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A digital tool based on Genetic Algorithms and Limit Analysis for the seismic assessment of historic masonry buildings

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Abstract

New technologies are changing the way engineers work within the construction sector. Newly developed software solutions have provided effective methods to explore the design space at the interface between Structural Engineering and Architecture, allowing more efficient design strategies. These technologies are based on the integration of parametric generation and visualisation of geometries with powerful numerical solvers, employing user-customised routines. While the construction industry is rapidly moving the design of new construction towards a fully digitalised process, the assessment and the analysis of existing structures with such tools are still largely unexplored. In this context, a visual script for the structural assessment of out-of-plane mechanisms in historic masonry structures subject to seismic loading has recently been proposed by the authors. This relies on two successive steps of analysis, which are integrated into a digital work-flow. Datasets describing the geometric configuration of masonry structures are employed to automatically generate a non-linear Finite Element (FE) model and investigate possible collapse modes. A preliminary global analysis is performed using the commercial software ABAQUS CAE. This, in combination with the Control Surface Method (CSM), allows identifying the most likely failure mechanisms which are described by the geometry of the macro-blocks. The parametric modelling of the macro-blocks geometry allows exploring the domain of possible solutions using the upper bound method of limit analysis. A Genetic Algorithms (GA) solver is used to refine the geometry of the macro-blocks and search the minimum of the upper-bound load multipliers, which guarantees equilibrium. The script is implemented in the visual programming environment offered by Rhino3D+Grasshopper. In this paper, a set of parametric analyses considering various input variables such as friction coefficient and opening incidence are performed to verify both the sensitivity and the accuracy of the proposed method.

Keywords: Visual Programming; Genetic Algorithms; Upper bound limit analysis.

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1. Introduction

Historical masonry structures are vulnerable to natural hazards, such as earthquakes. These cause damage to cultural heritage, heavy economic losses, and difficult reconstruction processes (Lourenço et al. (2011), Masciotta et al. (2016), Mendes and Lourenço (2019), Masciotta et al. (2017), Stepinac and Gašparović (2020), Stepinac et al. (2020)).

According to the classification proposed by D'Altri et al. (2019), two possible families of approaches can be adopted to assess the structural behaviour of masonry structures beyond the elastic limit: i) incremental-iterative analyses or ii) limit analysis-based methods. Most of the proposed methods available in the literature for the structural assessment of historical constructions rely on incremental-iterative analyses which can adopt either a static or dynamic approach (Fortunato et al. (2017), Olivito et al. (2019), Cascardi et al. (2020), Funari et al. (2020), Fabbrocino et al. (2019), Mehrotra et al. (2015), Savalle et al. (2020), Giouvanidis and Dong (2020)). It is worth noting that historic structures analysed by incremental-iterative analyses are strongly dependent on the characterisation of mechanical properties of construction materials composing the structure. Moreover, such methods tend to detect localised collapse mechanisms which can lead to a loss of equilibrium under modest loads, which not always represent the actual bearing capacity of the structure (Kita et al. (2020)).

Assessment procedures based on limit analysis theorems present a significant advantage: they do not require the accurate knowledge of the mechanical properties of materials composing the structure. For these reasons, these are frequently used in engineering practice for a conservative evaluation of the seismic acceleration, which is supposed to activate the collapse mechanism. In particular, the Upper Bound method is traditionally considered a powerful tool for seismic assessment of historical masonry structures (Heyman (1966)) which, however, present some drawbacks. The value of the load multiplier depends on the geometry of the failure surfaces; therefore, multiple (theoretically infinite) failure mechanisms need to be considered in order to evaluate the smallest of the kinematically compatible load multipliers. This can be done by either performed by an iterative procedure or very simplistically, by adopting the most likely *a-priori* collapse mechanisms on the basis of surveying crack patterns (D'Altri et al. (2019)). Some researchers have tried to address this issue by using optimisation routines which are able to indicate the most likely collapse mechanisms under a given hypothesis (Fortunato et al. (2018), Chiozzi et al. (2018)).

