Multi-Level Framework for Structural Analysis of an Old Masonry Building

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ABSTRACT

This research presents computational investigations to predict the overall macro-behaviour of a historic masonry building located in St. John's, NL, Canada, subjected to wind loading. The process begins with the documentation of the building, where principal geometrical features, construction morphology of the masonry walls, and the sizes and locations of the openings (e.g., doors and windows) are obtained using documentation methods. Continuum-based simulations (also denoted as macro-modelling) are performed following the standard non-linear finite element analysis (FEA) in which the geometrical properties are taken from the adopted documentation approach and automatically transferred into the solid shapes. The non-linear structural behaviour of the large-scale 3D macro-model is evaluated using the Mohr-Coulomb material model with different mesh sizes. The global structural behaviour as well as the most vulnerable sections of the building are identified, taking advantage of the computational efficiency of macro-modelling. Subsequently, a detailed structural analysis based on the discrete element method (DEM) is performed. The DEM-based approach represents brickwork assemblages as a system of discrete blocks in a fully discontinuous setting and simulates the interaction of masonry units at the contact points. Further insights are gained regarding the detrimental effects of existing cracks, which can be explicitly represented in the discontinuum-based analysis. The outcomes of this research highlight the integrated use of continuum and discontinuum-based modelling strategies in conservation engineering.

KEYWORDS

Historic masonry, computational modelling, continuum analysis, discontinuum analysis, structural assessment, structural analysis, collapse mechanisms

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INTRODUCTION

Unreinforced masonry (URM) structures are essential components of our cultural landscapes, accounting for over 70% of the existing building stock and representing centuries of history [1]. However, conserving old masonry structures presents significant challenges when considering extreme weather conditions, material aging and deterioration, and the absence of contemporary design codes tailored to address the specific needs of URM buildings [2]. These factors, combined with the complexities of irregular geometries, material heterogeneity, and existing damage, make effective structural analysis and appropriate strengthening of URM buildings particularly challenging. Additionally, the lack of clear guidance for the structural analysis of these buildings can lead to excessive interventions or even demolition. This risks the loss of heritage value through damage or destruction of character-defining elements and contributes to environmental and economic costs. To address these concerns, a systematic and integrated approach is necessary.

The present research explores multiple computational modelling strategies, including continuum, discontinuum-based, and simplified macro-block analysis, to predict the structural behaviour of a historic URM building subjected to wind loading. The reference case study is a three-storey landmark URM structure, built in the late 1800s in St. John's, Newfoundland, which exhibits several structural cracks. Through this research, in situ observations are utilized to inform the adopted advanced numerical models to accurately predict the building's performance using representative geometrical properties and boundary conditions. The findings highlight the integrated use of various modelling strategies and adopting in situ observations to provide a comprehensive understanding of the structural performance of a historic masonry building by exploring the strengths and limitations of different modelling strategies. All computational investigations were performed using 3DEC (three-dimensional discrete element code), a continuum and discontinuum-based analysis software developed by Itasca [3].

DOCUMENTATION AND COMPUTATIONAL MODEL GENERATION

The structural assessment of historic buildings begins with understanding the overall geometrical features of the building and its current condition. In this context, visual inspections and advanced surveying techniques are used to gather critical information on the building's existing condition and determine input parameters for computational modelling [4].

Visual Inspection and Masonry Quality Index (MQI)

The construction quality of load-bearing masonry structures (e.g., walls, arches, vaults, etc.) and mechanical properties of masonry constituents impact the behaviour and load-carrying capacity of masonry structures under vertical, lateral, and out-of-plane loading conditions. The masonry quality index analysis provides a practical methodology using qualitative and quantitative parameters that are determined through a visual survey to estimate the mechanical properties of masonry walls [5]. The method evaluates seven parameters, including the presence of continuous bed joints, staggered vertical joints, high-quality stones and mortar, and transversal connections between wythes [5]. Upon inspection, each criterion is assigned an outcome (fulfilled, partially fulfilled, not fulfilled), and properties are estimated accordingly. In the case study, the masonry walls are classified as "average quality," characterized by consistently sized and cut brickwork with straight horizontal courses and staggered vertical joints, but with notably poor connections between wythes. Based on this assessment, the elastic modulus is estimated at 1.5 GPa, and the compressive strength at 2.5 MPa.

