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A Visual Programming-Aided Discontinuum Approach for an Efficient Macro-Scale Seismic Analysis of Unreinforced Masonry Structures

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ABSTRACT

Accurate 3D geometric models are a critical step in the documentation and evaluation of old unreinforced masonry (URM) structures, where complex and irregular geometries are often present. However, detailed geometric documentation strategies such as close-range photogrammetry or 3D terrestrial laser scans often result in large, difficult to navigate digital files. Transitioning from these detailed, high-resolution models to functional 3D CAD models presents several challenges, including high computational cost and significant time investment. Traditional workflows often struggle to efficiently create workable models suitable for structural/seismic analysis, which can be overcome using novel strategies. This paper presents a visual programming approach to discontinuum analysis in a case study of a typical URM industrial building in Eastern Canada. This approach leverages a previously developed simplified modelling strategy, the Distinct-Element macro-crack-network, informed by the Equivalent Frame Method (EFM) as a discretization method implemented into a distinct element software for subsequent seismic analysis. The proposed workflow enables the rapid conversion of dense data into discretized models by automating repetitive tasks and integrating rule-based algorithms for model refinement. The case study analysis investigates the seismic response of a typical old URM industrial building constructed using clay brick masonry and located in Montréal, QC. Results from this study display the use of algorithms paired with a simplified modelling strategy to enhance understanding of the structural behaviour of old URM buildings.

KEYWORDS

Equivalent frame method, discrete element method, unreinforced masonry, visual programming, Eastern Canada

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INTRODUCTION

The creation of accurate numerical models allows for engineers, practitioners and researchers to carry out the structural analysis of existing unreinforced masonry (URM) structures, for use in conservation efforts and intervention designs. A variety of modelling strategies exist, ranging from detailed micro-models to more simplified macro-models [1] where the choice of which strategy to implement is driven by the availability of input information and output requirements dictated by the project [2]. The more detailed strategies provide greater precision in their ability to represent e.g. crack patterns and local mechanisms yet come at a high computational cost. The choice also between software for creating either continuous models such as in finite element (FE) analysis, discontinuous models utilizing discrete elements or more simplified approaches such as limit analysis [3,4] or equivalent frame model (EFM) based approaches [5,6] indeed plays a roll due to the inherent assumptions of each strategy and the quantity of detailed input information required to run each analysis. Discontinuous solutions, originally invented to solve soil mechanics problems, using the distinct element method (DEM) have been able to suitably represent URM in-plane (IP) and out-of-plane (OOP) behaviour at both a macro- and micro- level [7–11]. While some progress has been made to improve the computational efficiency of DEM analysis [7,8], these models still require comprehensive input information to carry out analyses and often require a high computational power where detailed analyses can take weeks to preform. Knowledge of geometric and material properties aids in decreasing epistemic uncertainties to improve confidence in results and while new technologies and developments have improved access to detailed geometrical and structural information e.g. [12,13], efficiently implementing these details into numerical models remains difficult due to high computational power and large time investments required.

With respect to geometric uncertainties, the available high fidelity measurement tools for recording geometry including 3D laser scanning or digital photogrammetry provides a quick and accurate manner for creating digital models or point clouds – often implemented for documentation efforts but not immediately usable in most numerical software. Converting such highly accurate renderings remains a time-consuming challenge, and while efforts to improve the process of converting to structural models have provided efficient tools in this process, none have been implemented for discrete element macro-modelling. Point cloud voxelization has been implemented by Kassotakis et al. [14] for a point cloud to DEM procedure, however this process is not automated. Data from LiDAR scans has also been successfully either semi-automated [15] or fully automated [16] to create building façades or FE models in which details of geometrical features (e.g. masonry block size, cracks) are not required. However, visual programming tools have been successfully implemented in the modelling of masonry patterns [17] and visual programming remains a useful tool to increase the automation in creation of FE [18] and DE models [19,20].