However, as reported in the literature (Cundari et al. (2017)), neglecting the result of non-linear analyses may produce a wrong assessment of the seismic vulnerability, particularly if the investigated structures do not show a pre-existent crack pattern which allows the user to postulate the most likely collapse mechanisms. With this regard, Mele et al. (2003), have proposed a "two steps" method of analysis. In the first step, the structures are investigated in the linear-elastic range with 3D finite element models, in order to determine the static and dynamic properties. Subsequently, a 2D pushover analysis of the single macro-elements is performed. The results obtained through pushover analyses were compared to the collapse loads derived from limit analysis, proving the ability of finite element non-linear model to provide reliable simulations of the actual response of masonry elements.

Recently, Funari et al. (2020) have developed a new two-step analysis method implemented using visual programming, which is able to manage the data arising by both non-linear static or dynamic analysis to detect the most likely collapse mechanism through the Control Surface Method (CSM) (Figure 1). The parametric modelling of the macro-blocks geometry allows exploring the domain of possible solutions using the upper bound method of limit analysis. A Genetic Algorithm solver is used to refine the geometry of the macro-blocks and search the minimum of the upper-bound load multipliers, which guarantees equilibrium.

The main aim of this paper is to perform a set of parametric analyses considering various input variables such as friction coefficient and opening incidence. These analyses are performed to verify both the sensitivity and the accuracy of the proposed method. The paper is organised as follows. Section 2 describes the work-flow as well as the optimisation tool developed. Section 3 reports parametric analyses developed on two benchmark case of studies. Finally, the relevant conclusions are discussed in Section 4.

2. Proposed procedure

The first stage of the procedure developed by Funari et al. (2020) is based on the analysis of the global structural behaviour, which is carried out through a non-linear static analysis. This step can be implemented into a generalpurpose non-linear FE software. The theoretical aspects relating to this step of the procedure are detailed in Funari et al. (2020).

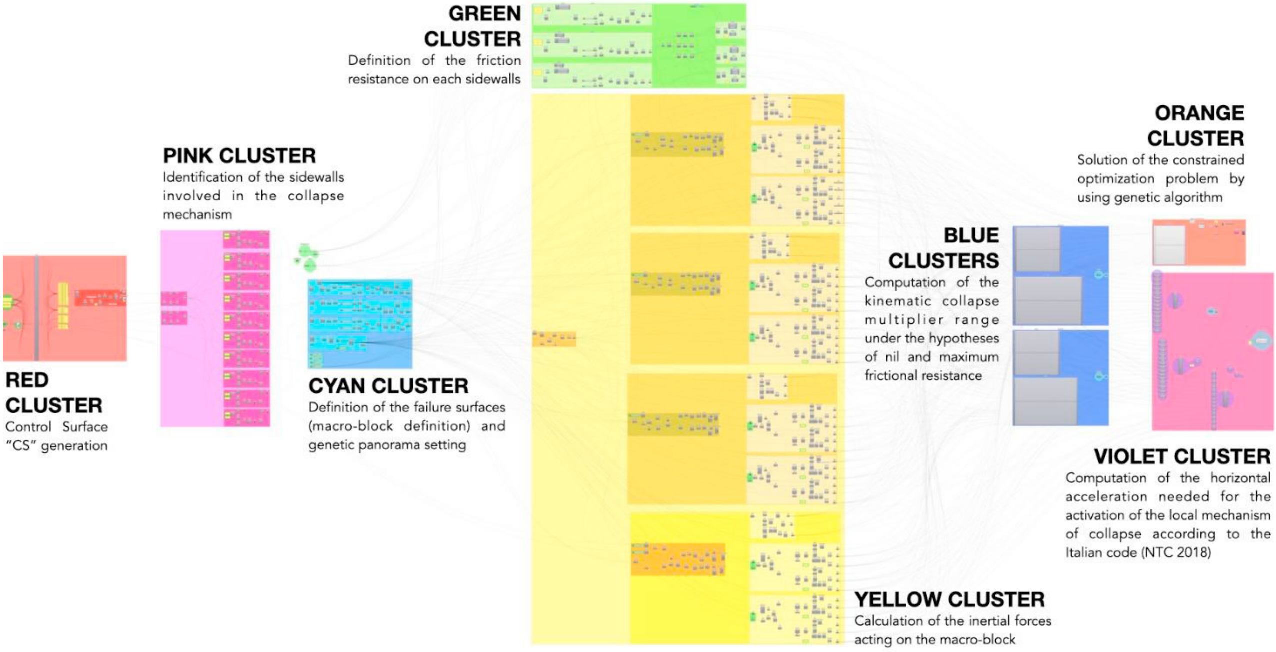


Fig. 1. Visual programming for structural assessment of out-of-plane mechanisms in historic masonry structures (Funari et al. (2020)).

