analysis problem for dry-masonry block structures with frictional behavior at the interface.

The limit analysis approaches have become today even more attractive, and easily applicable for professional purposes, if implemented within a *visual scripting environment* allowing efficient, interactive, and real-time assessments of masonry structures safety. This recent line of research is particularly interesting also because it renders the analysis of some masonry structural problems more accessible for professional applications. A first attempt to integrate limit analysis in a CAD software was proposed by Block [18], for Thrust Network Analysis (TNA) applied to masonry vaults; the approach was later enhanced into an interactive version by Rippmann *et al.* [19] for the design of free-form masonry vaults with thin tiles. Also, Stockdale and Milani [20] utilized the adoption of a data extraction technique and a limit analysis tool in AutoCAD for the safety assessment of masonry arches. Another more recent procedure, promoting the use of this approach in design contexts and integrating with CAD systems, was presented by Funari *et al.* [21], who utilized Grasshopper, a visual programming environment within Rhinoceros (CAD software) [22]. This tool offers a user-friendly interface, enabling rapid and intuitive assessment of structural safety allowing for parametric exploration and real-time visualization of collapse surfaces and failure mechanisms identified using genetic algorithms. The same authors, in a subsequent work [23], proposed an extension of the methodology for the rapid safety assessment of historic masonry structures subject to seismic non linear actions. The use of limit analysis in a visual scripting environment proves to be a computationally efficient and rapid approach for the parametric evaluation of collapse mechanisms. Another valuable contribution is given by Mousavian *et al.* [24], who introduced a Grasshopper plugin for evaluating out-of-plane mechanisms in multi-storey masonry buildings, displaying potential failure locations using a macro-block model. This tool calculates out-of-plane failure mechanisms using a limit analysis approach, taking into account geometric and construction parameters.

To this research line belongs the present work that uses the *Grasshopper visual scripting tool* for a rapid structural safety assessment of masonry walls, which can turn out particularly efficient in critical situations like post-earthquake scenarios. The proposed approach couples limit analysis with a CAD environment to enhance real-time evaluations of the collapse of masonry walls. It also employs an optimization algorithm, based on a linear programming technique, to effectively identify the collapse mechanisms and to evaluate the related collapse load multiplier. The promoted tool enables a rapid parametric adjustments of the input data and facilitates the immediate identification of the key factors that impact on the structural response. It also gives the possibility to verify some possible structural design restoration choices or, in an emergency situation, it allows us to verify the effectiveness of an immediate first intervention. The article is organized in five sections. After this introductory Section 1, Section 2 provides the basic theoretical assumptions. Section 3 expounds the promoted visual scripting method. Section 4 presents eight benchmark case-studies. Concluding remarks are finally drawn in Section 5.

2 Basic theoretical assumptions

The hypotheses assumed to carry on a kinematic limit analysis on a masonry wall, viewed as a system of interconnected rigid block macro-elements, which undergoes the Heyman's hypotheses of no tensile strength, infinite compressive strength and no sliding between macro-elements (the effect of friction is also neglected), are briefly presented. These assumptions imply that the analysis can be employed mainly for good quality masonry but in the presence of fractures between macro-elements. Indeed, the kinematic approach allows us to evaluate the collapse load multiplier, say α, for the considered macro-element together with the pertinent collapse mechanism. The macro-element is hereafter described with reference to the plane containing the centroidal transverse section of the three-dimensional masonry block, so handling the mechanical problem in 2D (Figure 1(a)).

In order to introduce the kinematics of a rigid block and with reference to a global coordinate system (O, x, y), the displacement of the generic point P, having coordinates x_P and y_p, can be expressed as a function of the horizontal and vertical displacement components, say u_G

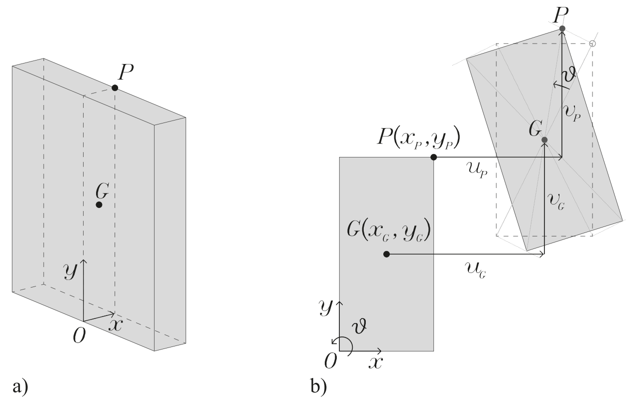

Figure 1: Kinematic parameters of the centroidal transverse section for the macro-element.

and v_G, of the centroid G and of its rotation ϑ around the centroid G. These three parameters are collected in a vector $\mathbf{q}$, as follows:

$$\mathbf{q} = [u_G, v_G, \vartheta], \tag{1}$$

and they are considered positive if consistent with the reference coordinate system, as illustrated in Figure 1(b).

Looking at Figure 1(b), the two displacement components u_P and v_P of the generic point P, collected in the vector $\mathbf{U}_P^T = [u_P\ v_P]$, are defined by

$$\begin{aligned} u_P &= u_G - (y_P - y_G)\vartheta, \\ v_P &= v_G + (x_P - x_G)\vartheta. \end{aligned} \tag{2}$$

Moreover, indicating with $\mathbf{S}$ the kinematic matrix:

$$\mathbf{S} = \begin{bmatrix} 1 & 0 & -(y_P - y_G) \\ 0 & 1 & (x_P - x_G) \end{bmatrix}, \tag{3}$$

the displacement $\mathbf{U}_P$ of the generic point P of the rigid block, can be expressed in compact form as

$$\mathbf{U}_P = \mathbf{S}\mathbf{q}. \tag{4}$$

The above kinematic parameters will permit us to describe the collapse mechanism determined by the application of limit analysis. The latter, applied through its kinematic approach, implies the solution of an optimization problem that minimizes the work required for collapse. The objective function is given by the application of the principle of virtual work and turns into the following balance equation between the stabilizing forces work, produced by the dead loads $\mathbf{P}_d$, and the destabilizing forces work, produced by the live loads $\mathbf{P}_l$, namely,

$$\mathbf{U}_d^T\mathbf{P}_d = \alpha\mathbf{U}_l^T\mathbf{P}_l, \tag{5}$$

where $\mathbf{U}_d$ and $\mathbf{U}_l$ are vectors collecting the application points of the loads $\mathbf{P}_d$ and $\mathbf{P}_l$, respectively.

In general, when the crack pattern is known, the multiplier α that induces collapse can be determined just using the balance equation (5), as in the case of the so-called simple overturning mechanism of a masonry wall macro-element [25], namely, $\alpha = \mathbf{U}_d^T\mathbf{P}_d/\mathbf{U}_l^T\mathbf{P}_l$. However, if the crack pattern is unknown, the balance equation is not anymore sufficient and it is necessary to solve an optimization problem.

To better explain the above assessments, two general cases of collapse mechanisms are addressed in the following with reference to a masonry wall macro-element whose kinematic boundary conditions, in terms of external constraints, are known as shown in Figure 2(a) and (b) by the fixed hinges A and the roller B. Such circumstance is given by the knowledge of the crack pattern detected *in situ* on a masonry wall. In particular, in Figure 2(a), the macro-block can rotate around the hinge A, as schematically sketched; in Figure 2(b), the macro-block divides into two parts due to the appearance of an internal hinge C of unknown position. This is the typical local collapse mechanism that occurs in masonry structures of historical heritage due to the so-called vertical bending mechanism of a facade wall [8]. The unknown position of the internal hinge, which determines the height of the two macro-blocks, introduces an additional variable, with respect to the simple overturning case, so, as already said, the equilibrium equation alone is insufficient to solve the problem and an optimization algorithm has to be employed.

In order to appropriately formulate the optimization problem, let us introduce a parameter $\mu > 1$, which correlates the unknown heights of the two blocks, h_1 and h_2, thereby locating the internal hinge. In particular, assuming $\mu > 1$, the two heights are given by the simple relations:

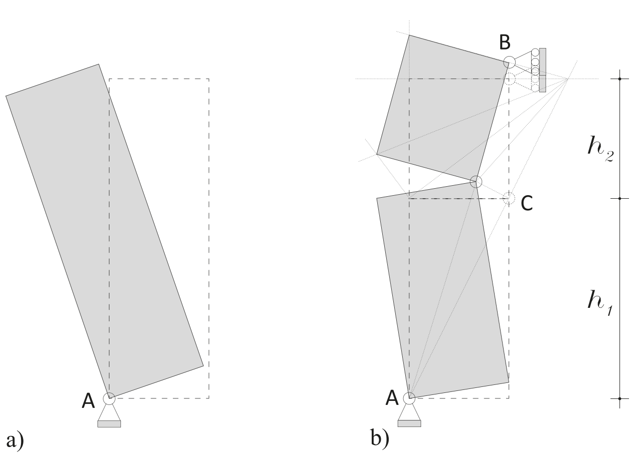

Figure 2: Schematic representation of a masonry macro-block collapse mechanism: (a) single macro-block rotating around the external hinge A and (b) two macro-blocks mutually rotating around the internal hinge C, of unknown position, satisfying the external constraints.

$$h_2 = \frac{h}{\mu}; \qquad h_1 = \frac{\mu - 1}{\mu} \quad \text{with} \quad \mu > 1. \tag{6}$$

The objective function of the optimization problem is then given by the multiplier α expressed by the balance equation (5), to be searched under a condition on μ, that is,

$$\min_{\mu} \alpha = \min_{\mu} \left[\frac{\mathbf{U}_d^T \mathbf{P}_d}{\mathbf{U}_l^T \mathbf{P}_l} \right] \qquad \text{s.t.} \quad \mu > 1. \tag{7}$$

The optimization problem (7) searches for the minimum of the coefficient α under a constrain on μ. The strict inequality of the parameter μ ensures that the position where the hinge arises is internal to the block and does not coincide with the upper end of the block. The problem given by (7) is solved by a linear programming technique, implemented through a *linprog* function in a Python code.