Table 1: Criterion Used for Predicting MQI.

#	Criteria	Evaluations
1	Stone/Brick Mechanical Properties and Conservation State (SM)	Partially Fulfilled
2	Stone/Brick Dimension Properties (SD)	Partially Fulfilled
3	Analysis of Stone/Brick Shape (SS)	Fulfilled
4	Wall Leaf Connections (WC)	Not Fulfilled
5	Horizontal Bed Joint Characteristics (HJ)	Fulfilled
6	Vertical Joint Characteristics (VJ)	Fulfilled
7	Mortar Mechanical Properties (MM)	Partially Fulfilled

Surveying Techniques

In situ surveying and documentation are essential to validate model geometry and assess the current condition of the historic masonry structure. In St. John's, surveying tools supplement the visual inspection and support the generation of building geometry for the computational models. Existing building documentation, such as elevations and floor plans, is referenced to create the geometric model using Rhinoceros, a computer-aided design (CAD) software [6]. Camera and drone photography are employed to create high-resolution ortho-rectified images, as shown in Figure 1a, to map existing damages and verify model geometry. Damage mapping on ortho-rectified photographs of the North and West faces of the northwest tower, as depicted in Figures 1b and 1c, highlights the extent of visible damage and areas requiring further assessment. Measurements are taken on-site to determine critical parameters, such as the extent of separation between wythes.

Figure 1: (a) Photogrammetric model of the East façade of the building; (b) and (c) Damage mapping on the ortho-rectified photograph of the North and West faces of the northwest tower.

COMPUTATIONAL MODELLING OF A HISTORIC URM BUILDING

This study presents a comprehensive approach to predicting the structural behaviour of the reference building using different modelling strategies. For all models, the building self-weight is computed, assuming a material density of 2000 kg/m³, and a roof load of 5.7 kPa (including factored dead and snow loads) is applied. The demand wind pressure distribution is calculated based on the static procedure prescribed by the National Building Code of Canada 2020 (NBCC) Clause 4.1.7, taking as input a 1/50-year reference velocity pressure of 0.78 kPa (NBCC Div. B, App. C) for St. John's [7]. The wind pressure distribution is shown in Figure 2.

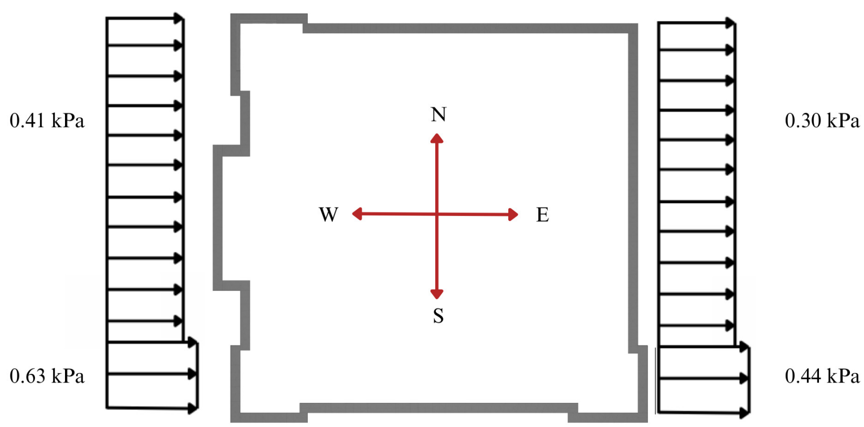

Figure 2: Wind Loading Profile for Case-Study Building.

Although NBCC Part 4 does not directly address modifications to existing structures, the simplified wind load calculations are considered reasonably representative of actual conditions. With the exception of façade ornamentation, the geometry of the building can be characterized as a squat box, resembling the NBCC's idealized 'low building' model. For example, a windward pressure of 0.63 kPa, assuming an air mass density of 1.293 kg/m³, corresponds to a wind speed of approximately 31.2 m/s (or 112.4 km/h), based on standard dynamic pressure relationships. Wind speeds of this magnitude, particularly during peak gust events, are recorded in St. John's, making the selected pressures realistic for early-stage assessment [8]. Moreover, the observed structural response of the models under these load conditions aligns with documented damage in the building, providing further confidence that wind pressure assumptions are plausible and applicable for preliminary computational modelling.