The optimisation procedure, which is aimed at searching for the actual load multiplier (α_0) that generates the activation of the failure mechanism, is described in the following. According to Casapulla and Argiento (2018), the load multiplier is detected by using the upper bound theorem of the limit analysis, also taking into account the "real" frictional resistance. The actual load multiplier α_0 is, therefore, investigated using the virtual work principle:

$$\alpha_0 \sum_{i=1}^{n} W_i \delta_{(x,y),i} - \sum_{i=1}^{n} W_i \delta_{(z),i} - \sum_{s=1}^{n} F_{act,s} \delta_{(x,y),s} = 0\,, \qquad (1)$$

where W_i are the forces of inertia arising from floors and roofs as well as the self-weights of the masonry walls and $F_{act,s}$ are the actual frictional forces computed as a weighted value in function of the inclinations of the crack line (Casapulla et al. (2018)), i.e.:

$$F_{act,s} = F_{\max,s}\left(1-\frac{\alpha_c}{\alpha_b}\right), \qquad (2)$$

where $F_{\max,s}$ are the frictional forces computed under the hypothesis of maximum frictional resistance (Casapulla et al. (2018)).

The minimum load factor capable of activating the failure mechanism is therefore computed through an optimisation routine while varying the position of the points that discretise the cracked surface. As shown in Figure 2, the position of the points X1 and X2, which represent the optimisation variables, discretise the cracks line. Their abscissa can vary within a range that is set by the user on basis of engineering experience as well as physical compatibility of the failure mechanism. Thus, the load multiplier is obtained by solving the following constrained minimisation problem:

$$\left\{ \min\ \alpha_0 : \frac{l}{2nh} \le \tan\alpha_c \le \tan\alpha_b \right. \tag{3}$$

where α_b is the crack inclination upper threshold (which depends by the blocks geometry (Casapulla et al. (2018))), α_c is the actual crack inclination which arises by the minimization of the load multiplier (α_0) (see Eq. (3)), and l, h, n are the brick length, the brick high and the number of vertical bricks rows, respectively.

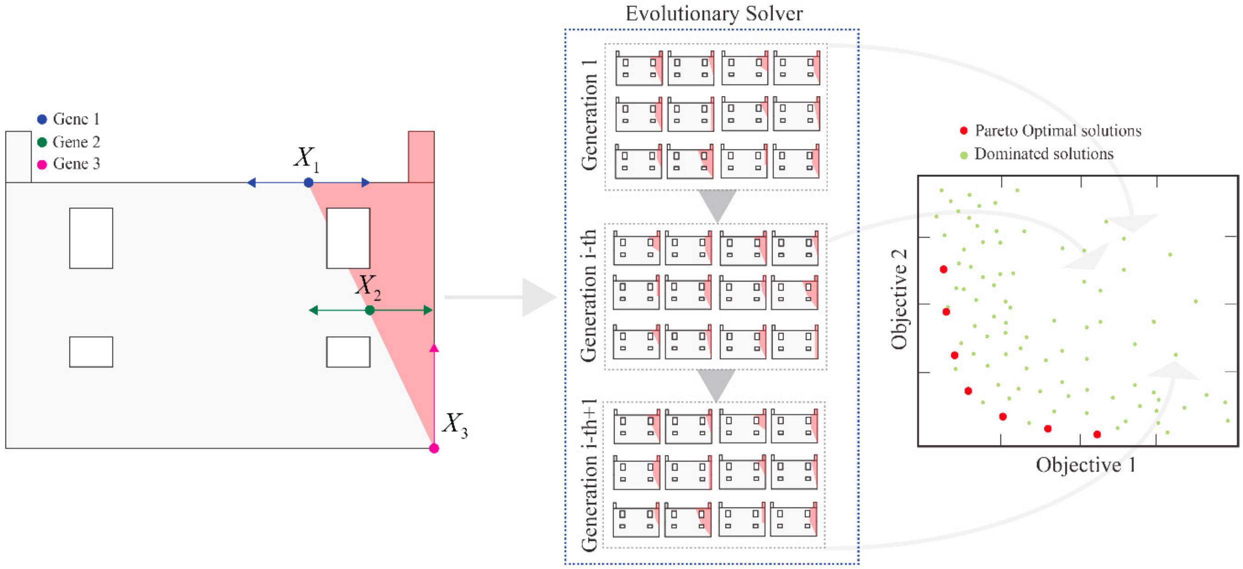


Fig. 2. Evolutionary Solver: Genes definition, generations representation and graphical representation of the genomes.

