Compression-only precast block construction system using BIM and custom interoperability tools for collaboration between engineers and architects

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Abstract

Currently, the construction industry contributes 8% per year to greenhouse gas emissions which is more than 3 times that of the aviation industry. Steel corrosion affects the durability of reinforced concrete structures, reduces their service life, and increases the lifecycle maintenance costs. For these reasons, this study proposes collaborative BIM-based workflows and design for a new sustainable compression-only structural block construction system. Computational and parametric design were used to create a compression-only shell structural shape through form-finding in Rhinoceros/Grasshopper 3D. Once the overall structural shape was obtained, it was thickened and tessellated thereby defining its discrete elements. The construction sequence of precast elements was implemented automatically with a cellular automata algorithm. Then, a custom tool was created that linked the structural shape generated to the structural analysis software DIANA and automated the phased analysis which incorporated the construction sequencing. Thereafter, finite element analysis (FEA) was used to evaluate the structural behaviour. Additionally, a collaborative workflow was set up such that engineers and architects can work together to create the most optimal structural shape in a BIM environment mediated through computational design tools. Through a case study to evaluate the framework, results show that with the proposed workflows, an infinite number of arbitrary compression-only structural shapes can be defined using form-finding principles. Although, there were tensile stresses present during the phased construction they can be further minimised with the use of minimal construction supports.

1. Introduction

In recent decades, the construction industry has been criticized due to its continued use of high energy-consuming materials such as steel and concrete in a manner that is wasteful and neither optimised nor sustainable thereby limiting its productivity [1]–[3]. Moreover, unlike other industries that have embraced digitisation and automation, the construction industry lags behind and has made little progress on this front and is far behind the manufacturing sector as well as the total economy trend [4]. Other critical aspects of contemporary construction materials are their durability and lifecycle. For instance, concrete has been the main material used for construction [2] because of its mechanical properties, ease of production, and ability to be moulded to the desired geometry. Although some historical concrete structures such as the Pantheon in Rome, have been standing for more than 2000 years, modern concrete structures require the use of steel reinforcement in addition to the concrete to resist external loading effects. The problem is that steel reinforcement is prone to rust, and this can happen when the concrete cracks and there is ingress of deleterious materials that reach the steel. This affects the durability of the entire structure and reduces its service life or increases rehabilitation and maintenance costs [5].

Shell structures have a thickness much smaller than their other dimensions. Due to their geometrical properties, these structures tend to have a reduced flexural stiffness and thus their stresses develop mainly via membrane action. In the 20th century some of the most extraordinary buildings were thin shell concrete structures by the likes of Pier Luigi Nervi, Felix Candela and Eero Sarinen. The advantages of shell structures are that, first, they are natural looking forms. Secondly, large open spaces and areas can be created without the need to use supports in between them. Third, due to their thinness, use of the membrane action and the high strength to weight ratio, the design is more efficient, and less material including steel reinforcement can be used. This makes them more environmentally friendly and durable [6], [7]. However, shell structures, particularly concrete ones, have some disadvantages which have led to their decline in use and popularity. The main one is the cost of the formwork which can be as much as a third of the total concrete cost on the project or 15% of the total construction cost. This cost is usually due to the difficulty and complexity in setting up and dismantling the intricate formwork and scaffolding [7], [8] and is therefore significantly increased when it comes to shapes from form-finding processes [9], [10]. Nonetheless, nowadays, innovative options for customisable formwork are being considered with the help of technology, computational design and inspired by the textile industry, but these are yet to become mainstream [11], [12].

2. Background

The present research has been inspired by and developed within the framework of the ongoing research project called "Perpectum". Perpectum combines the Latin words “Perpectuum” meaning everlasting and “tectum” meaning shelter [13]. Perpectum proposes an efficient and cost-effective construction by using i) sustainable concrete with no rebar thereby avoiding corrosion and leading to indefinite durability ii) customisable moulds for concrete structural panels iii) permanent pre-stressing cables, and iv) Integrated Project Delivery [13].

Consequently, this work proposes compression-only structures tessellated into precast panels cast on a flexible mould, constructed with in-situ self-sensing prestressing cables.

The panel size can be approximately 1m x 1m with ± 200mm (see Figure 1) to enable easy lifting without complex machinery required. A thickness of 300mm is selected preliminarily to assess structural performance. Some of the technological aspects including modular fabrication could be available with the current technology [11], [14].

