3D Non-periodic Masonry Texture Generation of Cultural Heritage Structures

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Abstract. Block-based models, which can account for the actual block-by-block masonry texture, are becoming more commonly used for the analysis of historical masonry structures, given their high accuracy in representing masonry mechanics and their computational demand which has become lately approachable. However, the implementation of full-scale models where every single masonry block is accurately represented can be time-consuming, and even impossible, due to lack of relevant data. In this contribution, a 3D non-periodic masonry pattern generator is proposed for the block-based analysis of full-scale historical structures. This approach uses as input the digital solid model of the structure, in terms of voxels, and a representative texture of a small portion of a wall. The generator automatically creates the block-by-block arrangement of the whole structure through a pseudo-statistically meaningful representation, also in case of multi-leaf walls. An example of cultural heritage structure is used to assess the effectiveness of the automatic generator. Then, pushover-like analyses are conducted by means of an available block-based model, investigating the masonry texture influence on full-scale mechanical responses.

Keywords: Multi-leaf masonry · Masonry mechanics · Non-periodic texture · Historical monumental buildings · Voxel

1 Introduction

Numerical modelling of masonry and historical structures can result essential to apply conservation strategies on cultural heritage (CH) buildings. In this framework, block-based models (that account for the actual block-by-block masonry texture) represent the most accurate option for the structural analysis of masonry structures [1], including also multi-leaf non-periodic masonry [2, 3]. The main drawbacks that characterize block-based models are: (i) their considerable computational demand, and (ii) the impossibility to geometrically accurately represent every single block in a full-scale masonry structure, due to non-periodic patterns and lack of relevant data [4].

Concerning drawback (i), the recent enhancement of computational facilities together with the recent development of efficient models allowed the block-based simulation of large-scale masonry structures, as shown in [5, 6].

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Concerning drawback (ii), a possible recent way to solve the issue, beyond image-based methods [7, 8] limited to plane and single-layer structures, considers pattern generators which can automatically generate the block-by-block geometry of the structure to be used in structural analysis. In this framework, a 2D generator for historic stone masonry has been developed in [9], whereas a 3D generator for stone masonry walls has been developed in [10]. Particularly, a multi-objective optimization packing approach has been developed to place the blocks in the wall and to fill the overall volume. Although this method allows to create realistic non-periodic multi-leaf masonry walls, also based on irregular blocks, the resulting finite element (FE) meshes have a large number of degrees of freedom and, so, a considerable computational effort. Therefore, the utilization of these FE meshes appears limited to homogenization and multiscale analyses, while their full-scale application appears still unlikely.

In this contribution, a 3D non-periodic masonry pattern generator is proposed for the block-based analysis of full-scale historical structures. This approach requires as input (in terms of voxels): (i) the digital solid model of the structure, and (ii) a representative texture of a small portion of a wall. Input (i) is also obtainable directly from point clouds of CH structures [11], while input (ii) could be obtained automatically from images [12].

The generator automatically fills the volume of the structure through a block-by-block arrangement that attempts to keep the blocks statistics of the representative texture, also in case of multi-leaf walls. Such 3D block-by-block texture is directly employable in block-based computational analysis of full-scale historical masonry structures.

An example of CH structure, namely the Alcaçova wall of the Guimarães castle (Portugal) [13, 14] characterized by 2 leaves of non-periodic granite blocks, is used to assess the effectiveness of the automatic texture generator. The generated texture is then employed in pushover-like analyses by adopting a 3D damaging block-based model previously developed in [15]. Finally, the influence of masonry texture on full-scale mechanical responses is discussed.

2 Masonry Texture Generator

The 3D masonry texture generator here proposed is based on voxels and requires as input:

(i) the digital solid model of the structure (target volume); and
(ii) a representative texture of a small portion of a wall.

The target volume allows the specification of fillable and non-fillable regions (e.g. openings), while all the block types and their statistics to be considered in the structure can be found in the representative texture.

Firstly, lintels are inserted above openings. Particularly, openings are automatically identified and lintels of a suitable size are introduced as special blocks. Then, edges and corners are filled. This filling procedure moves vertically, up to the edge/corner is eventually filled.

Finally, all the inner regions of the volume are filled with blocks. This last operation is carried out block-by-block, starting from the bottom row of a first leaf and repeated for the rows above. While filling a row, head joints are detected and a set of block types suitable to be inserted without vertical alignment are determined. If the available block types cannot guarantee to perfectly fill the volume, ad hoc block types are introduced to fill any remaining gap. A follow-up adjustment step, which tries to minimize the number of ad hoc blocks through the merging with neighboring blocks, is finally performed. The interested reader is referred to [16] for further details.