3 Visual scripting environment for limit analysis

The limit analysis optimization problem, described in the previous Section, is incorporated into Grasshopper, a visual programming tool. The use of this tool enables the seamless application of the well-established kinematic limit analysis approach for the evaluation of probable collapse mechanisms and related collapse load multiplier in masonry structures with cracked walls. The limit analysis is, in facts revisited within a visual scripting environment embedded in the CAD software, Rhinoceros. The innovation of this approach lies in the interactive framework provided to the user, allowing the visualization of both the masonry structure as input, directly imported from the CAD environment, and the evaluated most probable collapse mechanism as output, together with the relevant collapse load multiplier. The procedure is sketched in Figure 3 in the shape of a workflow organized into components, grouped into colored sections, each of which plays a distinct role in the overall solution process. To fix the ideas, reference is made to one of the benchmark cases analyzed next, i.e., the vertical bending mechanism in a masonry wall of a two-story building in which, due to the presence of known horizontal cracks at the top and at the bottom edge, playing the role of known external constraints as in the scheme of Figure 2(b), the action of out-of-plane loads creates an internal cylindrical horizontal hinge at an unknown position along the wall height giving rise to a collapse mechanism.

More precisely, the procedure begins with modeling the geometry of the two macro-elements and, as highlighted in

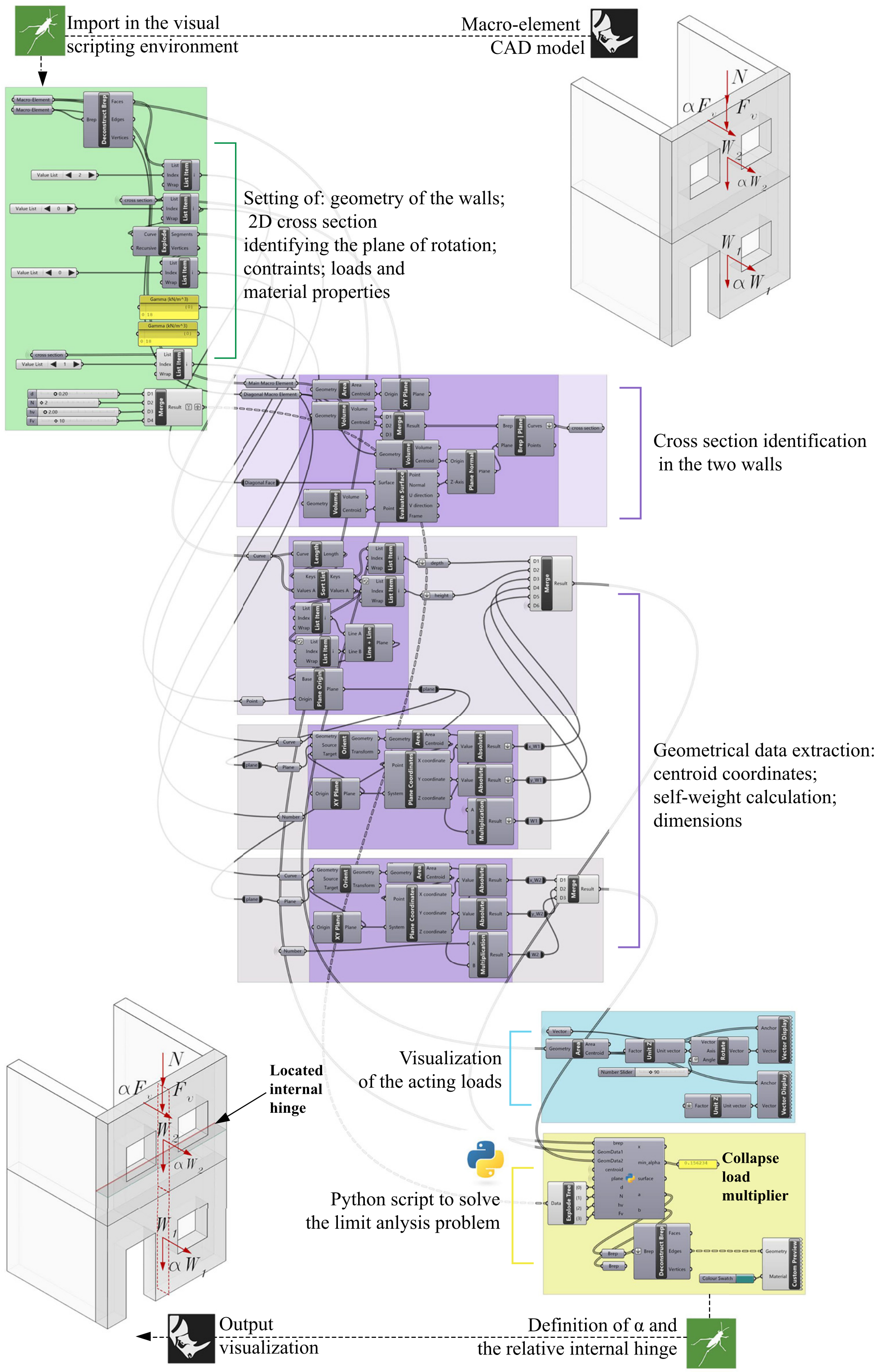

Figure 3: Workflow of the visual scripting for limit analysis of a double-story masonry facade exhibiting a vertical bending mechanism.

green in Figure 3, proceeds with importing the CAD model into the visual programming environment. Once the geometry is imported, the user can proceed by selecting the wall-cross-section coinciding with the plane where the rotations of the probable collapse mechanism can occur, specifying also the external constraints, the applied loads, and the material properties. In the central section, highlighted in purple, the visual script automatically identifies such wall-cross-section and extracts all geometrical data about the walls, including centroids position, self-weights, and dimensions. In the meantime, in the blue section, the visualization of the selected acting loads is provided. The final section, highlighted in yellow, represents the core of the visual scripting tool, where a Python code integrates all input data and implements the optimization algorithm to solve the kinematic limit analysis problem. The process concludes by providing the final output, *i.e.*, the collapse load multiplier and the corresponding collapse mechanism with the visualization of the predicted location of the internal cylindrical horizontal hinge.

It must be pointed out that the proposed visual scripting tool allows the user to modify input data interactively observing the effects of these changes in real-time. After an accurate *in situ* structural survey, this interactive limit analysis allows for a quick identification of the factors, such as geometry, material properties, or position and intensity of the applied loads, that may induce or conversely prevent the activation of an incipient collapse mechanism. Such, real-

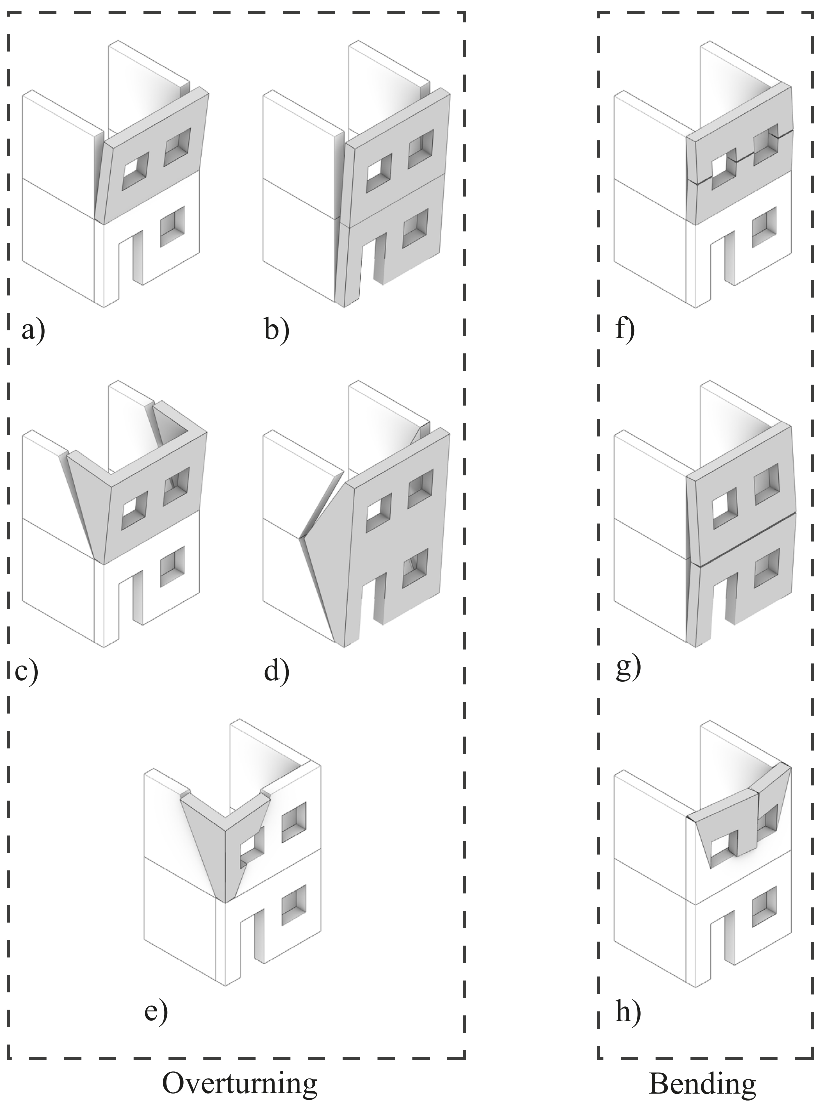

Figure 4: Analyzed out-of-plane collapse mechanisms: (a) simple overturning of a single-story wall, (b) simple overturning of a multi-story wall, (c) composed overturning of a single-story wall, (d) composed overturning of a multi-story wall, (e) composed overturning of a corner wall, (f) vertical bending of a single-story wall, (g) vertical bending of a multi-story wall, and (h) horizontal bending of a single-story wall.

time, visual information can indeed support the immediate evaluation of how input adjustments, corresponding to hypothesized structural restoration interventions, may influence an incipient collapse or may prevent it by providing valuable hints for choosing successful strategies aimed at improving the safety of the examined structure also in case of emergency, like immediately after a seismic event.

4 Analyzed benchmark examples

Eight out-of-plane collapse mechanisms are analyzed, all belonging to the two general cases of collapse mechanisms presented in Section 2. These mechanisms are often activated by external actions that induce the loss of equilibrium in an entire wall or in wider portions of the masonry structure. Out-of-plane mechanisms can indeed occur in masonry buildings, particularly in those lacking of a so-called box-type behavior, subjected to horizontal actions like, for example, the seismic ones. The activation of a specific collapse mechanism is influenced by various factors affecting out-of-plane behavior; these factors include the quality of connections between orthogonal walls, the interaction between walls, roof typology, arrangement of openings, loads exerted from the upper levels, or even the positioning of the masonry building within the urban texture.