Continuum-Based Analysis (Macro-Modelling)

Macro-modelling is the most common approach used in the structural analysis of large-scale URM buildings and is typically performed using the non-linear finite element analysis (FEA) [9]. Similar to the examples presented in the literature, it is primarily used to observe the global structural behaviour of the building under the prescribed wind loading and to estimate the associated load-carrying capacity [10], [11]. In the macro-modelling approach, masonry composite is idealized as a homogenous and isotropic material, using homogenized mechanical properties of the material [12], [13]. Given the deteriorated condition of the structure, a relatively low tensile strength, 0.15 MPa, is assigned. In the adopted continuum-based model, constant-strain tetrahedral elements are utilized, considering two different mesh sizes, denoted as medium and fine. The medium mesh consists of about 88,000 tetrahedral elements with 33,000 nodes, whereas approximately 400,000 elements and 110,000 nodes are contained in the fine mesh. The non-linear material behaviour of the masonry composite is captured using the Mohr-Coulomb failure criteria, following a strain-softening plastic material model and mechanical properties derived from the MQI method [14].

A fixed boundary condition is assigned at the structure's base, and the interior walls and diaphragms are excluded from this preliminary analysis stage. The analysis proceeds in three phases: first, self-weight is applied, followed by the vertical roof load. Once the structure reaches equilibrium under the prescribed dead loads, the wind pressure is introduced incrementally until the ultimate load-carrying capacity of the building is reached. The analysis is performed for wind loading in both the positive and negative Y-directions. The resulting failure mechanisms are shown in Figure 3, with overturning of the rear façade observed under positive Y-direction loading and overturning of the front façade observed under negative Y-direction loading.

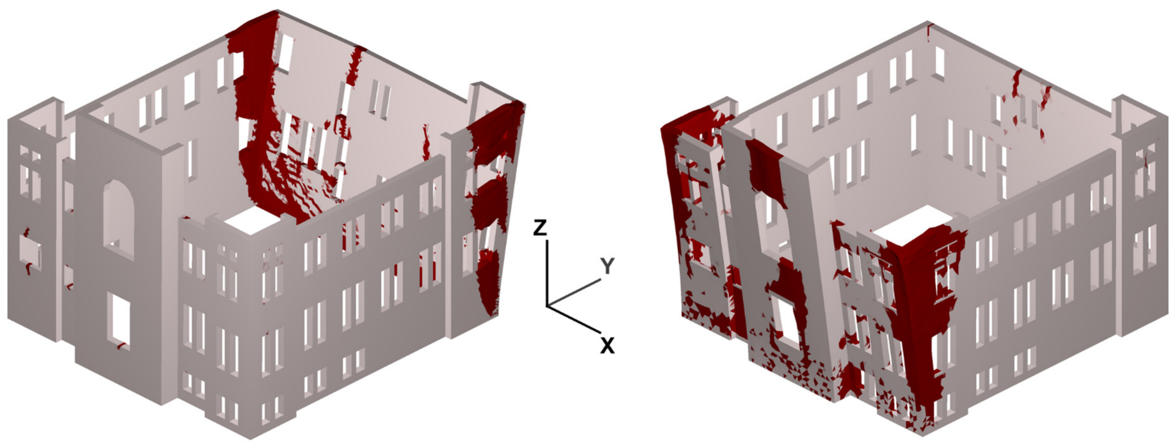

Figure 3: Continuum Model Failure Mechanism (Deformation Factor: 5), under wind loading applied in the positive Y-direction (left), negative Y-direction (right).

In Figure 4, the plastic tensile strain is plotted to visualize zones where the material reaches or exceeds the ultimate plastic strain (indicated in dark red). These plots offer critical insights into the crack locations and the associated failure mechanism under applied external loading. Furthermore, Figure 4 also compares the plastic tensile strain distribution obtained using the medium mesh (Figure 4a) and the fine mesh model (Figure 4b), highlighting the impact of mesh refinement on the crack resolution. No significant difference is observed in the capacity/demand ratio when comparing two computational models for the same failure mechanism. This ratio represents the building's resistance relative to the applied wind loads. The fine mesh yields a capacity/demand ratio of approximately 1.7, while the medium mesh model produces a slightly higher ratio of 1.9. As both values are over 1.0, they indicate that the building is predicted to have sufficient resistance to withstand the applied wind loads for this failure mechanism without accounting for localized failures or the impact of existing damages.