Ideally, the prestressing cables employed in Perpectum are low stress, non-metallic and cost-effective members made up of multiple layered and braided cables similar to those used in the marine industry. However, in this study, 20mm diameter steel cables are used to evaluate the validity of the proposed system. They can be replaced by marine cable technology, as they are mere unbonded tendons, and are useful mostly during construction. The construction system proposes sequential assembly of the concrete panels similar to masonry construction, to maintain robustness during construction. Each concrete panel is prestressed in two directions as it is added to the structure to maintain stability. The idea is to have technology that allows the concrete panels to have external anchor heads for the post tensioning that are decoupled after stressing to allow the next concrete panel to be placed as shown in Figure 1.

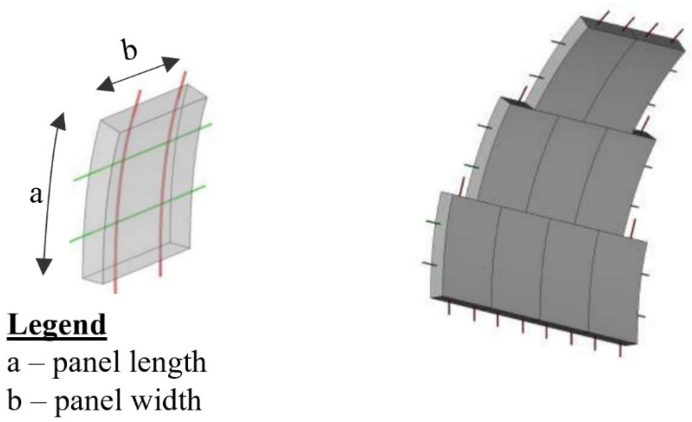

Figure 1
Perpectum individual and combined panel concept.

3. Proposed BIM framework

A workflow can be conceptualized to achieve the principles of Perpectum. For the sake of simplification, the workflow is limited to a simple project where the client, an architect and a structural engineer are the only role players. It is assumed that there are no Mechanical, Electrical and Plumbing (MEP) requirements in the project and responsibilities such as detailing are performed by the architect rather than a draughtsperson. The starting point is a client brief describing the project requirements, which results in a completed BIM model detailed enough to be handed over to the contractor for construction. Throughout the workflow, it is important that the structural engineering and architectural disciplines collaborate and provide continuous feedback to each other to prevent information latency. Similarly, the interoperability tools presented will prevent errors and information loss during the data exchanges.

The framework is shown in Figure 2 and Figure 3. The figures make use of Business Process Model and Notation (BPMN) and describe the workflow for a compression--only form-finding design and structural analysis of the construction system. The main themes of Processes 1, 2 and 3 are the Geometry Definition, BIM modelling and Structural Analysis respectively. Each of the processes are described in greater detail forthwith.