Hereafter, we focus the attention on two main categories of out-of-plane collapse mechanisms, making a distinction based on their mechanical behavior and whose kinematics can be handled as described in Section 2, looking at the kinematics of a single macro-block or at that of two macro-blocks. We distinguish then between *overturning mechanisms* and *bending mechanisms*. Moreover, the overturning mechanisms are further subdivided into *simple* and *composed* overturning mechanisms and this looking at the geometry of the macro-element, which may involve a single wall or the dragging of parts of walls orthogonal to the main wall. The involvement of a single level (story) of the building or of multiple levels is also taken into account. On the other hand, the bending mechanisms are subdivided looking at the orientation of the plane in which the bending mechanism develops, distinguishing between *vertical* bending and *horizontal* bending, again occurring either within a single building level or across multiple levels.

Figure 4(a)–(h) schematically illustrates the eight hereafter addressed out-of-plane collapse mechanisms, which have been classified and named following the study by Milano *et al.* [8] where a wider systematic survey of damage crack patterns in masonry structures with the identification of the related collapse mechanisms has been performed. Precisely, we distinguish the following: 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; and horizontal bending of a single-story wall. All the above eight out-of-plane collapse mechanisms are analyzed in detail here, using the approach described in Sections 2 and 3 and predicting the collapse load multiplier at the onset of collapse.

4.1 Simple overturning of a single-story wall

This mechanism involves an entire single-story wall, or wide portions thereof, that, when subjected to out-of-plane forces, may displace independently from the adjacent sidewalls, see the sketch of Figure 5(a). The mechanism involves a rigid rotation of the wall around a known external horizontal cylindrical hinge located at the base of the involved macro-element and extended along its whole horizontal size. Such simple overturning is typically restricted to the topmost level of the building or to specific wall portions situated just below the roof. The simple overturning of the macro-element can be analyzed by considering the centroidal transverse section of the entire single-story wall with the geometry, boundary, and loading conditions given in Figure 5(b).

In Figure 5(b), W denotes the self-weight of the wall; F_v is the vertical component of the thrust of arches or vaults, if present, on the wall; P_S represents the weight of the floor/roof acting on the wall. Three corresponding horizontal inertia forces are also considered by multiplying the moduli

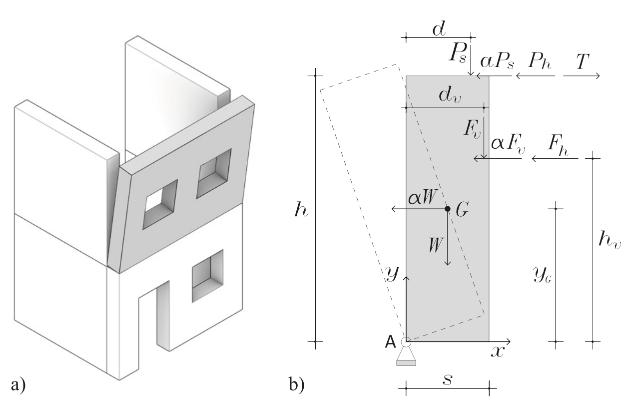

Figure 5: Simple overturning of a single-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

of the previous vertical actions by the load multiplier α. Two more horizontal loads are also considered, namely, P_h and F_h representing the static load transmitted from the head cover at the top of the macro element and the horizontal component of the thrust of arches or vaults on the wall, respectively. A further horizontal load T is finally considered to model the possible presence of tie rods at the top of the wall. The other geometrical data are also shown in Figure 5(b).

Eventually, in the most general cases which considers the presence of all the above actions, the collapse load multiplier is simply given by

$$\alpha = \frac{W \cdot \frac{s}{2} + F_v \cdot d_v + P_s \cdot d + T \cdot h - F_h \cdot h_v - P_h \cdot h}{W \cdot y_G + F_v \cdot h_v + P_s \cdot h}. \tag{8}$$

As said at closure of Section 3, the proposed visual scripting tool, after the input (*via* a CAD software) of the real geometrical dimensions of the wall, allows the user to consider, for the known collapse mechanism, both different combinations of the described loads or a tuning of their magnitude, getting, interactively and in real-time, the pertinent load multiplier as sketched in Figure 6(a)–(c) for three different possible loading conditions.

4.2 Simple overturning of a multi-story wall

This mechanism involves an entire facade of a multi-story building, or wide portions thereof, that, when subjected to out-of-plane forces acting at different levels, may displace independently from the adjacent sidewalls, see the sketch of Figure 7(a). The mechanism involves a rigid rotation of a multi-story wall macro-element around a known external horizontal cylindrical hinge located at the base of the involved macro-element and extended along its whole horizontal size. Following the rationale and the notation of the previous case, the simple overturning of the macro-element can be analyzed by considering the centroidal transverse section of each macro-element with the geometry, boundary, and loading conditions given in Figure 7(b).

If all the considered actions are present, the collapse load multiplier is given by

$$\alpha = \frac{\left[\sum_i W_i \cdot \frac{s_i}{2} + \sum_i F_{vi} \cdot d_{vi} + \sum_i P_{si} \cdot d_i + \sum_i T_i \cdot h_i - \sum_i F_{hi} \cdot h_{vi} - P_h \cdot h_{tot}\right]}{\left[\sum_i W_i \cdot y_{Gi} + \sum_i F_{vi} \cdot h_{vi} + \sum_i P_{si} \cdot h_i\right]}, \tag{9}$$

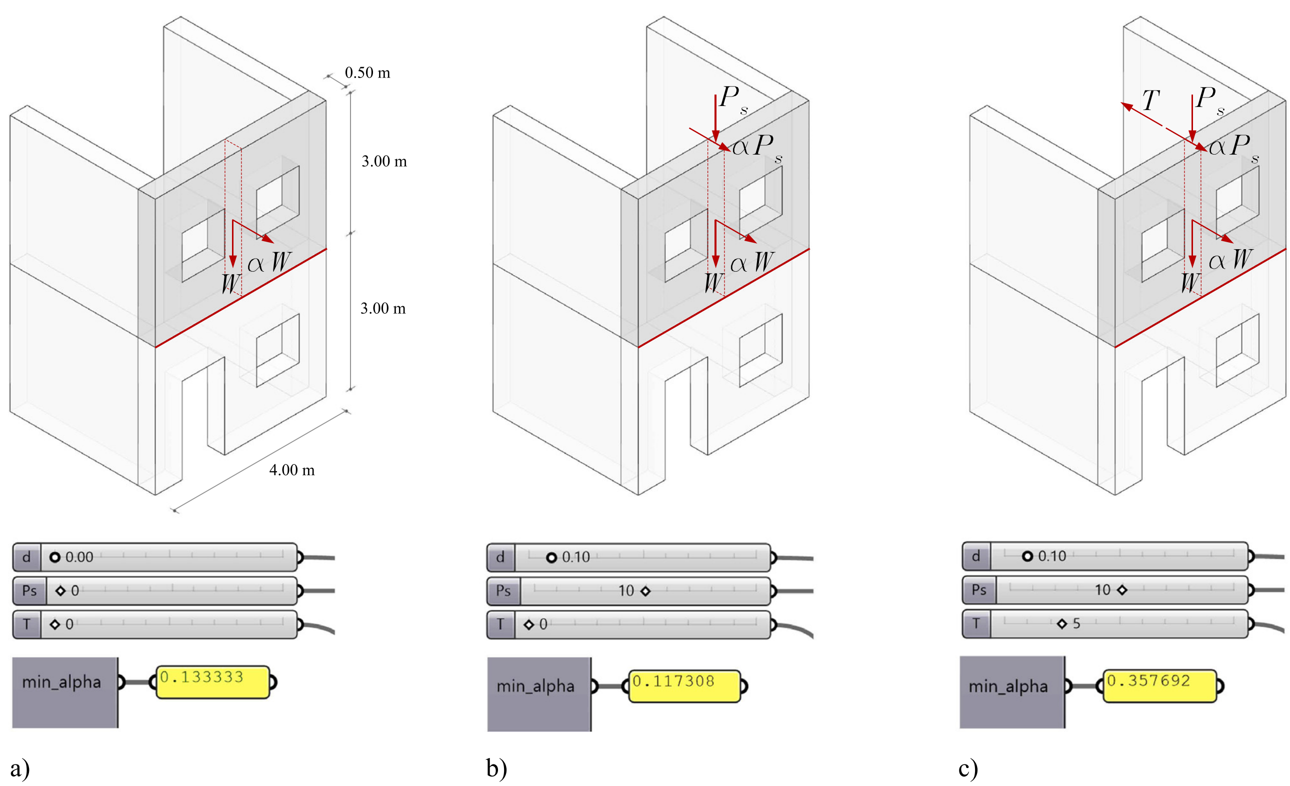

Figure 6: Output of the visual scripting tool, in terms of value of the collapse load multiplier for the assumed collapse mechanism, for three different loading conditions: (a) only wall self-weight, (b) wall self-weight plus weight of the floor/roof acting on the wall, and (c) loads as in (b) plus action exerted by tie-rods at the top of the wall.

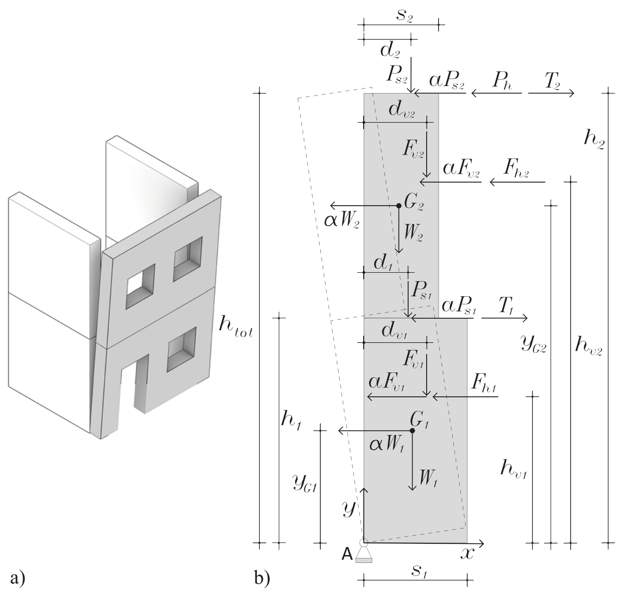

Figure 7: Simple overturning of a multi-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

while the output given by the visual scripting tool is given in Figure 8(a)–(c) for three different possible loading conditions.