The optimization problem reported in Eq. 3 is numerically solved by using an evolutionary solver. The ES uses techniques such as reproduction, mutation, selection and recombination. According to biological vocabulary, the variables which are allowed to change are called genes. Basically, as the i-th gene changes, the state of the model changes and it either becomes better or worse (depending on what the user is searching for). Initially, a population composed of randomised genes (dimension values) is generated and by assessing the fitness of each chromosome (permutation of genes), the initial landscape points of the search space are identified. New populations of chromosomes are then generated based upon parent selection, crossover and mutation, and the fitness reassessed until the required conditions are found (Rutten (2013)).

3. Results

3.1. Masonry wall without openings

A masonry wall loaded in its plane is here considered to validate the suitability of the proposed procedure to solve the minimisation problem described in Eq. (2). Figure 3 shows the geometry of the case study, which consist of an assemblage of bricks subjected to in-plane horizontal forces proportional to its self-weight. In the present example, a friction coefficient equal to 0.65 is considered, as in Casapulla et al. (2013).

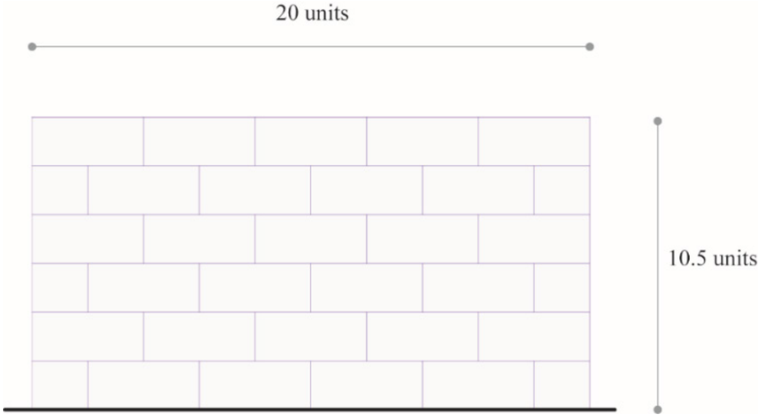


Fig. 3. Geometric configuration of the benchmark masonry walls subjected to in-plane horizontal loading.

In Tab.1, results in terms of upper and lower load multiplier as well as crack slope, are reported. The results obtained on the basis of the proposed formulation as well as the ones obtained by adopting the macro-block formulation proposed in Casapulla et al. (2013) are reported. In the same table, the results arising from the micro-modelling approach discussed in Casapulla et al. (2013) are also summarised.

Table 1: Predicted load factor and crack slope. Comparisons between the present model and both the macro and micro-modelling developed by Casapulla et al. (2013).

Proposed Model		**Macro-block model Casapulla et al. (2013)**			**Micro-block model Casapulla et al. (2013)**		
α_0	$\tan\beta$	α_{upp}	α_{low}	$\tan\beta$	α_1	α_2	$\tan\beta$
0.611	0.625	0.65	0.4221	-	06394	0.6393	-

The results obtained are in good agreement with those available from the micro-block formulation. In Figure 4, a comparison in terms of slope of the crack is reported. The crack line is almost perfectly overlapped with that obtained from both macro and micro modelling developed by Casapulla et al. (2013).