This paper presents refinements to a semi-automated procedure to create efficient DEM models using visual programming tools developed by the authors and validated in Zhang et al. [20]. This approach leverages the strategy applied in the Equivalent Frame Method (EFM) [6,21,22] to create a Distinct-element macro-crack network (MCN) for simplified discontinuous modellings, decreasing the computational cost associated with a more detailed approach. The proposed methodology facilitates the efficient conversion of dense datasets into discretized models by automating iterative processes and incorporating rule-based algorithms for model optimization, herein presenting further refinements for 3D building modelling capabilities. This work explores the application of the methodology and its application to a case study which examines the seismic response of a representative unreinforced masonry (URM) industrial building, constructed with clay brick masonry. The results highlight the abilities of algorithmic integration with simplified modeling techniques to increase understanding of the structural behavior of old URM buildings.

EQUIVALENT FRAME METHOD FOR STRUCTURAL ANALYSIS

Previous work in the simplified analysis of URM structures identifies EFM as an effective approach for seismic analyses, albeit requiring assumptions based on the definition of the structure into pier elements (vertical load bearing), spandrel elements (horizontal load bearing) and rigid nodes, defined as areas connecting piers and spandrels where no deformation is expected. EFM is a macro-scale approach to modeling, representing the global behaviour of a building according to anticipated mechanisms. In this strategy, structural elements (piers and spandrels) are connected to the rigid nodes to form a frame, where the nonlinearity and deformability are present. Often, EFM formulations used in software such as Tremuri [6] or elements defined by e.g. [23] imply the out-of-plane (OOP) failure modes will not govern due to proper connection between floor and roof diaphragms which restrict OOP modes. Recent expansion of element formulations for use in OpenSees by Vanin et al. [24] include OOP modes in their formulation, something not previously available. The EFM approach has been applied to discontinuous models previously using the Macro-DEM [8,25] discretization, albeit defining the failure surfaces a-priori in the modelling strategy. One challenge to the adoption of EFM is the identification of piers, spandrels and notes, often difficult for facades with irregular openings common of existing URM structures [26], as discussed later in this work. This framework has been successfully applied for the seismic analysis of old URM buildings around the world e.g. [5,22,27,28], widely adopted by researchers and practitioners alike.

PROPOSED FRAMEWORK FOR DISCRETIZED GEOMETRY

The distinct element macro-crack network (MCN) discretization, developed and validated by Zhang et al. [20], uses a semi-automated visual programming approach to identify macro-elements and further discretize these into a series of distinct blocks which compose the geometry. The results in this paper expand on the validated methodology to add further elements to the automation in the geometry including lintels and developing a method for full building geometries to be created, then tested on a case-study building in Montréal. This semi-automated procedure can be applied to any geometry in three basic stages. The first is to take a scaled geometry – a 3D point cloud, photogrammetric model or detailed, scaled photographs – and identify the piers, spandrels, rigid nodes and lintels on separate layers in Rhinoceros, a computer aided design (CAD) software. From here, the developed discretization code is run in Grasshopper 3D, a visual programming language that works within Rhinoceros, which takes the identified elements and discretizes each into blocks eight blocks. To prevent continuous vertical joints, the second stage involves adding lintels separate from the input surfaces, drawing at the top of the opening a spanning block for the lintel, which is further expanded across the façade in the second part of the Grasshopper code. The third stage, when required, is to address the wall-wall interface at each building corner. Depending on the thickness of the walls, a user-defined angle applies a cut at each corner in stage three of the implementation of the Grasshopper code. These stages are outlined in Figure 1 and further defined in this section.