4.3 Composed overturning of a single-story wall

This mechanism involves an entire facade of a single-story wall along with attached portions of the sidewalls and implies a rigid rotation of the macro-element around a known external horizontal cylindrical hinge located at the base of the macro-element and extended along its whole horizontal size as schematically shown in Figure 9(a). The adopted model simplifies the geometry of the portions of the sidewalls, dragged by the facade wall, by assuming them in the shape of two diagonal wedges (Figure 9(a)). Following the rationale and the notation of the previous cases, the composed overturning of a single-story wall can be still analyzed in 2D by considering the plane of symmetry of

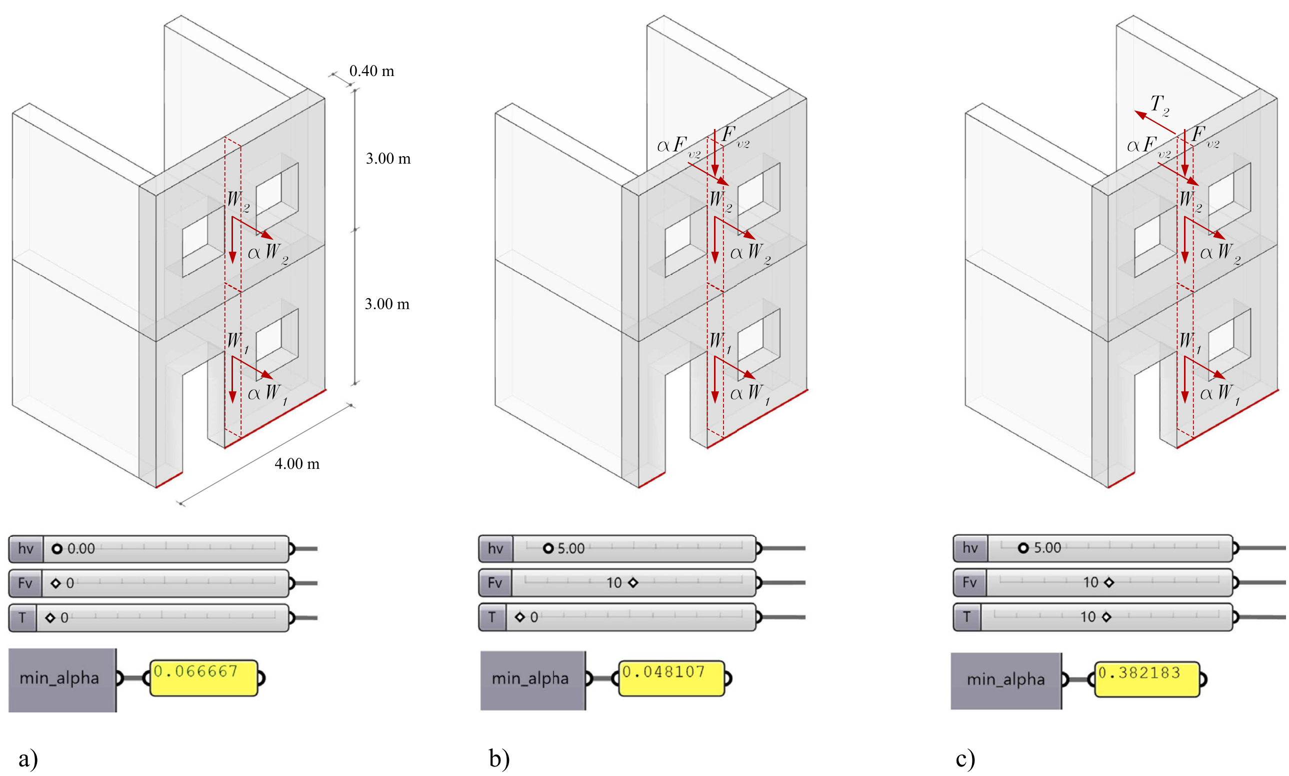

Figure 8: Output of the visual scripting tool, in terms of value of the collapse load multiplier for the assumed collapse mechanism, for three different loading conditions: (a) only walls' self-weight, (b) walls' self-weight plus action exerted by a vault present at the upper wall, and (c) loads as in (b) plus action exerted by tie rods at the top of the multi-story wall.

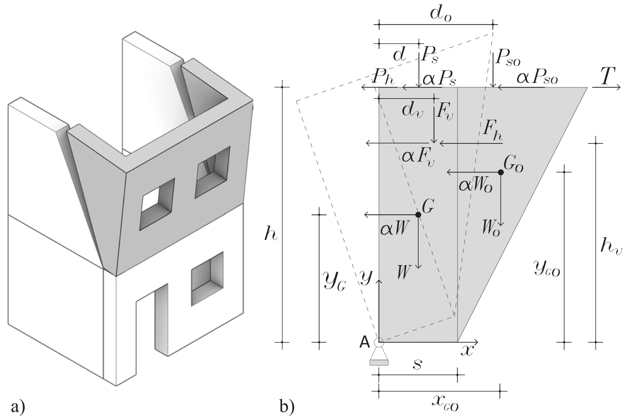

Figure 9: Composed overturning of a single-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

the whole rigid macro-element, containing the centroidal transverse section of the facade wall, on which the diagonal wedges, together with all the actions acting on them, are indeed projected as if they were acting on such symmetry plane, see the mechanical model of Figure 9(b). Such assumption does not alter, obviously, the balance at rotation, around the cylindrical hinge at the base of the macro-element.

If all the considered actions are present, the collapse load multiplier is given by

$$\alpha = \frac{\left[W \cdot \frac{s}{2} + F_v \cdot d_v + W_0 \cdot x_{G0} + P_s \cdot d + P_{s0} \cdot d_0 + T \cdot h - F_h \cdot h_v - P_h \cdot h\right]}{\left[W \cdot y_G + W_0 \cdot y_{G0} + F_v \cdot h_v + P_s \cdot h + P_{s0} \cdot h\right]}, \tag{10}$$

while the output given by the visual scripting tool is given in Figure 10(a)–(c) for three different possible loading conditions and in the hypothesis that the diagonal wedges are present only on one side.

4.4 Composed overturning of a multi-story wall

This mechanism involves an entire wide facade of a multi-story wall along with attached portions of the sidewalls extended to more than one single level. These portions, dragged by the multi-story facade wall, are modeled as double diagonal wedges as depicted in Figure 11(a). As in the previous cases, the mechanism implies a rigid rotation of the macro-element around a known external horizontal

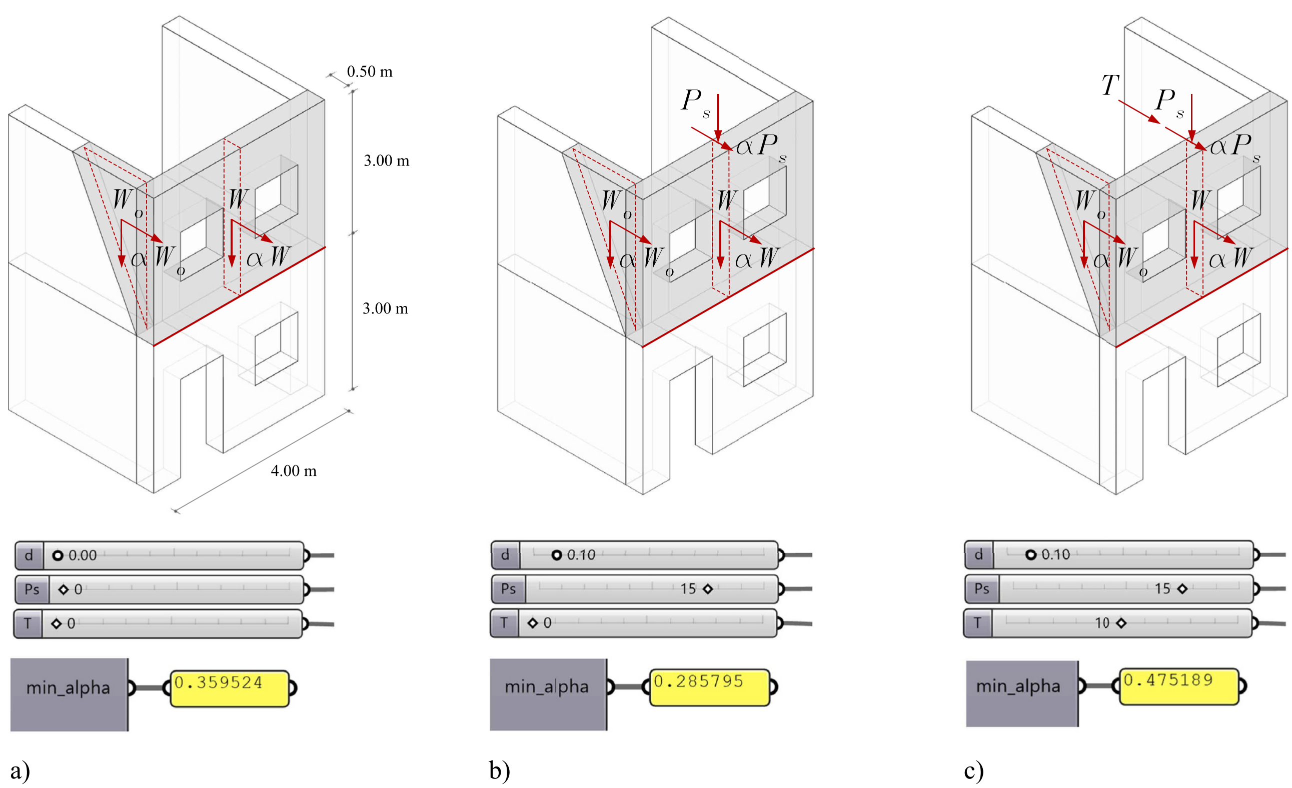

Figure 10: Output of the visual scripting tool, in terms of value of the collapse load multiplier for the assumed collapse mechanism, for three different loading conditions: (a) only self-weight of wall facade and diagonal wedges, (b) self-weights as in (a) plus action exerted by a roof on the top of the macro-element, and (c) loads as in (b) plus action exerted by tie rods inserted at the top of the facade wall at the corners.

