Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich, Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Digitally engineered stone masonry building structures

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Abstract

The materials currently most widely employed in the construction industry, steel and concrete, are extremely carbon intensive and constitute two of the world's hard-to-decarbonize sources of CO_2. In contrast, natural stone has a relatively low carbon footprint, particularly when it is quarried and processed close to its point of use. Although stone has been used in construction for millennia, historically load-bearing masonry buildings have consumed larger volumes of masonry materials than is strictly necessary, being characterized by thick walls and small openings. Also, masonry construction has traditionally required a skilled and plentiful workforce, which is no longer available. Here parametric modelling techniques linked to fast-running rigid block limit analysis models are here used to quickly identify materially efficient structural configurations for buildings. Also, the use of modern off-site construction techniques is discussed in the contribution, where the stone building is constructed in stages with off-site assembled stone structural elements. It is shown that optimization techniques can be used to design efficient temporary strengthening measures to aid the off-site assembly and safe staged construction of a building structure.

Keywords: masonry, construction, parametric design, limit analysis, optimization.

1. Introduction

Professionals in the Architecture, Engineering, and Construction (AEC) industry have formally acknowledged the climate crisis [1]. This acknowledgement comes from understanding the significant role the construction industry plays in contributing to human-induced climate change. According to a recent report of the United Nations Environment Programme, the construction sector is responsible for approximately 37% of energy and process-related carbon emissions, with building construction alone contributing around 25% [2]. There is therefore an urgent need to move away from carbon-intensive construction materials and processes.

Given the widespread reliance of the AEC industry on conventional carbon-intensive materials such as steel and concrete, efforts are now focused on mitigating the carbon footprint associated with these materials and exploring the viability of alternatives. Regarding the latter, there has been a notable resurgence of interest in natural materials, including earthen materials [3], timber and bamboo [4, 5], and stone. Stone, in particular, with its established history, has seen a recent revival in interest as a building material in the UK [6, 7].

The AEC industry is rapidly moving towards digital technologies to control the design and building process efficiently. Towards this end, Building Information Modelling (BIM), parametric modelling, and digital fabrication are key. Of these, parametric modelling methods are very useful in the early design stage, though are also useful in later stages of the design and building process [8]. It e.g., allows one to foresee the effects of changes in the geometric design.

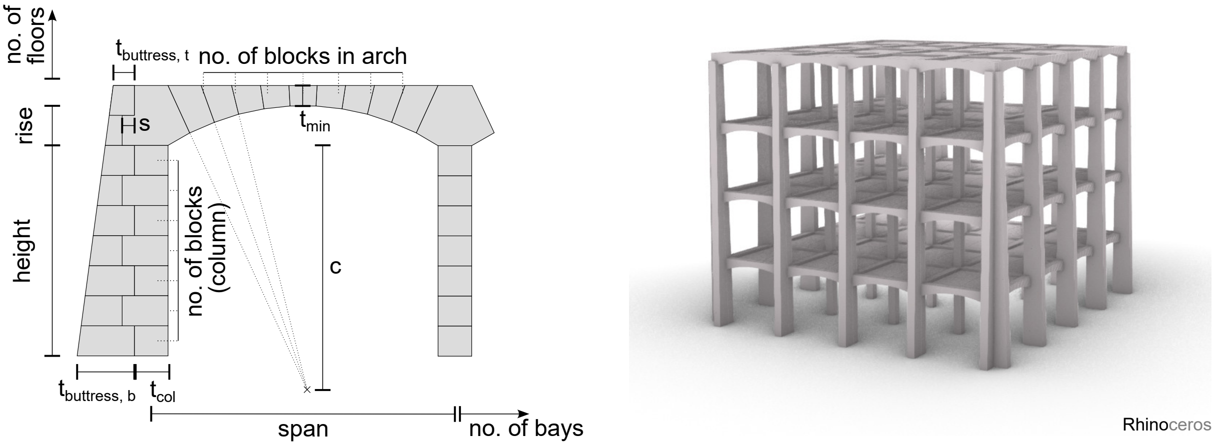
Modern Methods of Construction (MMC) have also emerged as a means of potentially simultaneously increasing productivity and reducing the carbon emissions associated with construction [9, 10], also recognized by the UK government [11]. Moving from traditional live building sites to off-site construction also has the potential to reduce waste, allow for mass customization and better quality control; also the scope for subsequent deconstruction and reuse is potentially increased. However, although MMC methods have been developing rapidly for steel and concrete constructions, similar progress has not been made when natural materials are involved, with traditional craft approaches usually dominating.