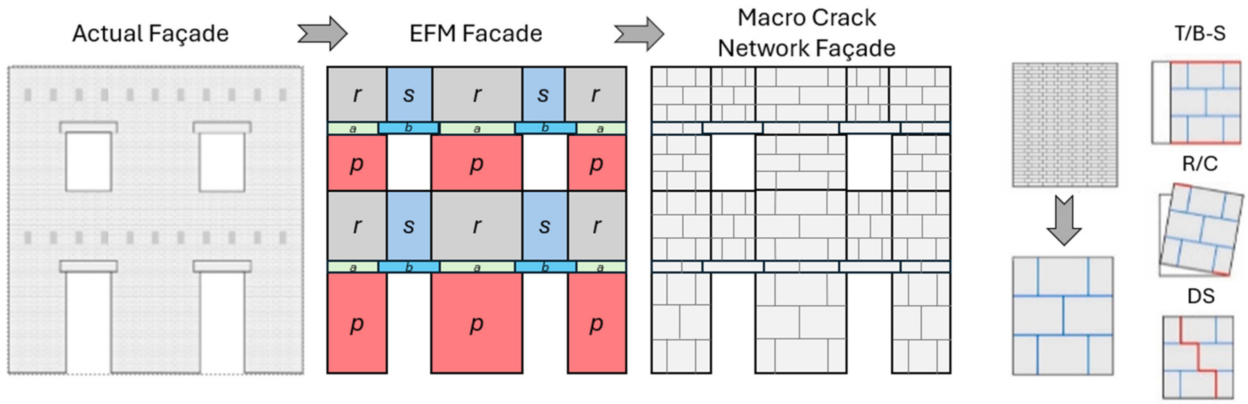

Figure 1: Stage 1 and 2 of the discrete macro-crack network (MCN) discretization using an EFM-inspired method and failure modes where elements are denoted as piers (p), spandrels (s), rigid nodes (s), blocks at the lintel height (a) or lintels (b) (adopted from Zhang et al [20])

The semi-automated program involves user knowledge of the wall surfaces, wall thickness and potentially manual block editing for irregular and non-rectangular geometries. In this program, surfaces are created to denote macro-elements where each user defined surface is discretized further into eight surfaces and extruded into 3D solid elements, defined to describe the main IP/OOP failure mechanisms of URM walls, including diagonal shear cracks, crushing and base sliding. This extrusion is highlighted in Figure 2 where the user input required is solely the thickness of the extrusion.

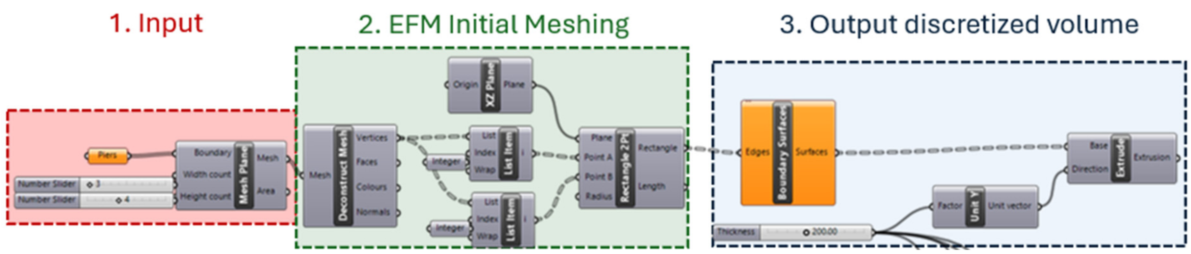

Figure 2: Grasshopper code for geometrical discretization and extrusion

In the second phase of the code, surfaces denoting lintels – saved to their own layer in Rhino – are extruded from a 2D surface to a 3D solid. To account for the building portion along the same level of the lintel, surfaces here are denoted on their own layer and each surface is split at the midpoint of the surface and extruded from a 2D mesh to a 3D solid. This creates blocks at the height of the lintels which facilitates a model without continuous vertical spanning joints. At this point, the code also considers the presence of bricks along the lintel layers which, as a result of the shape of the lintels themselves, need to be extruded separately from the other surfaces. As vertical joints at the height of the lintel need to align with the joints in the surrounding brick mesh, a special code was created to deal with this complexity. This phase of the code requires no user input beyond the definition of surfaces at the height of the lintels. The final phase of the code involves the creation of a vertical cut at the exterior edges of the façade, to facilitate an alignment in 3D of building walls. This approach identifies building interconnection at the wall corners, leaving a vertical interface at the wall intersections where properties can be further assigned. As the MCN approach defines the non-linear material properties in the zero-thickness interface between rigid blocks, this leaves the user able to define wall connections and interlocking. The code in Grasshopper 3D is summarized in

Figure 3 where user input is the angle of the corner cut (in orange), defined based on the thickness of intersecting walls.