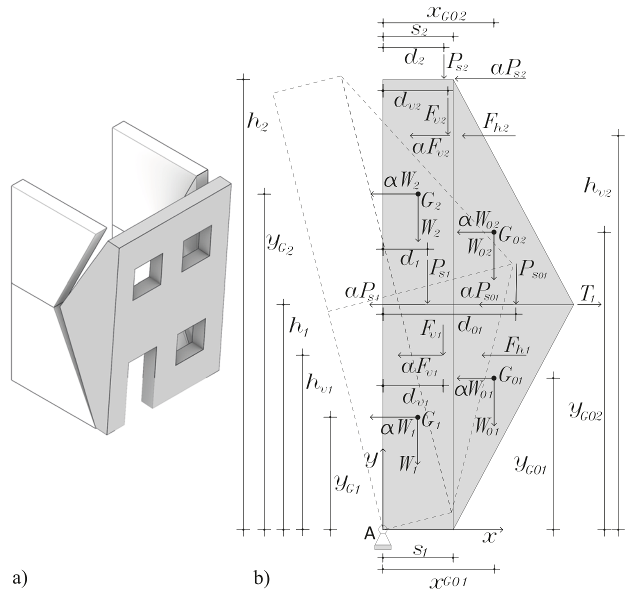

Figure 11: Composed overturning of a multi-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

cylindrical hinge located at the base of the macro-element and extended along its whole horizontal size as schematically shown in Figure 11(a). The 2D mechanical model, set on the symmetry plane of the macro-element and based on the same simplifying assumptions of the previous case not repeated here, can be assumed as given in Figure 11(b).

In the most general loading conditions, the collapse load multiplier is given by

$$\alpha = \frac{\text{num}}{\sum_i W_i y_{Gi} + \sum_i W_{0i} y_{G0i} + \sum_i F_{vi} h_{vi} + \sum_i P_{si} h_i + \sum_i P_{s0i} h_i} \tag{11}$$

with

$$\text{num} = \sum_i W_i \frac{s_i}{2} + \sum_i F_{vi} d_{vi} + \sum_i W_{0i} x_{G0i} + \sum_i P_{si} d_i + \sum_i P_{s0i} d_{0i} + \sum_i T_i h_i - \sum_i F_{hi} h_{vi},$$

while the output given by the visual scripting tool is given in Figure 12(a)–(c) for three different possible loading conditions and in the hypothesis that the diagonal wedges are present only on one side.

4.5 Composed overturning of a corner wall

This mechanism involves the rigid rotation of a detachment wedge, generated by two diagonal cracks that develop along two orthogonal walls at the corner of the building as

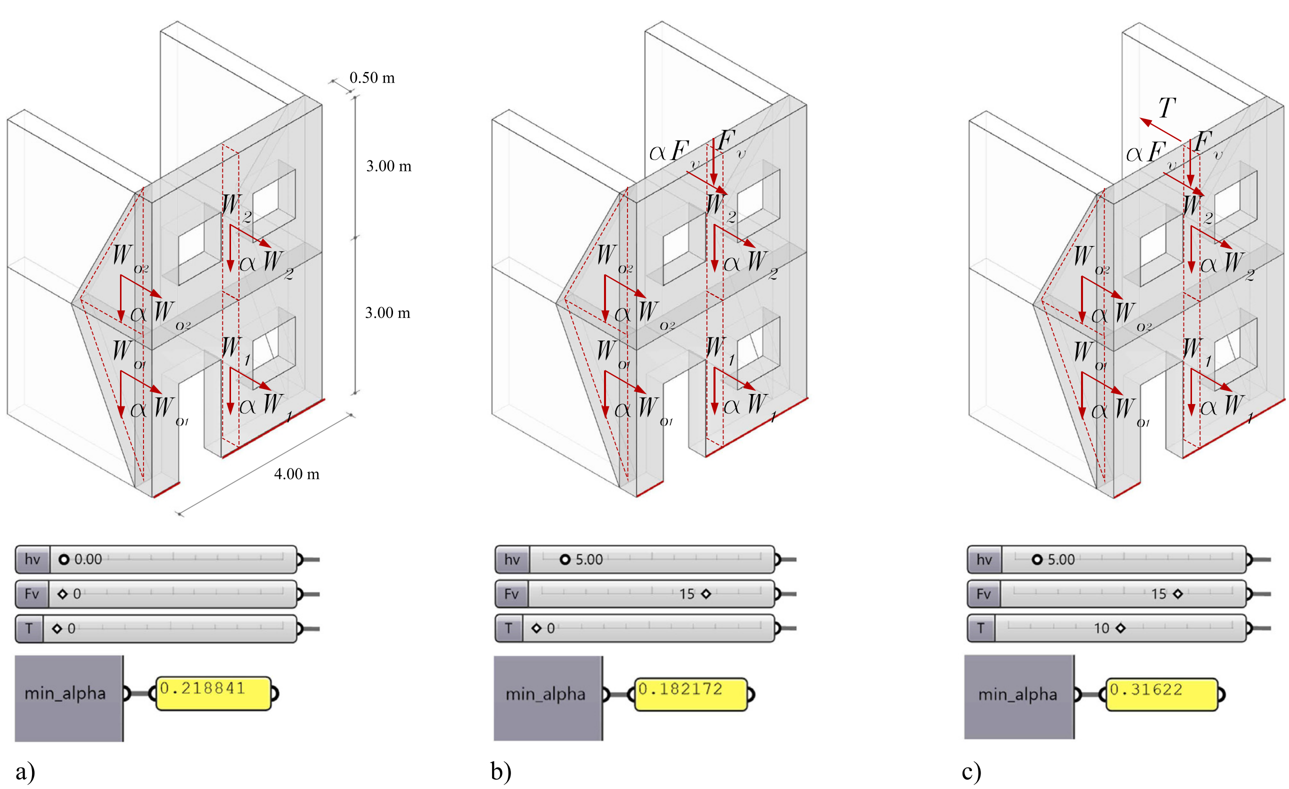

Figure 12: Output of the visual scripting tool, in terms of value of the collapse load multiplier for the assumed collapse mechanism, for three different loading conditions: (a) only self-weight of wall facade and double diagonal wedges, (b) self-weights as in (a) plus action exerted by a vault on the top level, (c) loads as in (b) plus action exerted by tie rods inserted at the top of the facade wall at the corners.

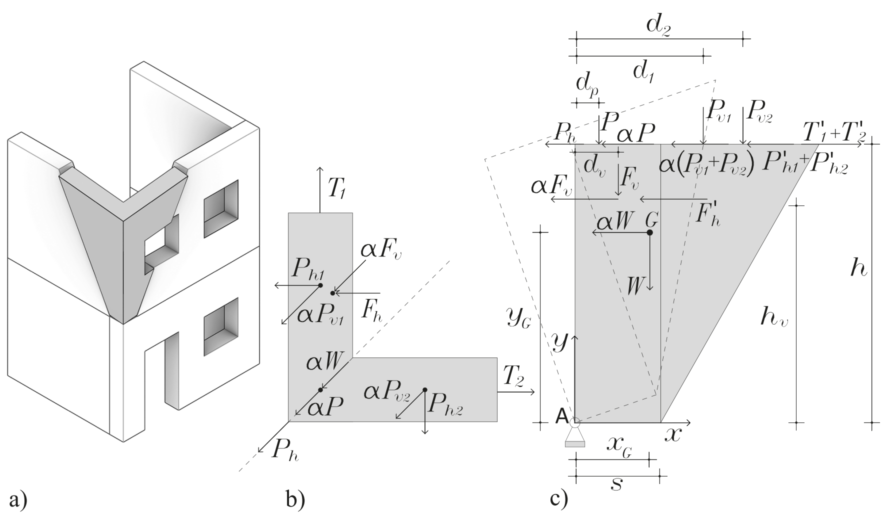

Figure 13: Composed overturning of a corner wall: (a) sketch of the collapse mechanism, (b) plane of rotation of the macro-element; and (c) geometry, boundary, and loading conditions of the mechanical model.

sketched in Figure 13(a). This may be observed in isolated masonry buildings or those located at the end of urban blocks, where the forces acting on the structure generate a thrust that concentrates at wall intersections. The mechanical model assumes that the mechanism occurs in the direction of the applied thrust, with a rotation of the macro-element around a hinge, of known position, located at the base of the macro-element. For simplicity, it is assumed that the plane of rotation is at 45° with the orthogonal walls as depicted in Figure 13(b). The problem is again