This short contribution focuses on bringing stone into the digital umbrella of the AEC industry, to help reduce the impact of construction on the planet. Section 2 presents a parametric model employing the Rhino/Grasshopper platform for the design and analysis of unreinforced stone masonry to enable designers (i.e., engineers and architects) to fully harness the potential of stone in a modern construction context. Section 3 briefly discusses how stone could be designed for offsite construction. Finally, concluding remarks are presented in Section 4.

2. Parametric design and analysis

2.1. Geometric model

A simple stonemasonry building with a rectangular footprint is considered for illustrative purposes in the present study. The structure is made up of a network of stone columns, arches, and buttresses; stone vaults could also be employed to carry floor loading although this is not explored further in this study. A key requirement is that for stability the thrust transmitted by arched elements needs to be balanced at column heads and/or be transferred to buttresses or other elements.



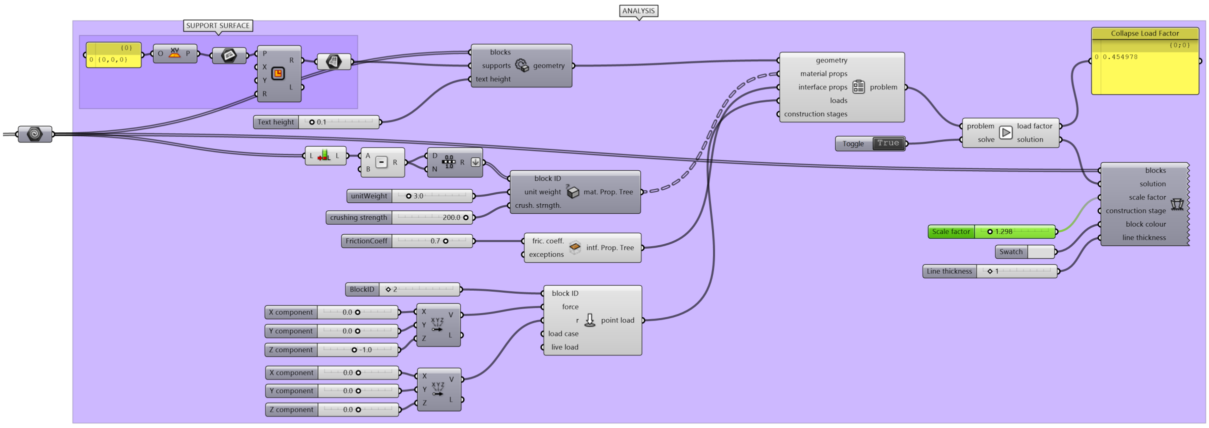
(a) (b)

Figure 1: Parametric model for the design of a simple stone masonry building: (a) parametric variables; and (b) visualization of a larger structure. The parametric model is implemented in the Rhino/Grasshopper environment.

The geometry of the exemplar building is defined in a parametric model in the Rhino/Grasshopper modelling environment (see Fig. 1), where parameters related to the topology of the structure (e.g., number of bays, stories etc) and the geometry of structural elements (e.g., column width and height, arch span, rise, and thickness) are the parameters that can be varied in the model. In this model, the designer can easily visualize the effects of parametric changes instantaneously.

2.2. Analysis workflow

To verify that the chosen geometry is structurally sound, the parametric model is linked to a numerical limit analysis model, here using a 3D version of the computationally efficient analysis engine employed by the LimitState:RING software [12]. Particularly since the design of stone masonry gravity structures is primarily a geometry problem, as opposed to a strength problem, integration of the analysis model into a parametric design environment serves to streamline the design process.



Text height 0.1
unitWeight 3.0
crushing strength 200.0
FrictionCoeff 0.7
BlockID 2
X component 0.0
Y component 0.0
Z component -1.0
X component 0.0
Y component 0.0
Z component 0.0
Toggle True
Scale factor 1.298
Line thickness 1
Collapse Load Factor {0;0} 0 0.454978

Figure 2: Custom written Grasshopper components for the analysis of an unreinforced stone masonry structure.

The analysis model is integrated into the parametric model through a set of custom-written Grasshopper components (see Fig. 2). These components allow the setting of the geometry, material properties, and loads on the structure. These parameters are then fed to the analysis software and the output is returned as the collapse load value and a visualization of the collapse mechanism (see simple example in Fig. 3).