A preliminary check of the consistency of the generator is here shown and discussed (Fig. 1). An example of representative texture used as reference is shown in Fig. 1a, arbitrarily taken from the case study in [13] with 10 block types, 2 of which are through-thickness. The target volume is created by scaling 3 times the width and the height of the representative texture (Fig. 1a), considering a thickness of 3 leaves. Hence, 3 samples are generated and considered. The block type content percentages (p) of the reference texture and the 3 generated samples are shown in Fig. 1b, while the arrangements of the 3 generated samples are shown in Fig. 1c. As it can be noted from these preliminary results, the generator produces statistically-consistent textures in a robust way.

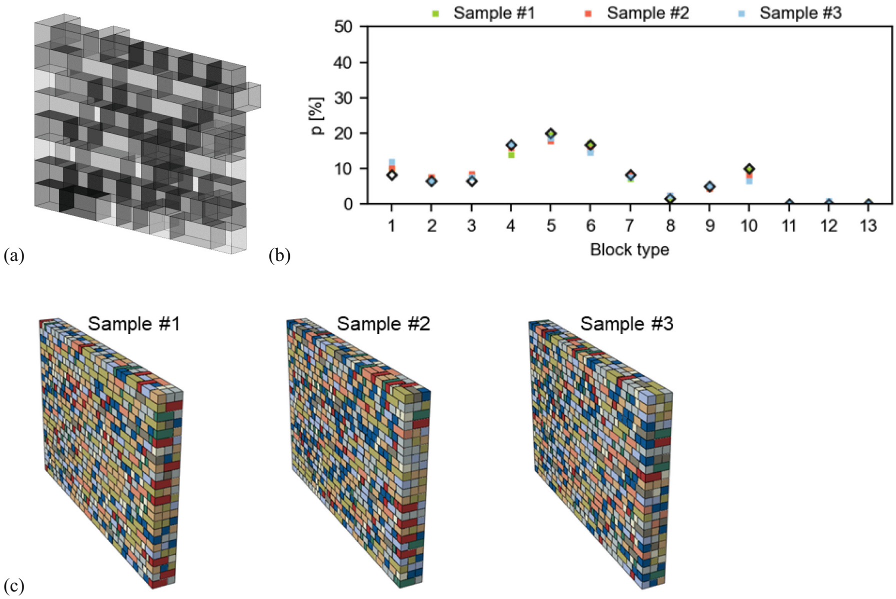


Fig. 1. Example of masonry texture generation. (a) Representative texture (reference). (b) Reference (black markers) and generated samples block type content percentages. (c) Arrangements of the generated masonry samples.

The generator is then employed for a CH structure, i.e. the Alcaçova wall of the Guimarães castle (Portugal) [13, 14], see Fig. 2. The target volume of this structure is taken from [13], where few geometrical simplifications were adopted. Accordingly, the target volume is composed of 2 leaves of blocks and 7 openings (Fig. 2a). The masonry texture generated by means of the representative texture in Fig. 1a is shown in Fig. 2b ("Actual texture"), while the texture generated with the same representative texture, but without through-thickness blocks, is shown in Fig. 2c ("Without through-thickness blocks"). As it can be noted, the overall filling of the target volume is guaranteed by means of this 3D masonry texture generator.