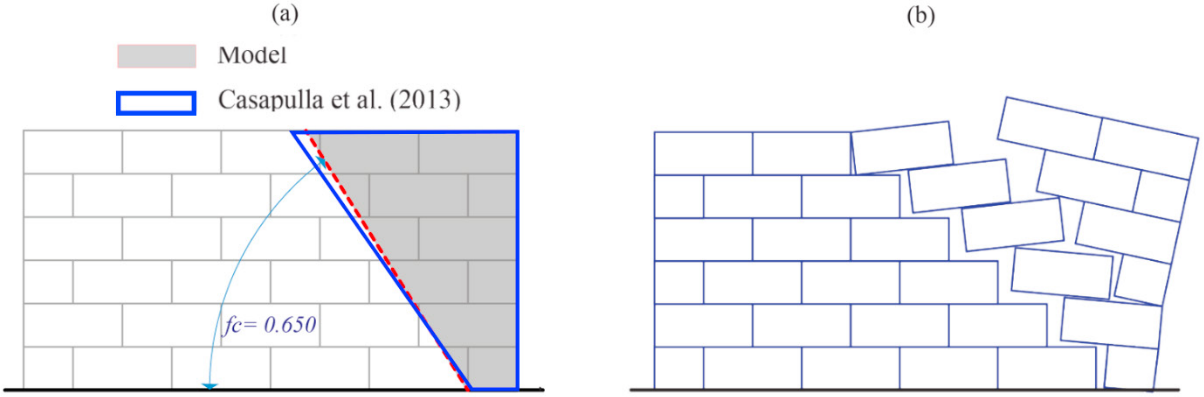


Fig. 4. Predicted macro-block geometry, comparisons with macro (a) and micro (b) modelling proposed in Casapulla et al. (2013).

In order to verify the influence of the friction coefficient and to investigate its sensitivity, a parametric analysis has been performed. To this end, the following values of the friction coefficient are considered:

- fc=0.550;
- fc=0.600;
- fc=0.650 (reference);

- fc=0.700;
- fc=0.750;
- fc=0.800.

In Figure 5, comparisons in terms of obtained macro-block geometry are reported. It is worth noting that once the friction coefficient increases, a bigger macro-block is involved in the failure mechanism, thus providing a larger load multiplier. Figure 6 shows a synoptic representation of the cracks obtained by changing the friction coefficient.

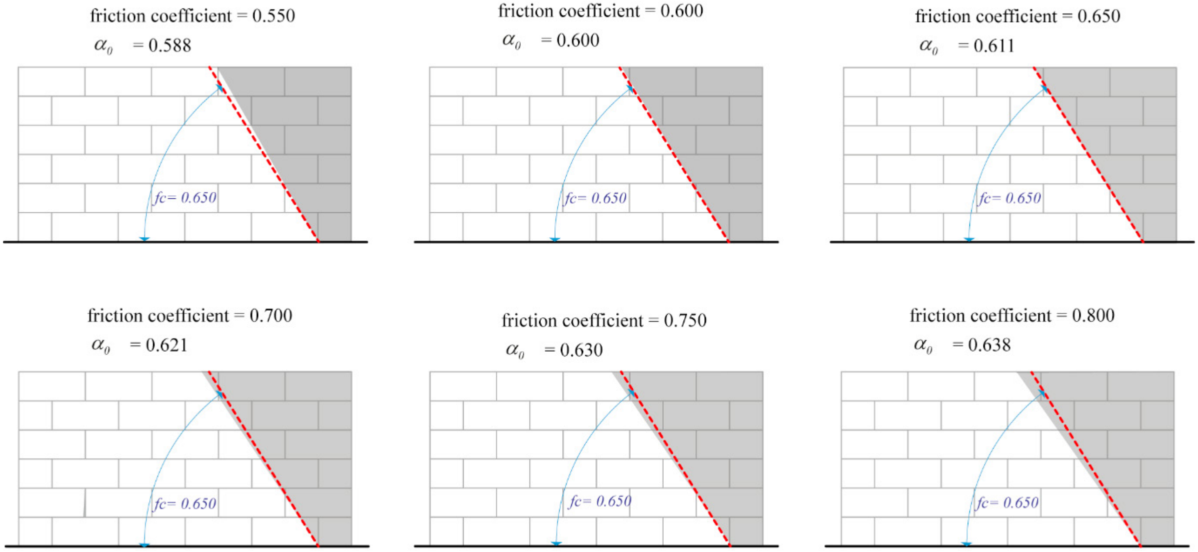


Fig. 5. Predicted macro-block geometry by adopting different friction coefficient.