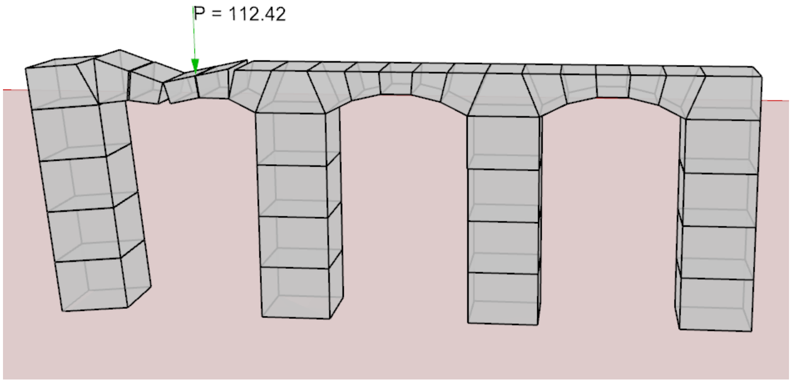
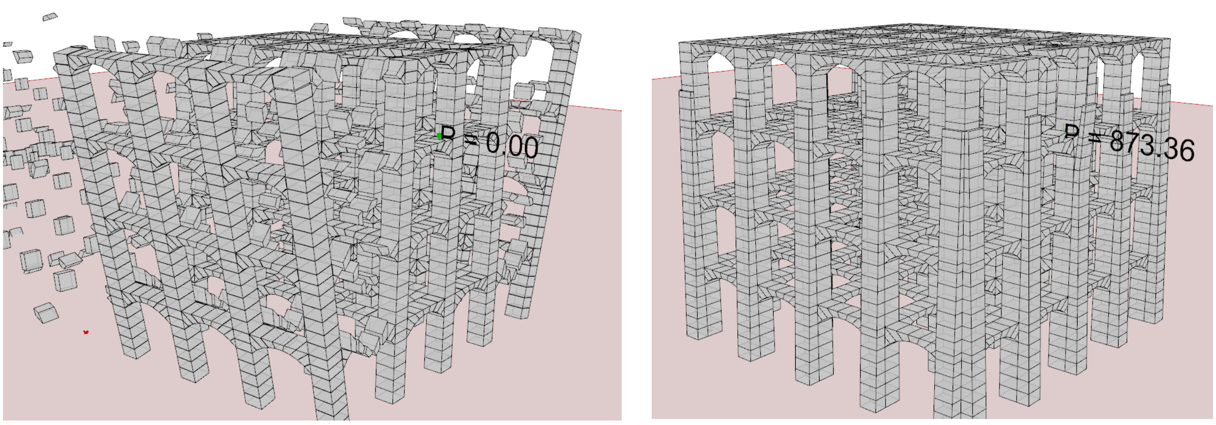


Figure 3: Visualisation of a simple collapse mechanism in the Rhino canvas.

The geometry of the structure is passed to the 'Geometry Preprocess' component [⚙] as a list of meshes, where each mesh corresponds to a block within the structure. The support surfaces are also passed to the component. Within this component, the interfaces between blocks are computed and the processed geometry data is passed onto the ‘Problem’ component [▤]. In addition to the pre-processed geometry, the ‘Problem’ component also takes in material property [⬢], interface property [◈], and loading data [⤓]. Both the above parameters are passed the appropriate block numbers, visualized via the ‘Geometry Preprocess’ component.

The ‘Solve’ component [▷] sends the problem to the LimitState:RING software via an API and in return obtains the collapse load and the formation of the individual blocks at collapse. The latter can then be plugged into the ‘Visualize Collapse Mechanism’ component [⛫], where the collapse mechanism along with the corresponding collapse load is visualized in the Rhino canvas (see e.g., Fig. 3).



(a) without buttress

(b) with buttress

Figure 4: A stone building (a) without, and (b) with adequate buttress elements. The parametric model with the embedded rapid limit analysis capability makes modelling what-if scenarios quick and easy.

Figure 4 presents a comparison of two stone buildings, one without and one with buttress elements at external columns. The analysis shows that the structure is not stable without the presence of buttress elements (load carrying capacity = zero), but is stable when buttresses elements are added, with these in this case ensuring the load-carrying capacity is significant. The geometry can however quickly and easily be changed in the parametric modelling environment, with the corresponding load-carrying capacity reported.