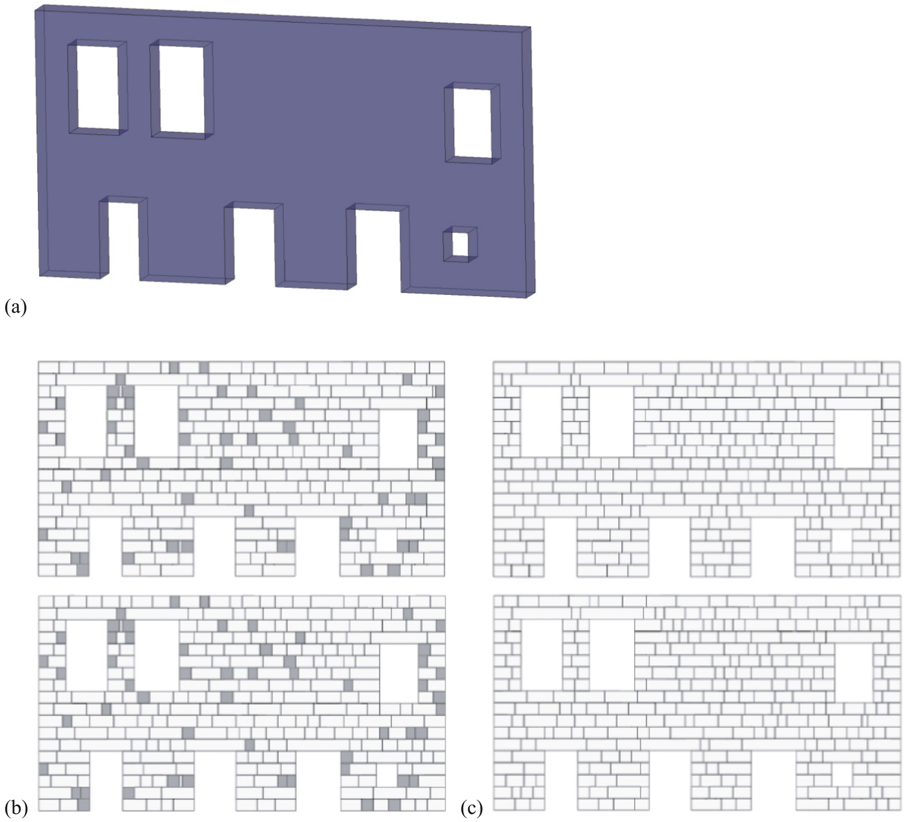


Fig. 2. CH structure texture generation. (a) Simplified digital solid model of the Alcáçova wall. Masonry textures of the two leaves: (b) Actual texture (through-thickness blocks are highlighted in dark grey), (c) Without though-thickness blocks.

3 Structural Analysis

3.1 Numerical Modelling

The generated textures (Fig. 2b-c) are then employed in pushover-like analyses using the 3D damaging block-based model developed in [15]. Such model is characterized by 3D damaging blocks and zero-thickness joints modeled through contact-based cohesive-frictional interfaces. The interested reader is referred to [15] for additional details. The mechanical characterization has been conducted in agreement with [13].

The damaging behavior of blocks relies on the plastic-damage continuum constitutive law developed in [17]. Such law accounts for isotropic damage by means of two damage scalar variables, $0 \leq d_t < 1$ for tension and $0 \leq d_c < 1$ for compression. The main input of the continuum constitutive law is represented by tensile and compressive uniaxial stress-strain curves, which are given for the case study in Table 1 together with the elastic properties of blocks.

Table 1. Block mechanical properties.

Young's modulus [MPa]		4800			
Poisson's ratio [\]		0.17			
Density [kg/m^3]		2700			
Tensile uniaxial nonlinear response			Compressive uniaxial nonlinear response		
Stress [MPa]	Inelastic strain	d_t [\]	Stress [MPa]	Inelastic strain	d_c [\]
1.0	0	0	12.0	0	0
0.1	0.001	0.9	12.0	0.004	0
			1.2	0.012	0.9

The joint response relies on a node-to-surface cohesive-frictional contact formulation. In the normal direction, the contact constrain is enforced by means of the Lagrange multiplier method. In addition, a cohesive response is activated in tension, governed by the normal cohesive stiffness K_t, the tensile strength f_t, and the excursion of normal displacement u^F in the softening branch, assumed linear. In the shear direction, a cohesive-frictional response is activated. The cohesive response is governed by the shear cohesive stiffness K_s^c, the cohesion c, and the slip excursion δ^F in the softening branch (linear), while the frictional response is merely governed by the friction angle ϕ. In particular, the frictional contribution is assumed to reach the plateau contemporarily to the peak of cohesion. The joint mechanical properties used for the CH example are given in Table 2. It should be pointed out that the intralayer joints have been assumed without cohesion, i.e. only friction has been considered.