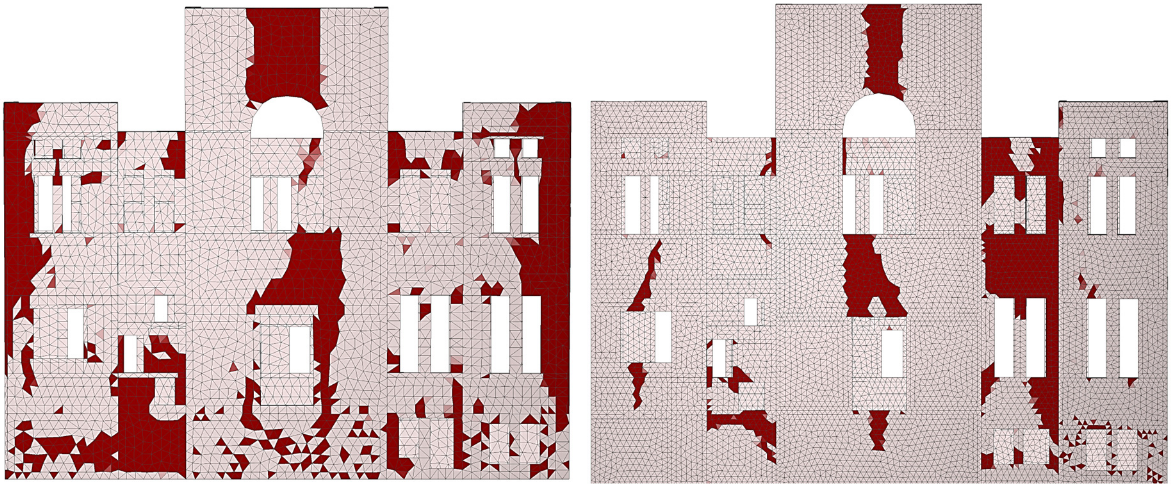

Figure 4: Plastic Tensile Strain Distribution on the Front Façade for Medium Mesh (left) and Fine Mesh (right) under the applied wind loading in the negative-Y direction.

Macro-Block Analysis

In this section, a rigid macro-block analysis using the upper-bound theorem of limit state analysis is employed to cross-check the non-linear FEA and gain further confidence in the results of the macro-modelling. It is worth noting that the adopted macro-block analysis also serves as a simplified structural analysis tool, operating under the following assumptions: masonry has zero tensile strength, infinite compression strength, and no sliding failure can occur. Accordingly, the load multiplier is computed based on the prescribed failure mechanism in line with the plastic tensile strain distribution observed in the macro-modelling results depicted in Figure 5. The capacity/demand ratios shown in Figure 6 are plotted against drift percentage, which is defined as the displacement normalized by the total building height. The capacity/demand ratio based on the macro-block analysis is found to be 2.0, which is in close agreement with results from the macro-modelling approach. The results of both analyses correspond with the overturning failure mechanism of the front façade, where all predictions indicate sufficient capacity to resist the applied wind loads. While the macro-block analysis predicts the highest capacity/demand ratio, its practical and less intensive input parameter requirement makes it suitable for preliminary assessments of URM buildings.

Figure 5: Macro-blocks and Failure Mechanism for the Overturning of the Front Façade.