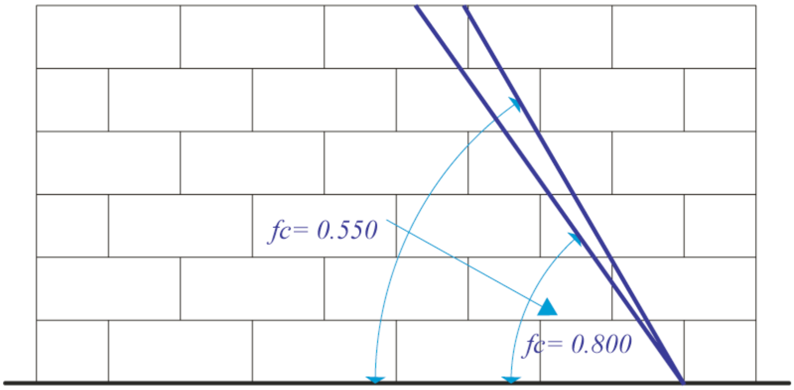
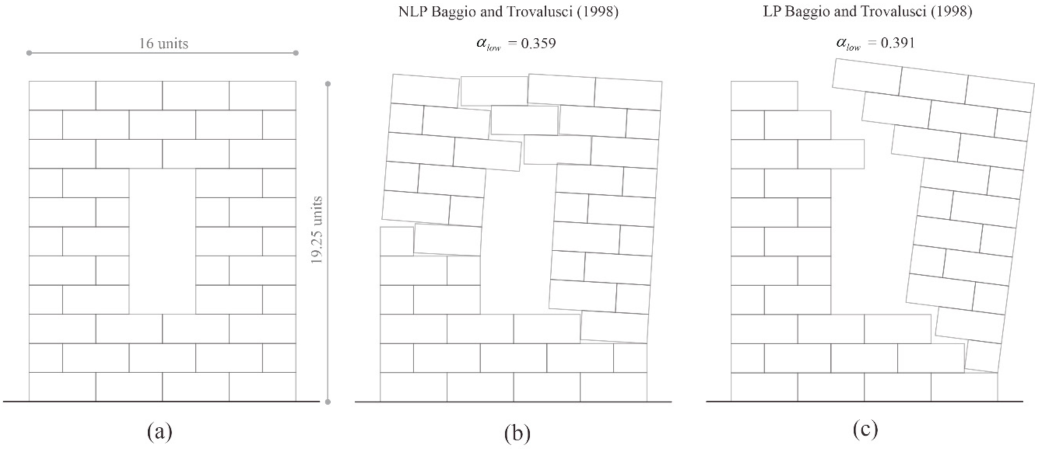


Fig. 6. Comparison in terms of crack lines as a function of the friction coefficient.

3.2. Masonry wall with an opening

The second case study aims to investigate the behaviour of a masonry wall with an opening. The geometry, the boundary conditions and the mechanical parameters are taken in agreement with Baggio and Trovalusci (1998), which developed a computer procedure to determine the collapse using a non-standard limit analysis where the masonry is modelled as a discrete system of rigid blocks in dry contact. The structural model, as well as the results obtained by using the Non-Linear Program (NLP) and the Linear Program (LP) (Baggio et al. (1998)), are represented in Figure 7. As shown in Figure 7c, the crack pattern is mainly featured by the overturning of rigid blocks that assume the structural behaviour of a macro-block.



(a) (b) (c)

Fig. 7. (a) Masonry wall with an opening; (b) failure mechanism under self-weight and live horizontal body NLP; (c) failure mechanism under self-weight and live horizontal body LP.

The proposed digital tool integrates the same assumptions reported in Casapulla et al. (2018) ,which are here not reported for sake of brevity.

In Figure 8 the obtained macro-block geometry is reported. The geometry of the macro-block is in perfect agreement with that obtained by Baggio et al. (1998), whereas the load multiplier computed by using the proposed macro-block approach is lower. This conservative result is in agreement with the engineering assumptions of the macro-block approach, which allows the users to get an evaluation of the seismic safety of the structure strongly reducing the computational efforts.