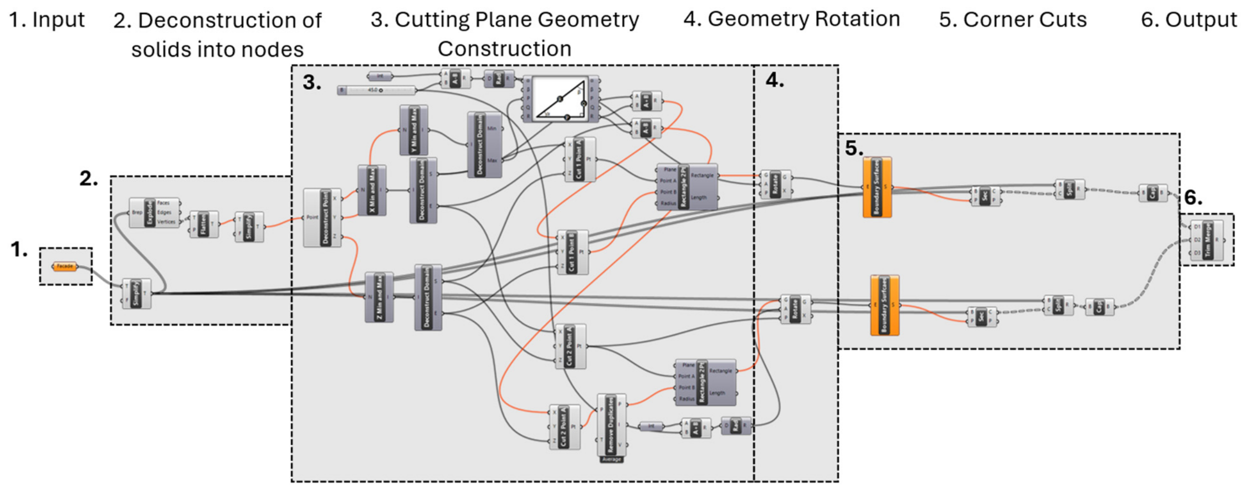

Figure 3: Grasshopper code for building corners to create aligned surface interfaces at wall intersections

The mechanics of the discretization, designed for implementation in a distinct element program, are detailed further in Zhang et al. [20], yet can be summarized by the efficient and accurate combination using rigid blocks and implementing non-linear softening behaviour at the zero-thickness interface between blocks. The joint-softening constitutive model, developed by Pulatsu et al. [7] for use in 3DEC, a distinct element program by Itasca [29], employs fracture-energy based softening contact laws in compression, tension and shear. The contact laws enabled reasonable capturing of masonry behaviour, with a comparable computational time to the behaviour of brittle contacts. The applicability of this contact law is constrained by the definition of fracture energy, as experimental tests measuring fracture energy are limited, and parameters are often estimated based on formulas for concrete [30].

VALIDATION OF PROPOSED FRAMEWORK

The proposed framework for creation of relevant geometry, and extended program capabilities, is validated further in this work based on the treatment of irregular openings and 3D applications. To treat irregular openings along a building façade in EFM, three approaches have been defined [26]. With openings at different heights, the minimum approach takes minimum clear height between two openings as the height of each element while the limit approach takes the midpoint between two opening corners at a 30º maximum inclination. Finally, the average approach involves taking the midpoint between two opening corners with no maximum inclination to create each element. In this work, irregular facades were treated according to the minimum approach, to simplify the geometries and consider the presence of lintels which were not included in the original discretization approaches proposed. Two asymmetrical facades were replicated in order to refine the developed code. A two story façade with inverted floor configurations modelled by Singh et al [31] and façade with a large window on the second floor [32] were considered. Both facades were modelled following the minimum approach and Grasshopper 3D was used to convert the facade from a 2D geometry to a 3D geometry, shown in Figure 4.