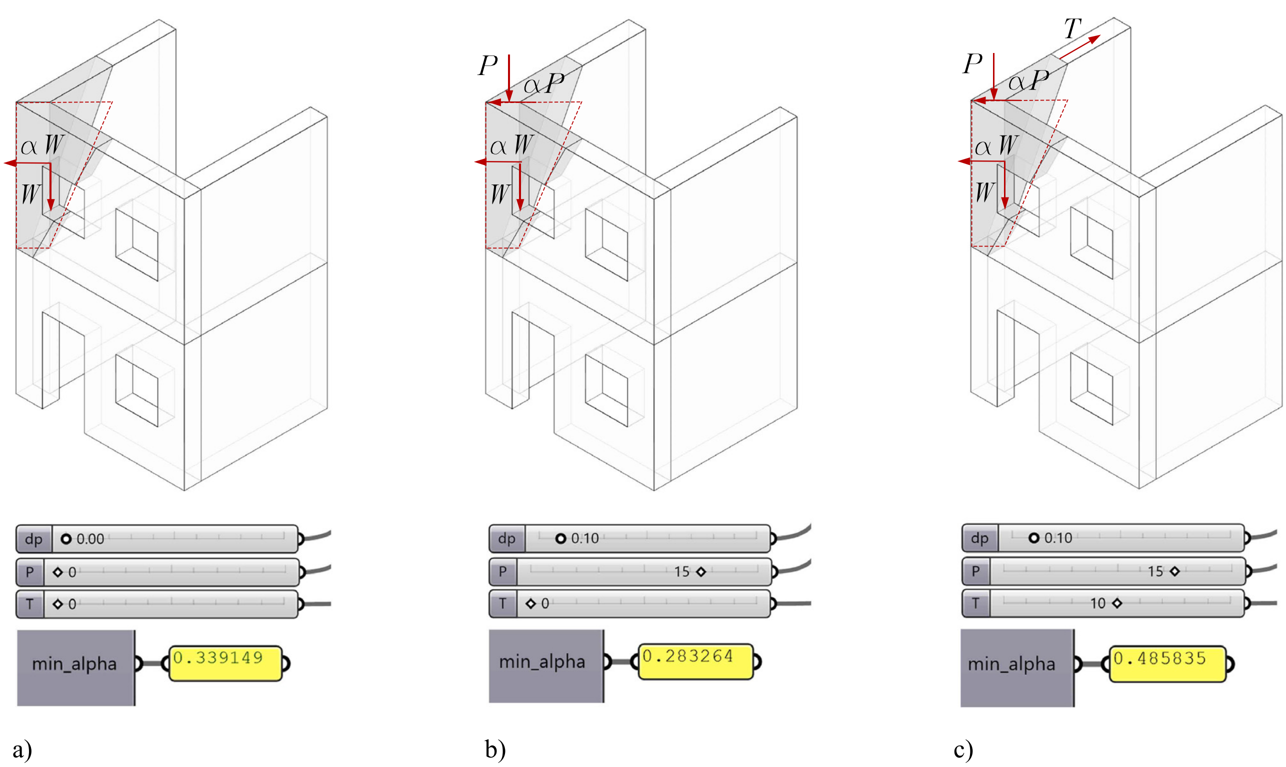

Figure 14: Output of the visual scripting tool, in terms of value of the collapse load multiplier for the assumed collapse mechanism, for three different loading conditions: (a) only self-weight of the macro-element, (b) self-weight as in (a) plus action exerted by a ridge beam of the hip roof, and (c) loads as in (b) plus action exerted by a tie rod at the top of a corner wall.

handled as a plane one, Figure 13(c), considering the plane of rotation and the projection on it of all the acting loads. The projections of the horizontal components are denoted with a prime. In the examined case, P is the load transmitted by the ridge beam or the rafter of the hip roof; P_{v1}, P_{v2}, and P_{h1} and P_{h2} are, respectively, vertical and horizontal components of loads applied to the top of the orthogonal walls from either side of the corner.

In the most general loading conditions, the collapse load multiplier is given by

$$\alpha = \frac{\text{num}}{Wy_G + F_v h_v + (P + P_{v1} + P_{v2})h} \tag{12}$$

with

$$\text{num} = Wx_G + F_v d_v + Pd_p + P_{v1}d_1 + P_{v2}d_2 + (T_1' + T_2')h + \\ -F_h' h_v - (P_h + P_{h1}' + P_{h2}')h,$$

while the output given by the visual scripting tool is given in Figure 14(a)–(c) for three different possible loading conditions.

Remark. The above examined mechanisms, of simple and composed overturning, can be considered alternative collapse modes, each associated with either weak or strong connections between the facade and the sidewalls and/or the roof. The effectiveness of these connections and the exactness of the corresponding collapse mechanism have to be evaluated by an accurate structural survey by inspecting for inclined or vertical cracks on the walls, at the corners, near the roof, the vaults, *etc*. It is also of outmost importance to retrieve the real geometry of the masonry elements, to assess the quality of the connections as well as to quantify the magnitude of all the acting loads together with their exact location and direction. It is worth noting that, in the absence of precise information, the user may consider more than one single mechanism and assume as collapse multiplier the lowest value among the ones calculated within the analyzed collapse mechanisms. The user is also allowed to check, interactively, the effectiveness of tie rods or other possible design solutions oriented to assure structural safety.

4.6 Vertical bending of a single-story wall

The mechanism is characterized by the out-of-plane rotation of two blocks of a facade wall around an horizontal cylindrical hinge arising along the wall's height between two consecutive levels. The crack pattern also includes vertical cracks between the single facade wall and the sidewalls, as sketched in Figure 15(a). This collapse mechanism typically occurs in masonry facade walls restrained, by tie rods or beams, at the top and bottom edges of the story. Obviously, there is no "bending," in the rigorous mechanical sense, within the assumed rigid block description, but, this naming, generally adopted, makes sense if we look at the general deformation of the wall which reminds a flexure on a vertical symmetry plane orthogonal to the wall mid-plane, which is in fact the plane of rotation of the two generated masonry blocks. The 2D mechanical model, set on the vertical symmetry (rotation) plane of the divided wall is given in Figure 15(b), where a generic vertical load, N, is also applied at the top of the macro-element. It is worth noting that, as in the overturning mechanisms examined before the position of external constraints (horizontal hinges A and B) are known. However, the position of the intermediate cylindrical hinge C is not known *a priori*, it indeed enter the analysis which determines its correct (most probable) position by an optimization procedure in which the self-weights, W_1 and W_2, as well as the heights, h_1 and h_2, of the rotating blocks enter with an optimization parameter μ, already introduced in Section 2 with reference to Figure 2(b) and Eqs (6) and (7).

The collapse load multiplier is given by

$$\alpha = 2\frac{(\mu - 1)(Nd + P_s a + F_v d_v - F_h h_v) + s(W + N + P_s + F_v)}{(\mu - 1)(Wh/\mu + 2F_v h_v)}, \tag{13}$$

with

$$h_1 = \frac{\mu - 1}{\mu}h;\ \ h_2 = \frac{h}{\mu};\ \ W_2 = \frac{W}{\mu};\ \ W_1 = \frac{\mu - 1}{\mu}W,$$

while the output given by the visual scripting tool is given in Figure 16(a)–(c) for three different possible loading conditions.

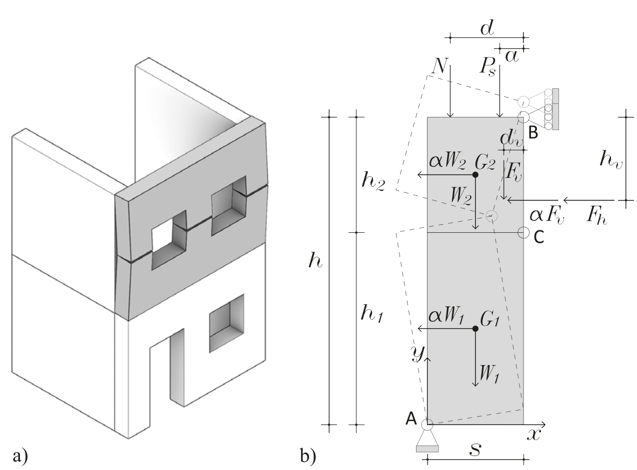

Figure 15: Vertical bending of a single-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

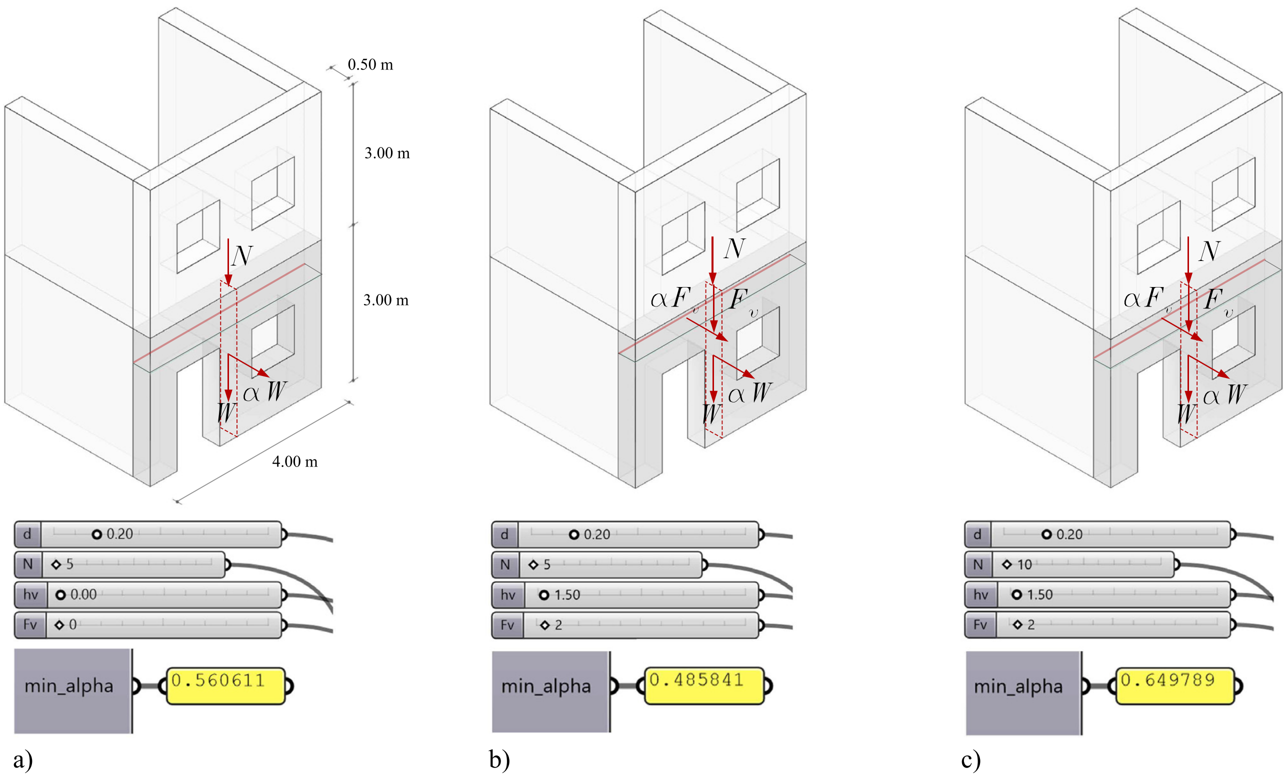

Figure 16: Output of the visual scripting tool, in terms of predicted internal hinge and value of collapse load multiplier, for three different loading conditions: (a) self-weight of the wall plus a fixed value of a vertical load N, (b) loads as in (a) plus action exerted by a vault, and (c) loads as in (b) with a greater value of N.