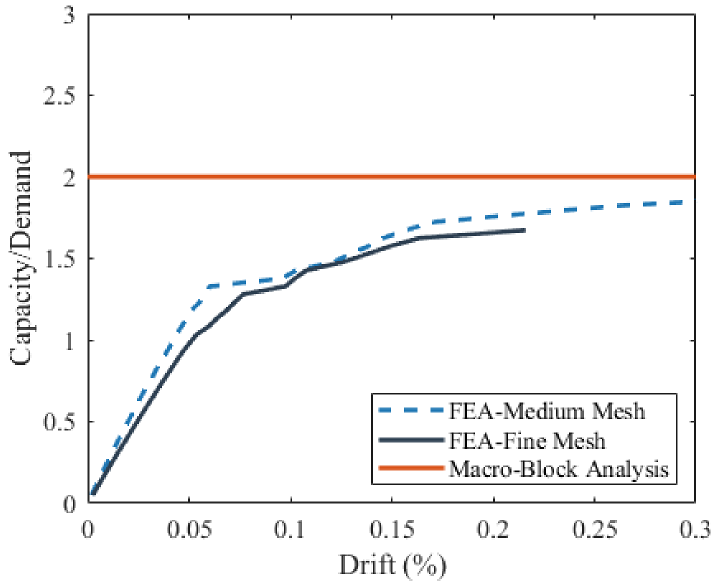

Figure 6: Capacity/Demand Comparison for Global Failure.

A Detailed Look at the Cracked Section of the Building

While the presented analysis provides valuable insights into the global behaviour of the structure, the *as-is* condition of the building includes significant structural cracks that must be considered to predict possible local failure mechanisms. The existing damages, particularly the detachment of the outer wythe of bricks in the northwest tower, are critical factors influencing the building's structural integrity. The observed cracks extend vertically along the northwest tower, seen in Figure 7, with gaps up to 10 centimeters wide documented between the outer two wythes of bricks. To explicitly consider the cracked section in the structural analysis, a different computational modelling strategy based on the discrete element method (DEM) is utilized. This approach aims to provide a detailed understanding of how the cracked section of the northwest tower influences structural behaviour and affects the load-carrying capacity of the structure.

Figure 7: Detachment of the outer wythe of the northwest tower.

Discontinuum-Based Analysis

The adopted discontinuum-based analysis represents the URM masonry via a system of rigid blocks that interact mechanically along their contact surfaces [15], [16]. Briefly, the proposed DEM-based simulations enable explicit representation of the cracks that can develop through the contact points between the adjacent blocks where brittle elasto-plastic contact constitutive models are defined [17], [18]. The readers are referred to the relevant studies regarding the most recent developments, applications, and the computational procedure of DEM [19- 24].

The adopted DEM-based model considers the contact properties between the outer wythe of the northwest tower and the rest of the building to have a very low tensile capacity (i.e., 20 kPa) to mimic the severely damaged and cracked section. Furthermore, the weak vertical joint starting from the bottom and reaching up to the top window height of the tower is included to reflect the as-is condition of the building. In Figure 8, the results of the discontinuum-based analysis are provided, where the discrete block representation of the URM building and the local collapse mechanism of the exterior wythe of the northwest tower can be visualized. Rather than the overturning of the west façade of the northwest tower, a one-way bending failure is observed, with the highest displacements toward the center of the northwest tower captured when considering the existing vertical cracks in the simulation (replicated as very weak contact planes in the numerical model) [21]. Accordingly, a significantly low capacity/demand ratio (<1) is obtained, given the local collapse mechanism noticed in the building. The capacity/demand ratio comparison is presented in Figure 9, which highlights the differences between the global and local failure mechanisms for the building under the same wind loading. The predicted local failure mechanism, focusing on the northwest tower, underscores the vulnerable condition of the building when the existing cracks and the separation of the outer wythe of masonry are considered. These findings also emphasize the susceptibility of the tower to localized failure in damaged regions and highlight the importance of targeted interventions.