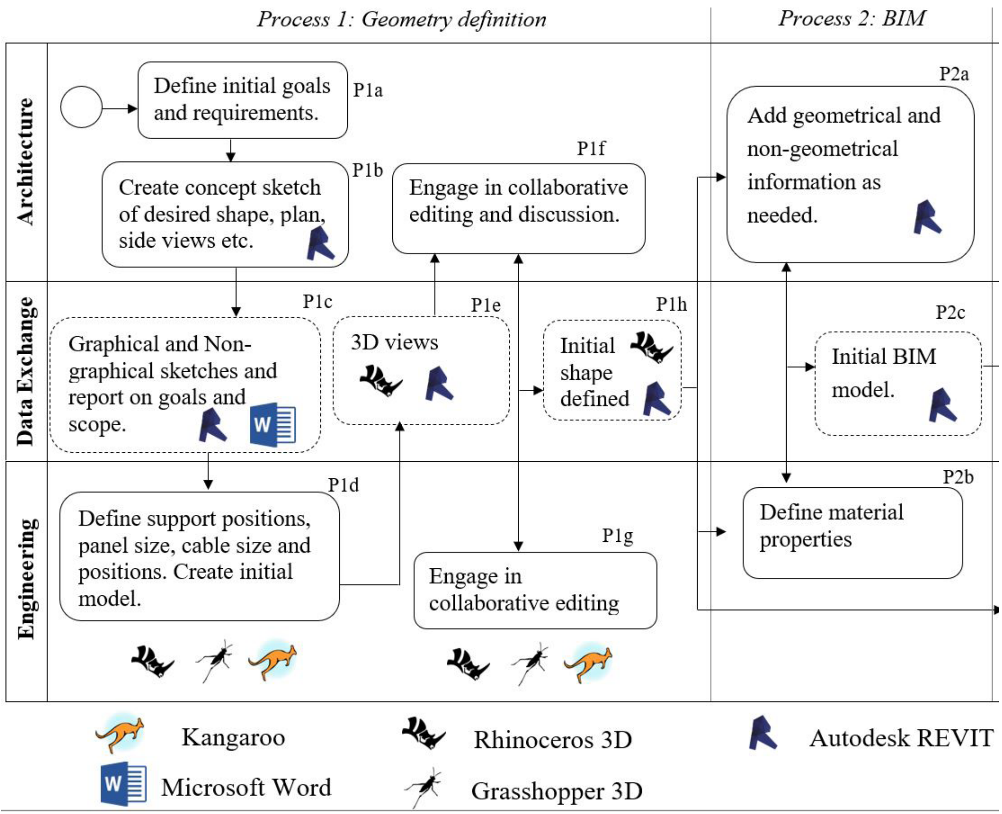

Figure 2
Collaborative BIM--based workflows–Process 1 and 2.

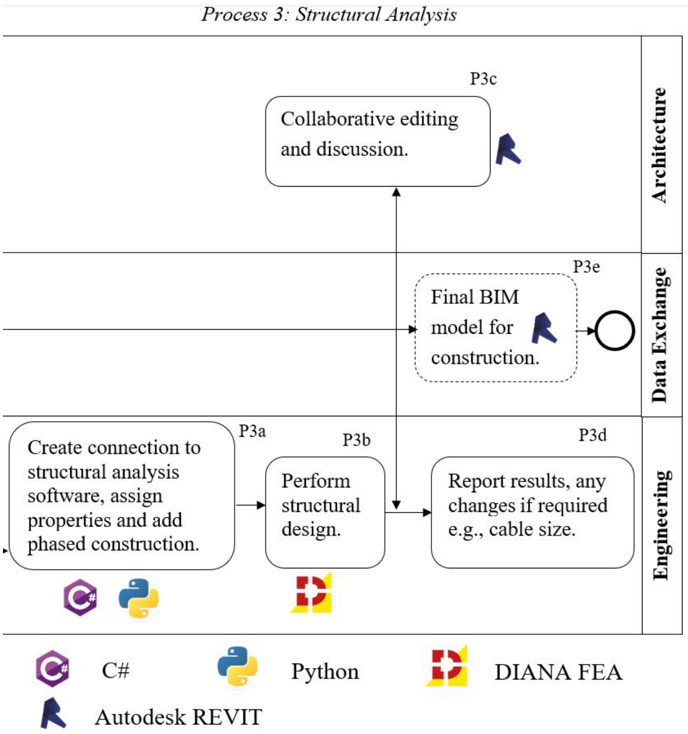

Figure 3
Collaborative BIM--based workflows – Process 3.

Process1, Geometry Definition is the most important process as its implementation affects the downstream processes. Initially, it requires the architect to obtain a brief from the client and produce the project scope (Process 1a) and preliminary concept sketch (Process 1b). Process 1b specifies Autodesk REVIT (Revit) as the software of choice but since the sketch is only for discussion purposes, any suitable software can be used. This information is shared with the engineer (Process 1c) who then defines the preliminary parametric model by using Grasshopper 3D and performs form-finding in Kangaroo (Process 1d). Process 1 concludes with an agreed upon structural shape in Rhinoceros 3D (Rhino) and Revit (Process 1h) which relies on the collaborative effort from both the structural engineer and the architect (Process 1e-g). Due to the *Rhino.Inside.Revit* plug in, the Rhino geometric shape is then immediately available in Revit (Process 1h).

The BIM process serves as the starting point for the construction model which is finalised in the third process. The process involves the development of the Revit model by the architect (Process 2a) including defining the non-geometrical information and increasing the level of detail where required (Process 2b). This is based on information provided by the structural engineer and the project requirements. The result of Process 2 is a preliminary BIM model in Revit (Process 2c).

Finally, the third process is Structural Analysis whose purpose is to evaluate the construction viability of the geometry defined in Process 1 with the proposed phased construction system. The process makes use of the Revit model from Process 1h and the custom interoperable tool using C# and Python (Process 3a) to transmit the geometry for the structural analysis (Process 3b). If only minor changes are required to the model, they are communicated to the architect (Process 3d) who produces the final BIM model to be used for construction (Process 3e) based on Process 2c. The framework is flexible and adaptable hence the engineer is also free to amend the model if required such as changing support conditions including adding temporary supports or other loads during Process 3b. However, major changes to the geometry, would necessitate a return to Process 1.

4. Parametric modelling and computational design procedure

The form-finding and construction sequencing procedures of Process 1 were carried out through the Visual Programming Language (VPL) Grasshopper 3D that is executed within the Rhinoceros 3D version 7 Computer-Aided Design (CAD) software.