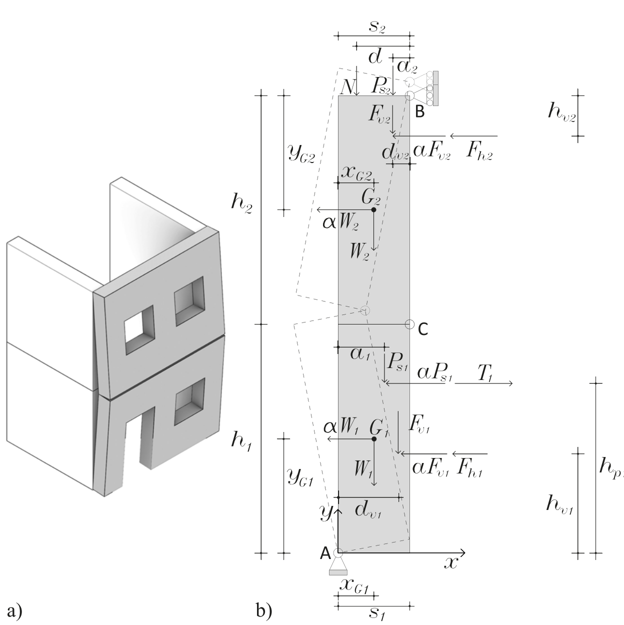

Figure 17: Vertical bending of a multi-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

4.7 Vertical bending of a multi-story wall

The mechanism is substantially the same as the previous one but it involves the out-of-plane rotation of two blocks generated by a horizontal cylindrical hinge arising in a facade multi-story wall, *i.e.*, a wall between more than two levels where, the intermediate ones are lacking effective connections. The mechanism is schematically sketched in Figure 17(a). The remarks made for the previous mechanism hold true and the adopted mechanical model is the one given in Figure 17(b).

The collapse load multiplier is given by

$$\alpha = \frac{\text{num}}{W_1 y_{G1} + F_{v1} h_{v1} + P_{s1} h_{p1} + (W_2 y_{G2} + F_{v2} h_{v2})(h_1/h_2)} \tag{14}$$

with

$$\begin{aligned}\text{num} = {} & W_1 x_{G1} + W_2\left(s_2 + x_{G2}\frac{h_1}{h_2}\right) + F_{v1} d_{v1} + F_{v2} s_2 + F_{v2}\frac{h_1}{h_2} d_{v2} \\ & + P_{s1} a_1 + P_{s2}\left(s_2 + a_2\frac{h_1}{h_2}\right) + N\left(s_2 + d\,\frac{h_1}{h_2}\right) + T_1 h_{p1} \\ & - F_{h1} h_{v1} - F_{h2} h_{v2}\frac{h_1}{h_2}\end{aligned}$$

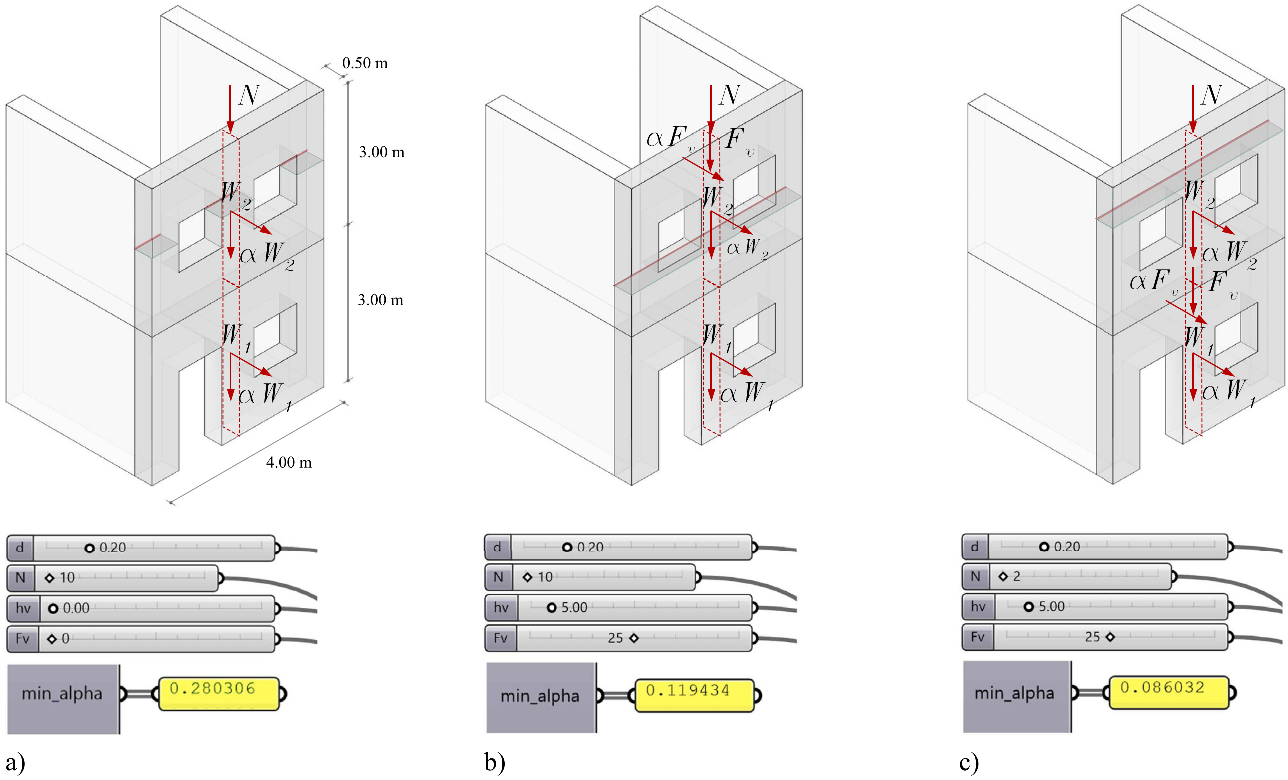

Figure 18: Output of the visual scripting tool, in terms of predicted internal hinge and value of collapse load multiplier, for three different loading conditions: (a) self-weight of the wall plus a fixed value of a vertical load N, (b) loads as in (a) plus action exerted by a vault at upper level, and (c) loads as in (a) plus action exerted by a vault at lower level.

and

$$h_1 = \frac{\mu - 1}{\mu} h; \quad h_2 = \frac{h}{\mu}; \quad W_2 = \frac{W}{\mu}; \quad W_1 = \frac{\mu - 1}{\mu} W,$$

while the output given by the visual scripting tool is given in Figure 18(a)–(c) for three different possible loading conditions.

4.8 Horizontal bending of a single-story wall

The mechanism involves the ejecting, due to out-of-plane forces, of an upper portion of a facade wall and the detachment of wedge-shaped, or trapezoidal-shaped, blocks given by the arising of cylindrical hinges oriented obliquely and vertically, as sketched in Figure 19(a). This behavior, typically occurring at the last top level, is due to the presence of good connections with the sidewalls, which provide sufficient restraint to prevent overall overturning, but to the absence of good connection with the roof structure. An excessive wideness of the facade wall may then allow for horizontal bending deformation. The ejected portion of the wall is divided into two macro-blocks rotating around two known external hinges, A and B, and one unknown internal hinge, C, as shown in Figure 19(b) where the mechanical 2D model is set in the horizontal plane of rotation of the upper edges of the two generated blocks.

The collapse load multiplier is given by

$$\alpha = \frac{H \cdot s\left(1 + \frac{L_1}{L_2}\right) - \sum_i P_{hi1} d_{i1} - \sum_i P_{hi2} \frac{L_1}{L_2} d_{i2}}{W_1 x_{G1} + W_2 \frac{L_1}{L_2} x_{G2} + \sum_i P_{vi1} d_{i1} + \sum_i P_{vi2} \frac{L_1}{L_2} d_{i2}} \tag{15}$$

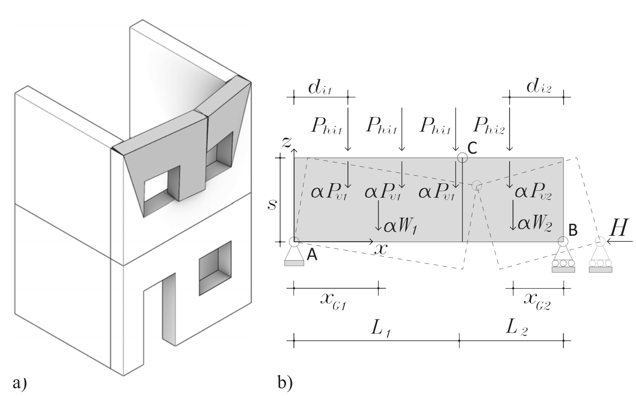

Figure 19: Horizontal bending of a single-story wall: (a) sketch of the collapse mechanism and (b) geometry, boundary, and loading conditions of the mechanical model.