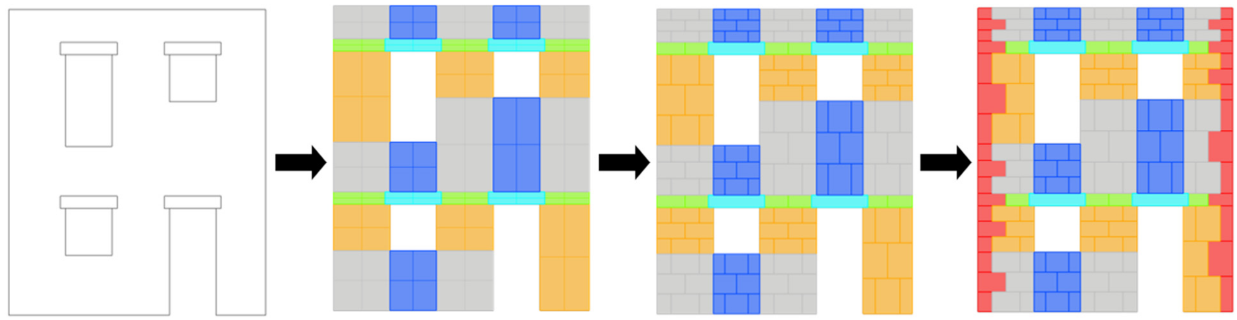

Figure 4: EFM idealization for irregular façades, validation of different approaches using the macro-crack network discretization

The facades were divided into surfaces coinciding according to the EFM and lintel layers and lintels were included to replicate the façade's geometry. Each surface type was set to different layers in Rhino and extruded one after the other, as described in the above section. Modelling irregular geometries validated the code for generating accurate geometries for simple and more complex facades, requiring only a scaled outline of a building which can be easily acquired from photogrammetry or 3D laser scans. This approach is further considered in the next section, following a case study.

CASE STUDY APPLICATION: RUE SAINT PATRICK

Eastern Canadian URM buildings comprise a significant portion of the existing building stock, vulnerable to even the moderate seismic events which compose the region's earthquake hazard. The ability to create accurate, accessible models increases the knowledge on the structural assessment of these buildings. The case-study building in this paper is a typical brick masonry industrial building constructed along the Lachine Canal in Montréal, one of the city's most important industrial centers of the 19th century and remains a vital portion of the city's cultural fabric. This two story URM building has three-wythe brick masonry walls and an interior heavy timber frame constructed with cast-iron connections, shown in Figure 5.

a) b) c)

Figure 5: Rue Saint Patrick building a) street view b) laser scan and c) connection of the interior timber frame