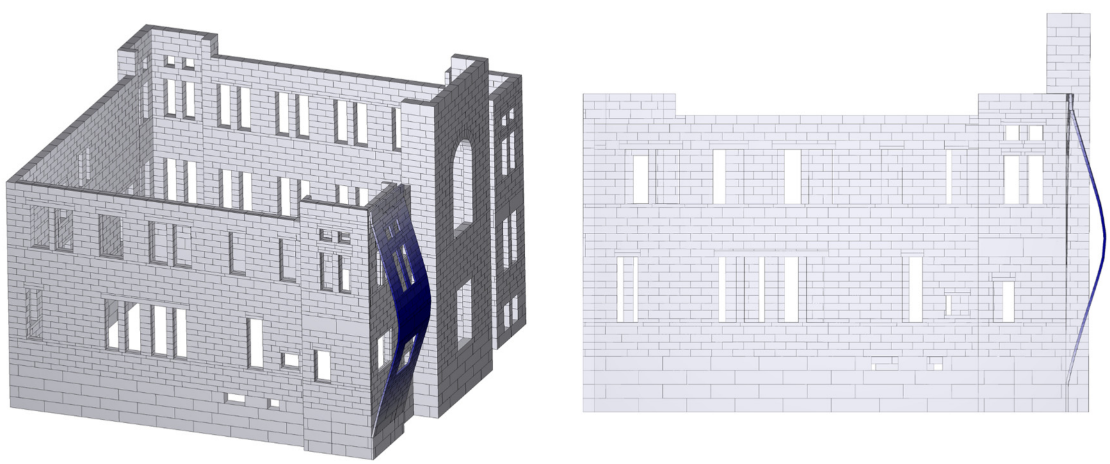

Figure 8: DEM Model Local Failure Mechanism (Deformation Factor: 5).

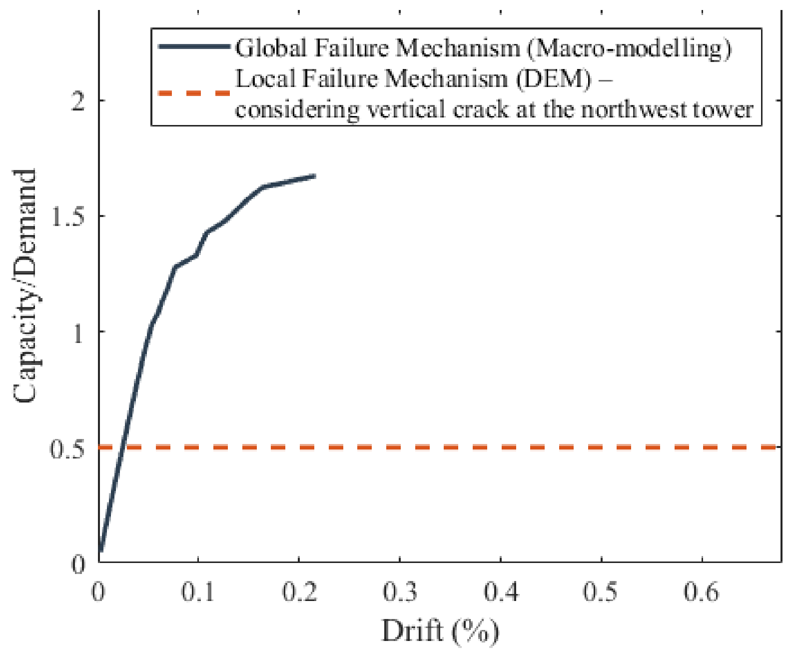

Figure 9: Capacity/Demand Comparison Between Local and Global Failure.

CONCLUSIONS

Preserving historic URM buildings requires a systematic assessment of their safety and performance. While various simplified or advanced structural analysis strategies are proposed in the literature, no holistic approach is available that leverages the combined usage of traditional and modern structural analysis techniques. However, by effectively applying different computational modelling techniques, engineers and architects can avoid unnecessary construction costs and irreversible interventions in historic structures. To this end, this study demonstrates the value of various modelling approaches, such as continuum, discontinuum, and simplified macro-block, to holistically evaluate the structural behaviour of a historic masonry building. Continuum models provide insights into global behaviour; however, their reliance on homogenized material properties limits their ability to accurately capture the complexities of unreinforced masonry, especially with existing damage. Discontinuum models can capture local behaviour as they model individual units and their interactions. The results explicitly indicate that the reference building is in a vulnerable condition when the detached section of the northwest tower is considered and does not meet the expected wind loading requirement. Future iterations of the model will incorporate critical structural components such as interior walls, diaphragms, roof structures, and trusses to accurately capture building behaviour. Additionally, the model will consider existing and proposed retrofits implemented in the northwest tower, including helical wall ties to reconnect separating wythes and plated threaded rods connecting the floor diaphragm, to assess the effectiveness of proposed interventions.

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