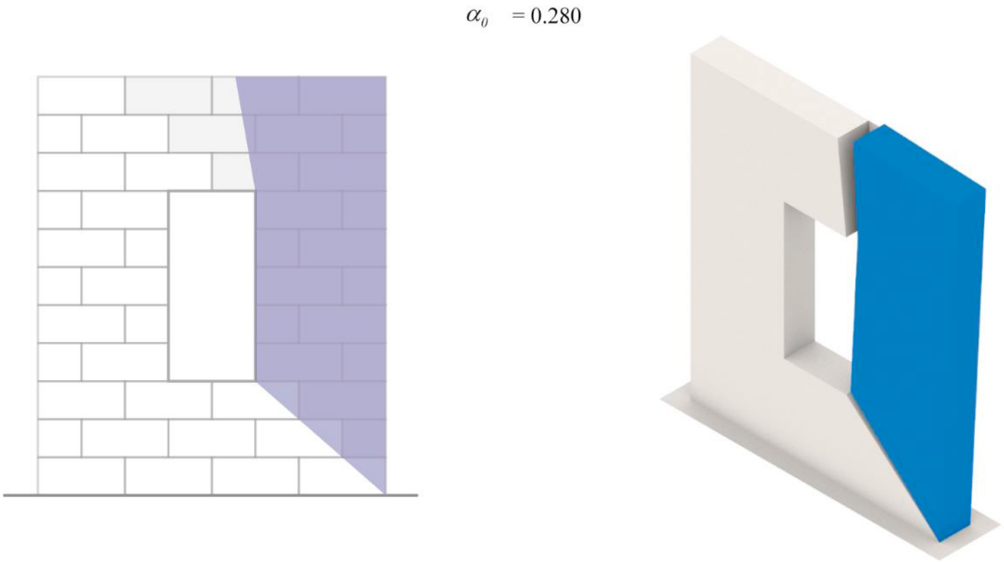


Fig. 8. Predicted macro-block geometry by using the proposed model.

4. Conclusions

In this work, a novel digital procedure for the assessment of masonry structures is proposed. The method embeds an upper bound limit analysis of the problem under the hypothesis of no-tension capacity for the masonry material and a concurrent static check. Based on such failure surfaces, genetic algorithms are used to generate a variety of different collapse mechanisms that are kinematically compatible. Additionally, genetic algorithms are employed to search for the failure mode corresponding to the minimum value of the load multiplier that is also statically equilibrated. The work-flow is integrated into a computational tool implemented in the visual programming environment offered by Rhinoceros3D+Grasshopper. This is well suited to be confidently used by practitioners, also allowing the user to make decisions using his engineering judgement.

Finally, the parametric study emphasises the effects produced by the use of different values for the frictional coefficient as well as the capability of the proposed method to identify the macro-block geometry when an opening is present. Although GA algorithms may require high computational efforts, they make possible a robust implementation of a multidimensional constrained optimisation problem. Furthermore, the adoption of the upper bound theorem of the limit analysis under the hypothesis of the macro-blocks discretisation strongly improves the computational efficiency without requiring the detailed knowledge of the mechanical properties of materials and providing a solution of the structural problem showing good accuracy.

References

Baggio, C. and P. Trovalusci, 1998. Limit analysis for no-tension and frictional three-dimensional discrete systems. Mechanics of Structures and Machines 26(3), 287-304.

Casapulla, C. and L.U. Argiento, 2018. In-plane frictional resistances in dry block masonry walls and rocking-sliding failure modes revisited and experimentally validated. Composites Part B: Engineering 132, 197-213.

Casapulla, C., A. Maione, L.U. Argiento, and E. Speranza, 2018. Corner failure in masonry buildings: An updated macro-modeling approach with frictional resistances. European Journal of Mechanics, A/Solids 70, 213-225.

Casapulla, C., F. Portioli, A. Maione, and R. Landolfo, 2013. A macro-block model for in-plane loaded masonry walls with non-associative Coulomb friction. Meccanica 48(9), 2107-2126.

Cascardi, A., F. Micelli, M. Aiello, and M. Funari, 2020. Structural analysis of a masonry church with variable cross-section dome. Brick and Block Masonry-From Historical to Sustainable Masonry: Proceedings of the 17th International Brick/Block Masonry Conference (17thIB2MaC 2020), July 5-8, 2020, Kraków, Poland, 220.

Chiozzi, A., G. Milani, N. Grillanda, and A. Tralli, 2018. A fast and general upper-bound limit analysis approach for out-of-plane loaded masonry walls. Meccanica 53(7), 1875-1898.

Cundari, G.A., G. Milani, and G. Failla, 2017. Seismic vulnerability evaluation of historical masonry churches: Proposal for a general and comprehensive numerical approach to cross-check results. Engineering Failure Analysis 82, 208-228.