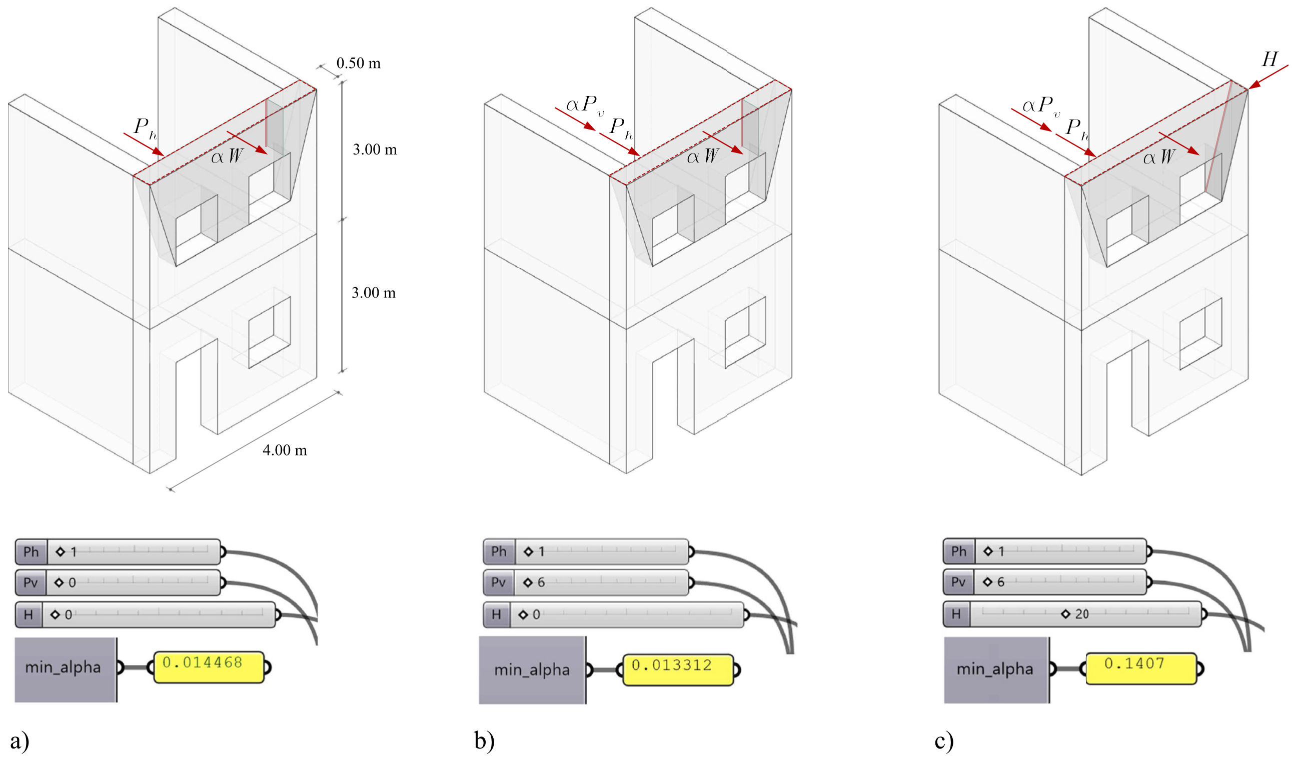

Figure 20: Output of the visual scripting tool, in terms of predicted internal hinge and value of collapse load multiplier, for three different loading conditions: (a) self-weight of the wall plus a fixed horizontal component of the roof P_h, (b) loads as in (a) plus a vertical load P_v which give rise to αP_v, and (c) loads as in (b) plus a load H exerted by the side wall.

with

$$L_1 = \frac{\mu - 1}{\mu}L; \;\; L_2 = \frac{L}{\mu}; \;\; W_2 = \frac{W}{\mu}; \;\; W_1 = \frac{\mu - 1}{\mu}W,$$

where the load H denotes the reaction force that the bracing wall, or a tie rod, can exert to counteract the thrust generated by the horizontal bending mechanism; P_{hi} and P_{vi} denote, respectively, the horizontal and vertical component of the ith load transmitted from the top to the wall. The lengths L_1 and L_2, which define the location of the internal hinge C, depend on the optimization parameter μ, in the same way as h_1 and h_2 in the case of vertical bending.

The output given by the visual scripting tool is given in Figure 20(a)–(c) for three different possible loading conditions.

Remark. The general remarks drawn at the end of the overturning mechanisms hold true also for bending type mechanisms. It is worth noting that the tuning of some active loads, as N in the vertical bending or H in the horizontal one, affect the location of the calculated internal hinge and eventually of the collapse multiplier. In the case of Figure 20c, for example, the value of H is so high to impede the formation of an internal hinge and of the mechanism. Such type of information give to the user very useful hints for design purpose.

5 Concluding remarks

A visual scripting environment for kinematic limit analysis of masonry walls subjected to out-of-plane loads has been presented. The masonry walls have been modeled by a rigid-block-based approach while limit analysis has been applied in its standard kinematic shape, aimed to predict a collapse mechanism and the related load multiplier *via* an optimization procedure.

The proposed visual scripting approach renders the limit analysis interactive, allowing for a quick identification of the factors, such as geometry, material properties, or position and intensity of the acting loads that may induce or conversely prevent the activation of an incipient collapse mechanism due to the existence of cracked walls.

The potential of such interactive in-real-time visual information relies on the possibility for the user of an immediate evaluation of how input adjustments, corresponding to hypothesized structural restoration interventions, may result successful to improve the safety of the examined masonry structure also in case of emergency, like immediately after a seismic event.

The approach has been validated by analyzing eight well-known benchmark cases-study and the obtained results seem to prove its practical applicability. Nevertheless, the results presented in this study are to be viewed as a first attempt aimed to develop an efficient visual scripting predictive tool for masonry walls safety assessment.

Some research goals, such as the analysis of geometrically more complex masonry systems; the prediction of mechanisms with sliding rigid-blocks, other theoretical assumptions that are able to render the rigid-blocks-based modeling closer to the real masonry behavior, are the object of an ongoing research.

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References

[1] D’Altri AM, Sarhosis V, Milani G, Rots J, Cattari S, Lagomarsino S, Sacco E, et al. Modeling strategies for the computational analysis of unreinforced masonry structures: review and classification. Arch Comput Meth Eng. 2020;27(4):1153–85. doi: 10.1007/s11831-019-09351-x.

[2] Spagnuolo R. Out-of-plane local mechanism analysis with finite element method. Curved Layered Struct. 2021;8(1):130–6. doi: 10.1515/cls-2021-0012.

[3] Zeng B, Li Y. An improved method for statistics estimation of out-of-plane load resistance of masonry walls using design-code models and mechanics-based finite element models. Eng Struct. 2024;319:118725. doi: 10.1016/j.engstruct.2024.118725.

[4] Mazzeo M, Laudani R, Santoro R. Uncertainty effect on seismic capacity assessment in the out-of-plane failure mechanisms of masonry structures by probabilistic and non-probabilistic approaches. Develop Built Environ. 2024;17:100366. doi: 10.1016/j.dibe.2024.100366.

[5] Galassi S, Zampieri P. A new automatic procedure for nonlinear analysis of masonry arches subjected to large support movements. Eng Struct. 2023;276:115359. doi: 10.1016/j.engstruct.2022.115359.

[6] Portioli FP, Lourenço PB. Nonlinear static analysis of masonry structures with mortar joints and cracking units by optimization-based rigid block models. Earthquake Eng Struct Dyn. 2024;53:3963–82. doi: 10.1002/eqe.4206.

[7] Ministero delle Infrastrutture e dei Trasporti. CNTC19 - Circolare applicativa delle Norme Tecniche delle Costruzioni di cui al D.M. 17-01-2018 (NTC 2018). Gazzetta Ufficiale N. 42 del 20-02-2018. 2019 (in Italian).

[8] Milano L, Mannella A, Morisi C, Martinelli A. Illustrative sheets of the main local collapse mechanisms in buildings existing masonry and related kinematic models of analysis. Annex to the Repair and Strengthening Guidelines of structural elements, infills and partitions, DPC - ReLUIS; 2009.

[9] Casapulla C, Argiento LU, Maione A, Speranza E. Upgraded formulations for the onset of local mechanisms in multi-storey masonry buildings using limit analysis. Structures. 2021;31(4–5):380–94. doi: 10.1016/j.istruc.2020.11.083.

[10] Casapulla C, Maione A, Ceroni F, Prota A, Di Ludovico M. Limit analysis and design-oriented approach for out-of-plane loaded masonry walls strengthened by grouted anchors. Eng Struct. 2023;285:115991. doi: 10.1016/j.engstruct.2023.115991.

[11] Wang P, Milani G. Development of a computational limit analysis-based tool for seismic vulnerability assessment in historical masonry buildings. In AIP Conf Proc. 2024;3094 49001. doi: 10.1063/5.0213378.

[12] Baggio C, Trovalusci P. Limit analysis for no-tension and frictional three-dimensional discrete systems. Mech Struct Machines. 1998;26(3):287–304. doi: 10.1080/08905459708945496.

[13] Baggio C, Trovalusci P. Collapse behaviour of three-dimensional brick-block systems using non-linear programming. Struct Eng Mechanics. 2000;10(2):181–95. doi: 10.12989/sem.2000.10.2.181.

[14] Ferris MC, Tin-Loi F. Limit analysis of frictional block assemblies as a mathematical program with complementarity constraints. Int J Mech Sci. 2001;43(1):209–24. doi: 10.1016/S0020-7403(99)00111-3.

[15] Gilbert M, Casapulla C, Ahmed HM. Limit analysis of masonry block structures with non-associative frictional joints using linear

programming. Comput Struct. 2006;84(13–14):873–87. doi: 10.1016/j.compstruc.2006.02.005.

[16] Gilbert M. Limit analysis applied to masonry arch bridges: state-of-the-art and recent developments. In ARCH'07 – 5th International Conference on Arch Bridges; 2007. p. 13–28.

[17] Nodargi NA, Intrigila C, Bisegna P. A variational-based fixed-point algorithm for the limit analysis of dry-masonry block structures with non-associative Coulomb friction. Int J Mech Sci. 2019;161–162:105078. doi: 10.1016/j.ijmecsci.2019.105078.

[18] Block PPCV. Thrust network analysis: exploring three-dimensional equilibrium. Doctoral Dissertation, Massachusetts Institute of Technology; 2009. https://dspace.mit.edu/handle/1721.1/49539.

[19] Rippmann M, Lachauer L, Block P. Interactive vault design. Int J Space Struct. 2012;27(4):219–30. doi: 10.1260/0266-3511.27.4.219.

[20] Stockdale G, Milani G. Diagram based assessment strategy for first-order analysis of masonry arches. J Build Eng. 2019;22:122–9. doi: 10.1016/j.jobe.2018.12.002.

[21] Funari MF, Spadea S, Lonetti P, Fabbrocino F, Luciano R. Visual programming for structural assessment of out-of-plane mechanisms in historic masonry structures. J Build Eng. 2020;31:101425. doi: 10.1016/j.jobe.2020.101425.

[22] R. McNeel. Grasshopper – Algorithmic Modeling for Rhino 5. 2024. https://www.grasshopper3d.com/.

[23] 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. Appl Sci. 2021;11(3):942. doi: 10.3390/app11030942.

[24] Mousavian E, Argiento LU, Casapulla C. Visual programming for macro-block analysis of multi-storey masonry buildings. In COMPDYN2021 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. 2021; Eccomas Proceedia COMPDYN (2021)752–763. www.eccomasproceedia.org.

[25] Cifani G, Petrucci G, Lazzaro D, D'Alessandro S, Cialone G, Martinelli A, et al. Repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura. ITC-CNR, L'Aquila 2006. In Italian. https://publications.cnr.it/doc/164095.