A geometrical survey of the building was completed using a Leica RTC360 3D laser scanner to create a point cloud of the building's exterior and interior. The point cloud was cleaned and post-processed and sections taken in order to be exported and scaled in Rhinoceros for the creation of the geometrical model. After the creation of the façade, the geometry was imported into 3DEC where a pushover analysis in the negative and positive *x*- direction were completed. The definition of the masonry materials is described in Table 1 where brick material properties were used to describe the unit material of the rigid blocks and masonry material behaviour is defined in the zero-thickness interface at contact points between blocks. The contact points are defined by normal (k_n) and shear springs (k_s), calculated according to the height of each block (h), as $k_n = E_m/h$ and $k_s = G_m/h$ where E_m and G_m are the elastic and shear modulus of masonry. The same values of h for the vertical joints are used, as limited impact has been noticed when accounting for head joints explicitly [33]. Values are informed based on tests completed on samples extracted intact from the building for testing in the Jamieson Structures Laboratory on McGill campus. Compression tests on 5 half bricks were completed according to CSA A82 and ASTM C67. Brick beds were capped at the interface of 15mm steel plates with a high strength gypsum to smooth out any deformities, including frogging, to avoid stress concentrations. The bricks were tested in a 4500 kN MTS load frame under displacement control at a monotonic rate of 0.0085 mm/s until failure. Compressive strength and elastic stiffness (measured as the slope between 5-30% of peak stress) values were calculated using results measured by two 50mm extensometer placed on the front and back faces of the brick. Monotonic and cyclic compression tests on extracted masonry triplets were conducted according to ASTM C1314 in the same load frame. Tests were completed with a displacement rate of 0.01 mm/s and axial displacements were measured with two vertical ±15mm LVDTs glued to steel plates (15-40mm thick) capped to the top/bottom of the triplets using a high strength gypsum. These values were used to inform the contact properties, summarized in Table 1, where G_c is the fracture energy in compression, G_f^I and G_f^{II} are the mode-I and II fracture energy in tension and shear, respectively, and the cohesion is taken as the flexural strength (assumed $f_t = 0.05 f_c$) [33].

Table 1: Contact properties – brick masonry walls with solid masonry units and lime mortar

Specimen type	Comp. strength, f_c (MPa)	Young's modulus, E (MPa)	Flexural strength, f_t (MPa)	Cohesion, c (MPa)	$\theta_{0,res}$ (°)	G_f^I (N/m)	G_f^{II} (N/m)	G_c (N/m)
Brick	64	21949	3.2	3.2	35	90.3	902	27774.4
Masonry	4.47	1464	0.22	0.22	28	23	228	16850

A static pushover analysis in the negative and positive in-plane direction was completed to assess the performance and capacity of the Rue Saint Patrick building. This model was created in a simplified manner – using a cantilever boundary condition in which only the base is fixed and assuming the only vertical loads are gravity. This is a simplified model setup designed for the sole purpose of demonstrating the capabilities of the framework and its ability to represent multiple failure types and analyze large structures in a small timeframe. In this analysis, an increasing displacement was applied at the first and second floor levels, at the points where the timber beams would be attached to the masonry wall, as measured by the 3D laser scan. The pushover loads were applied until a reduction in 10% of the force-capacity was reached, which was after 60mm of applied displacement in the negative x-direction and 81mm in the positive x-direction. The completed analyses took 178/252 minutes, in the -/+ directions respectively.

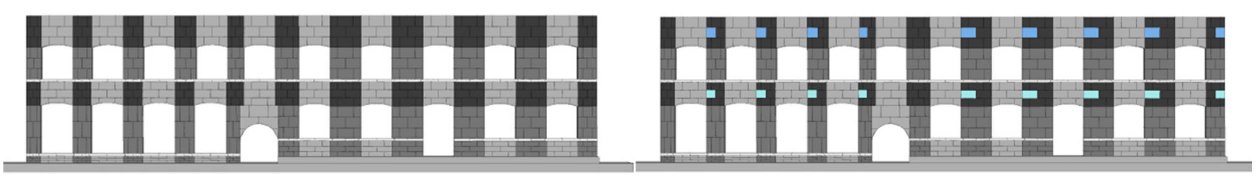

Figure 6: Geometry created using the Grasshopper code and imported into 3DEC

Results are summarized in Figure 7 and Figure 8 where the displacement contours and force-displacement graphs are shown. The main failure mechanisms involve the rocking of the piers and the opening of diagonal cracks in squat piers on the first floor, as seen in Figure 7 where the deformed shape is scaled ten times for the damage locations to be visible. In the case of this façade, one of the main vulnerabilities lie in the slender masonry piers which experienced the greatest amount of rocking. The slender piers, located on the east (left) face of the façade have an aspect ratio of 2.46. Initial damage typically starts to appear at the interface between the nodes and spandrels, close to where the pushover load is applied. The first cracks along component diagonals were detected typically in the centre of the façade in the slender piers of the second floor and at the base of the piers closes to the door openings along the application of the load. This was seen both in the negative and positive load directions. The main differences between the two loading directions was the capacity, with the façade retaining capacity when load was applied in the positive x-direction.