D'Altri, A., V. Sarhosis, G. Milani, J. Rots, S. Cattari, S. Lagomarsino, E. de Miranda, A. Tralli, and G. Castellazzi, 2019. A review of numerical models for masonry structures. Numerical Modeling of Masonry and Historical Structures: From Theory to Application, 1.

Fabbrocino, F., M.F. Funari, F. Greco, P. Lonetti, R. Luciano, and R. Penna, 2019. Dynamic crack growth based on moving mesh method. Composites Part B: Engineering 174.

Fortunato, A., F. Fabbrocino, M. Angelillo, and F. Fraternali, 2018. Limit analysis of masonry structures with free discontinuities. Meccanica 53(7), 1793-1802.

Fortunato, G., M.F. Funari, and P. Lonetti, 2017. Survey and seismic vulnerability assessment of the Baptistery of San Giovanni in Tumba (Italy). Journal of Cultural Heritage 26, 64-78.

Funari, M.F., S. Spadea, F. Fabbrocino, and R. Luciano, 2020. A moving interface finite element formulation to predict dynamic edge debonding in FRP-strengthened concrete beams in service conditions. Fibers 8(6).

Funari, M.F., S. Spadea, P. Lonetti, F. Fabbrocino, and R. Luciano, 2020. Visual programming for structural assessment of out-of-plane mechanisms in historic masonry structures. Journal of Building Engineering 31.

Giouvanidis, A. and Y. Dong, 2020. Seismic loss and resilience assessment of single-column rocking bridges. BULLETIN OF EARTHQUAKE ENGINEERING.

Heyman, J., 1966. The stone skeleton. International Journal of solids and structures 2(2), 249-279.

Kita, A., N. Cavalagli, M.G. Masciotta, P.B. Lourenço, and F. Ubertini, 2020. Rapid post-earthquake damage localization and quantification in masonry structures through multidimensional non-linear seismic IDA. Engineering Structures 219.

Lourenço, P.B., N. Mendes, L.F. Ramos, and D.V. Oliveira, 2011. Analysis of masonry structures without box behavior. International Journal of Architectural Heritage 5(4-5), 369-382.

Masciotta, M.G., L.F. Ramos, and P.B. Lourenço, 2017. The importance of structural monitoring as a diagnosis and control tool in the restoration process of heritage structures: A case study in Portugal. Journal of Cultural Heritage 27, 36-47.

Masciotta, M.G., J.C.A. Roque, L.F. Ramos, and P.B. Lourenço, 2016. A multidisciplinary approach to assess the health state of heritage structures: The case study of the Church of Monastery of Jerónimos in Lisbon. Construction and Building Materials 116, 169-187.

Mehrotra, A., A. Arede, and M.J. DeJong, 2015. Discrete element modeling of a post-tensioned masonry arch. Civil-Comp Proceedings.

Mele, E., A. De Luca, and A. Giordano, 2003. Modelling and analysis of a basilica under earthquake loading. Journal of Cultural Heritage 4(4), 355-367.

Mendes, N. and P.B. Lourenço, *Chapter 4 - Seismic assessment of historic masonry structures: out-of-plane effects*, in *Numerical Modeling of Masonry and Historical Structures*, B. Ghiassi and G. Milani, Editors. 2019, Woodhead Publishing. pp. 141-162.

Olivito, R.S., S. Porzio, M.F. Funari, C. Scuro, and F. Demarco, 2019. A numerical-geometrical methodology to represent out-of-plane mechanisms of unreinforced masonry structures by using pushover analysis. 1, 1263-1271.

Rutten, D., 2013. Galapagos: On the logic and limitations of generic solvers. Architectural Design 83(2), 132-135.

Savalle, N., É. Vincens, and S. Hans, 2020. Experimental and numerical studies on scaled-down dry-joint retaining walls: Pseudo-static approach to quantify the resistance of a dry-joint brick retaining wall. Bulletin of Earthquake Engineering 18(2), 581-606.

Stepinac, M. and M. Gašparović, 2020. A review of emerging technologies for an assessment of safety and seismic vulnerability and damage detection of existing masonry structures. Applied Sciences (Switzerland) 10(15).

Stepinac, M., T. Kisicek, T. Renić, I. Hafner, and C. Bedon, 2020. Methods for the assessment of critical properties in existing masonry structures under seismic loads-the ARES project. Applied Sciences (Switzerland) 10(5).