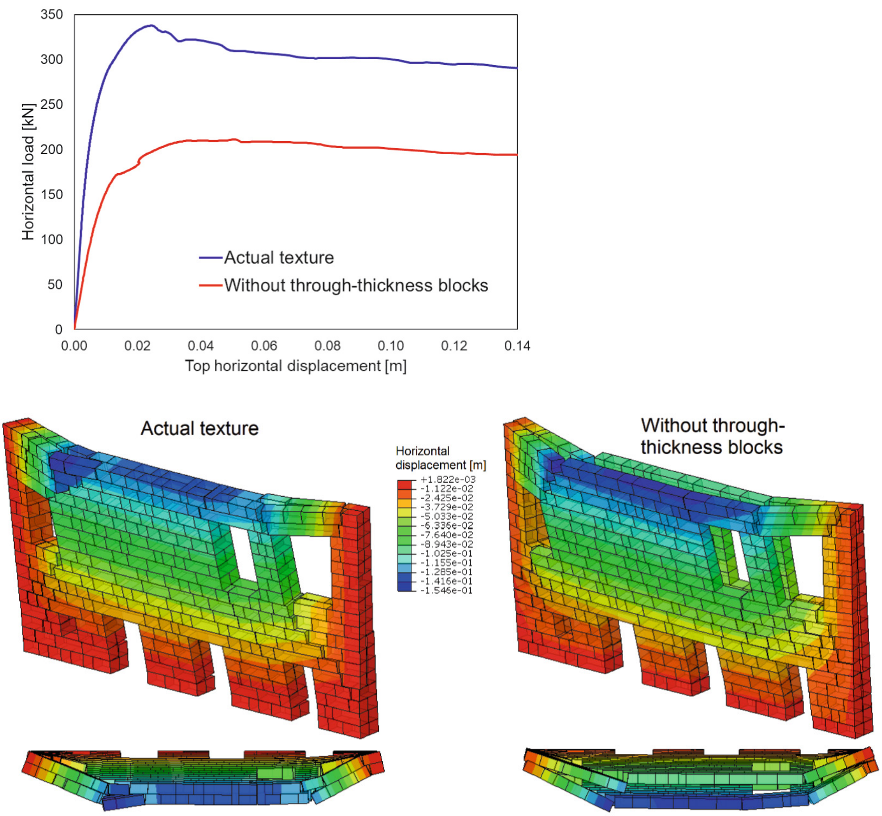
Table 2. Joint mechanical properties.

Tensile response		Shear response	
f_t [MPa]	0.05	c [MPa]	0.05
u^F [mm]	0.5	δ^F [mm]	0.5
K_t [N/m^3]	$1.0 \cdot 10^{10}$	K_s^c [N/m^3]	$0.5 \cdot 10^{10}$
		ϕ [°]	30

The generated models are then employed in nonlinear static analyses. Particularly, the wall is uniformly loaded out-of-plane, clamped at the base, and horizontal supports are placed on two vertical edges of the sides (that attempts to mimic the constraint given by orthogonal walls).

3.2 Numerical Results

In this section, the results of the out-of-plane analyses for the “Actual texture” and the case “Without through-thickness blocks” are shown and discussed (Fig. 3). In particular, the pushover curves are shown in Fig. 3a, while the collapse mechanisms are shown in Fig. 3b, in terms of horizontal displacement contour plots. As it can be noted, considerable differences appear between the “Actual texture” and the case “Without through-thickness blocks”, both in terms of (i) pushover curves (Fig. 3a), where a remarkably lower horizontal capacity and overall stiffness is observed in the case “Without through-thickness blocks” with respect to “Actual texture, and (ii) collapse mechanisms (Fig. 3b), where a complete detachment between leaves is only observed in the case “Without through-thickness blocks”.



(a)

(b)

Fig. 3. Numerical results of the out-of-plane loaded CH structure: (a) pushover curves, and (b) collapse mechanisms.

According to these preliminary results, the presence of few through-thickness blocks appears to have a beneficial contribution to the out-of-plane capacity of the wall, preventing the detachment between leaves.

4 Conclusions

In this contribution, a pattern generator for 3D non-periodic masonry structures has been proposed. This generator requires as input the digital solid model of the structure and a representative texture of the wall, both in terms of voxels, to automatically fill the overall volume of the structure through a block-by-block arrangement that attempts to keep the blocks statistics of the representative texture. This approach showed to be effective also in case of multi-leaf walls, and appeared directly employable in block-based computational analysis of full-scale historical masonry structures.

The Alcaçova wall of the Guimarães castle (Portugal), characterized by 2 leaves of non-periodic granite blocks, has been used as benchmark to assess the effectiveness of the automatic texture generator, which proved to be robust and efficient in providing convenient inputs for full-scale block-based analysis of CH structures.

The generated textures have been then employed in out-of-plane pushover analyses by adopting an available damaging block-based model. Preliminary results highlighted that the presence of few through-thickness blocks appears to have a beneficial contribution to the out-of-plane capacity of the structure, preventing the detachment between leaves.

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