2.3. Further developments

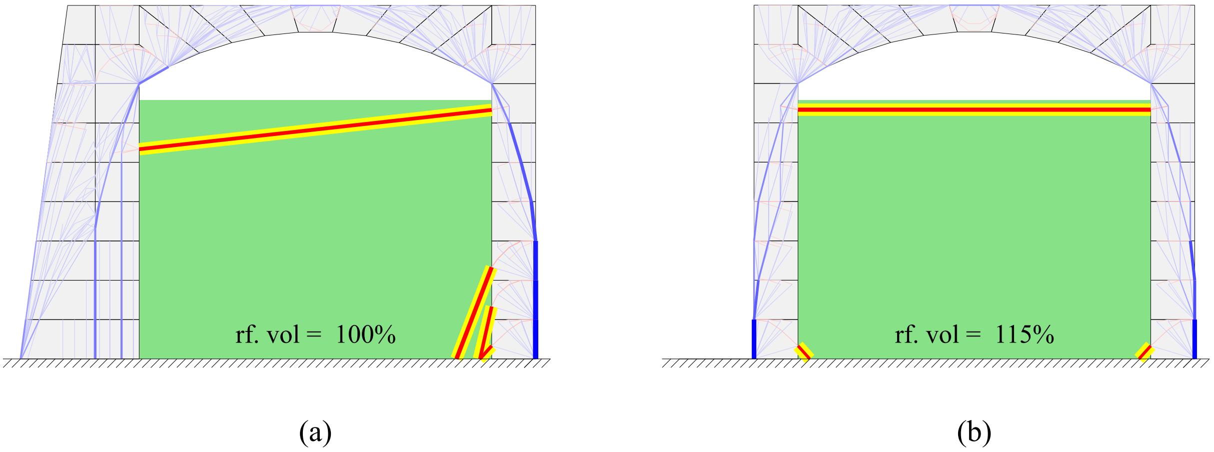
The analysis model presented herein is currently being extended to consider multiple load cases in order to enable stability during construction stages to be evaluated. Furthermore, optimization components are being developed to enable the designer to minimize material usage while maintaining the desired level of safety. Geometry rules will also be added to the geometry model to keep the block stereotomy practicable, considering both production and transportation.

Once a suitable final design is identified considering aesthetics, safety, and economy, the relevant CAD data can then be passed directly to the stonemasons yard for cutting, taking advantage of CNC saws and other suitable digital fabrication tools.

3. Design for off-site construction

Considering off-site construction to benefit from MMC, a staged construction process with off-site assembled stone structural elements (e.g., columns and arched elements) is now briefly considered. This will require temporary supports (i.e., strengthening elements, such as tie-backs for columns) to ensure the stability of the structure during each construction stage.

The design of these temporary supports can be informed by the layout optimization procedure presented for the placement of strengthening elements in masonry structures in [13], which is an extension of the thrust layout optimization (TLO) procedure presented by Nanayakkara et al [14]. In the latter contribution an automated procedure to visualize the flow of forces within masonry gravity structures is presented, extended in [13] to identify the optimal locations of external strengthening elements (where the goal is to find the minimum volume of additional strengthening elements to achieve a given load-carrying carrying capacity).



(a) (b)

Figure 5: Optimal placement of ties (highlighted in yellow) to ensure stability: (a) during construction, with a buttress providing lateral stability in the final structure; (b) after construction with ties instead providing lateral stability to the final structure. The force flow within the structure is presented as a thrust layout (after [14]). Design domain shown shaded in green; red and blue lines indicate tension and compression forces, respectively.

Figure 5 presents a thrust layout along with the optimal placement of additional strengthening elements required. Here, in the first case the lateral stability of the final structure is provided by a buttress and in the second the ties will be present in the final structure to provide lateral stability. The force flow (i.e., the thrust layout) within the structure is indicated in blue and red lines, corresponding to compression and tensile forces respectively (with the thickness corresponding to the magnitude of the force). The strengthening elements are highlighted in yellow, with a red colour indicating elements carry tensile forces. The solution is obtained using the extended TLO procedure and the strengthening design domain (i.e., where strengthening elements are allowed to be present) is shaded in green.

The same basic optimization approach can potentially also be used to automatically identify the locations and sizes of temporary steel harnesses, or other elements, required to transport assemblages of stone block elements from the stomemason's yard to the construction site: In both cases, given the relevant load cases, boundary conditions, and the domain where additional elements are to be placed, the optimization procedure will locate the additional strengthening needed, which in the latter case will be the location of steel harnesses. The detailing of the steel-to-stone connections can be done as a post-processing step.

4. Concluding remarks

In this paper, the design and construction of load-bearing stone masonry buildings has been viewed in a modern context, with the potential for modern parametric design methods and off-site construction methods to be applied highlighted. In the proposed workflow, building geometries are generated parametrically with structural stability is also assessed within a parametric modelling software environment. Construction sequencing is also considered, together with automated design of additional reusable supporting elements required to ensure that unreinforced stone assemblages are stable during erection. The approaches described are currently being further developed with a view to realizing a complete design and analysis workflow for modern unreinforced stone masonry buildings.

Acknowledgments

The financial support provided by the Engineering and Physical Sciences Research Council (EPSRC) for the ongoing Knowledge Exchange project ‘Digitally engineered stone-masonry building structures’ is gratefully acknowledged.

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