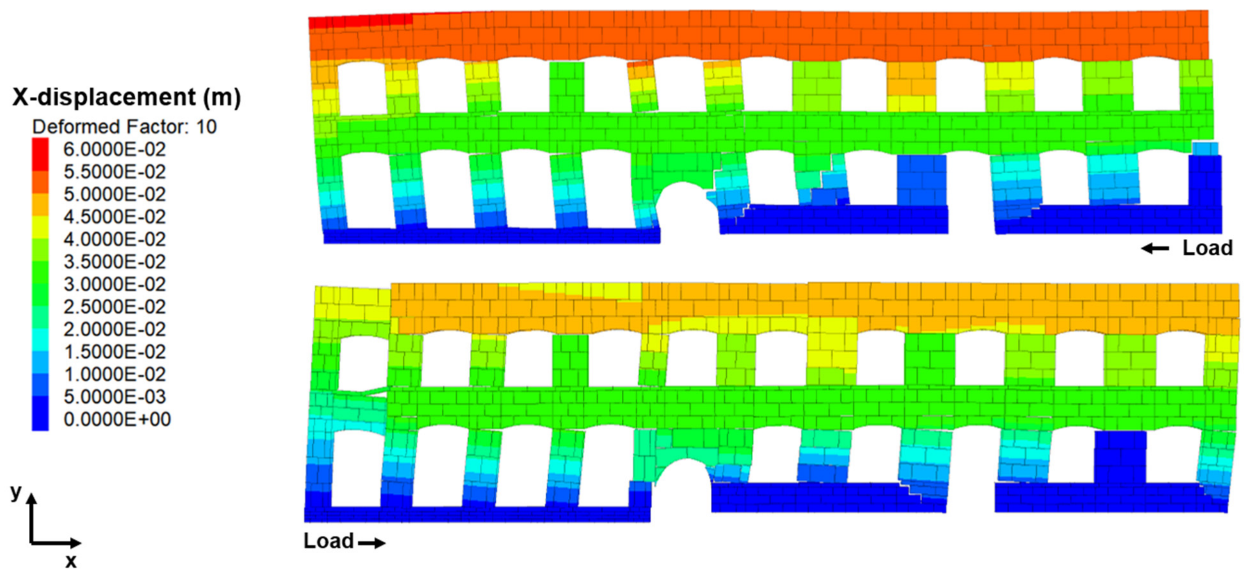

Figure 7: X-displacement contours of the pushover analysis in the negative and positive direction at an applied 60mm

The force-displacement curves in Figure 8 summarize the in-plane resistance to increasing applied displacements. In both curves, the façade remains elastic until 12/20 kN of load (positive/negative directions), or an applied displacement of 5mm. After this, initial damage can be seen at the interface between macro-elements and diagonal cracks in squat piers at the base of the façade. The rocking of the piers continues to dissipate energy throughout the analysis represented by the sharp decreases in capacity, which is shortly regained after. The behaviour of the façade notably changes depending on the direction of the applied load, where in the -x direction the peak capacity is reached after 0.02 to 0.04 m of applied displacement (range given depending on measured location) in contrast to the +x direction which reached load capacity at 0.035-0.06 m of applied displacement and drops swiftly after.

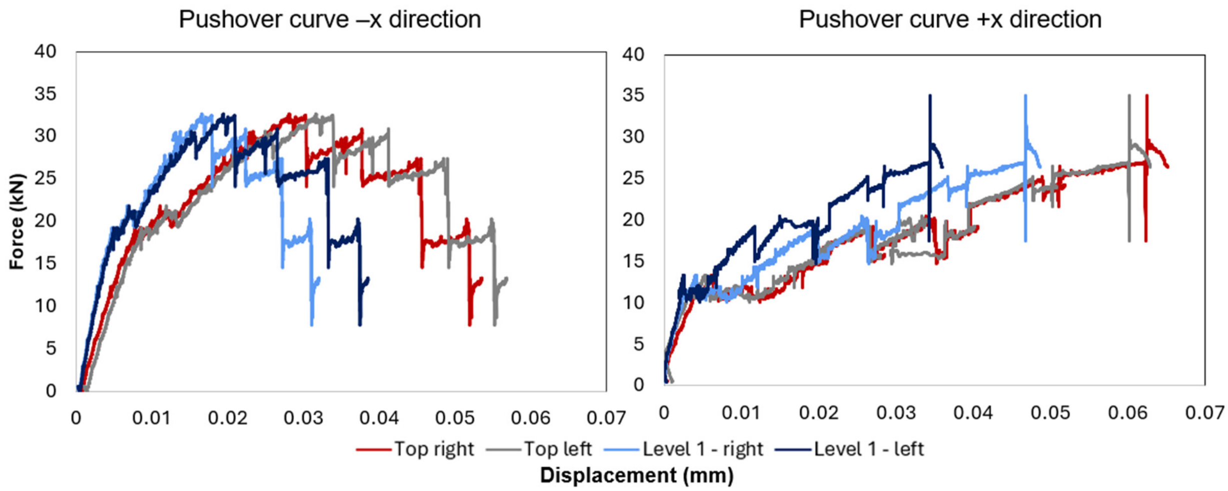

Figure 8: Force-displacement curves in the negative and positive x-direction of applied pushover load

To further investigate the IP/OOP behaviour of this building, 3D pushover analyses as well as the modelling of the entire structure are warranted with more representative boundary conditions and load scenarios. These aspects were beyond the scope of this paper, yet the analysis provided herein presents the validation of the DCM discretization strategy, the framework and its ability to decrease the burden inherent in building geometrically accurate structural models in numerical modelling software from dense point-clouds and datasets.

CONCLUSIONS

This paper investigates the application of a code created to streamline the creation of numerical models from often dense and difficult to navigate geometrical files using a visual programming approach in Grasshopper 3D, a Rhinoceros plugin, useful in the creation of accurate numerical models which help researchers and practitioners better understand the behaviour of unreinforced masonry (URM) buildings. The approach utilizes a previously developed simplified modeling strategy, the Distinct-Element macro-crack-network, implemented using theory from the Equivalent Frame Method (EFM) for discretization and loaded in a distinct element software for seismic analysis. The paper describes advances made to the previously published code, improving the discretization and automation at the building openings, expanding the approach to be usable for a full building and validating with irregular openings through conceived EFM methodologies. Requiring only minor user inputs, including wall thickness and initial discretization using surfaces to identify various building components, the application of this approach should be able to extend to cases with limited or detailed geometrical information, from scaled images to dense 3D point clouds, to facilitate the creation of simplified numerical models. In this work, pushover analyses were completed on a case-study building in Montréal where a 3D laser scan was used as the baseline for the creation of the numerical model. Material properties were informed by laboratory tests of extracted masonry materials and implemented into the material model. Results from the case study analysis display the in-plane behaviour of a typical Eastern Canadian building, and conclusions from this display the in-plane vulnerabilities of slender masonry piers to rocking failure and squat piers to diagonal cracking. Further research into a full building analysis to identify global mechanisms is required. The results of this study highlight how algorithms, combined with a simplified modeling strategy, can improve the analysis and interpretation of the structural behavior of old URM buildings. By leveraging computational techniques, this study highlights how algorithms alongside simplified modelling strategies can aid in structural and seismic assessment to support the conservation of existing masonry structures.

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