Since the form-finding is achieved by the application of forces to a network of points connected by springs, the first stage consists in the definition of a network with 1m length subdivisions in each direction. The sizes of the divisions of the network are chosen to keep the resulting panels the same size as much as possible and in consideration of the space for the post tensioned cables. However, the panel edges change to 1m ± 200mm after the form-finding is carried out.

The network of points which are then used to form the lines which are in turn used to define the surface. Depending on the desired shape, some of points on the boundary of the mesh were selected to be the support points. These are the points that will remain in the same position when the form-finding is carried out. The points inside the boundary of the mesh connecting the lines of the mesh were assigned a vertical upward force to move the points, find equilibrium and generate a shape. Additionally, all the lines between the points of the mesh were assigned a spring stiffness that provides resistance to movement when the vertical force is applied.

Subsequently, the mesh, forces and springs, supports and number of iterations were used as inputs to the Physics SOLVER “ZombieKangaroo” to perform the form-finding. A fixed number of iterations was selected for the solver to establish equilibrium based on the input parameters. When the solver is run, the output is a 3-dimensional funicular-shaped mesh. Varying the starting points, support locations, spring stiffness and vertical force results in an infinite number of arbitrary shapes.

The next step was the creation of individual solid panels by thickening and tessellating the mesh output to obtain the 3D structure segmented into panels. The last step was the assignment of a numbering system to each panel and corresponding cables using a cellular automata algorithm based on the selected construction sequence.

5. Case study

A case study is carried out to assess the proposed framework and the theory. The idea is to use the framework to create a compression-only structural shape from form-finding and assess the structural viability of the proposed construction system, as mentioned before. An outdoor shading space at Parque da Cidade, in Guimarães, Portugal is proposed. The shell structure is expected to experience wind and snow loading.

Parametric modelling and computational design are conducted as part of Process 1. The starting surface (Figure 4b) is made up of two long parallel curves joined to two short parallel curves as shown in Figure 4a. Support positions are chosen to be along the two short curves (Figure 4c), then the surface is divided into springs and nodes where the force is applied (Figure 4d) to produce a freeform surface (Figure 4e). For the case study, a network of 14x10 cells is chosen so that the resulting panels from form-finding are approximately of size 1m by 1m. The form-finding and tessellation process results in the mesh and solid panels with a thickening of 300mm (Figure 4f).

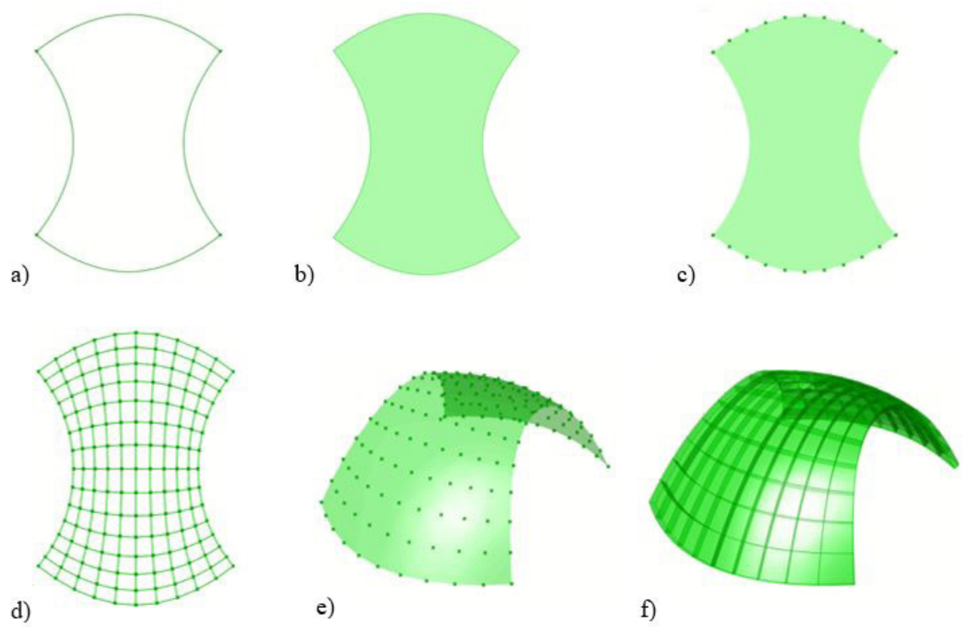

Figure 4
Parametric modelling sequence and results in Rhinoceros 3D.

After the connection to Autodesk REVIT (Revit), a custom interoperability tool is used such that the geometry is automatically transferred from Revit to DIANA FEA using a Python script, negating the need to re-define it. The panels are assigned the concrete material properties while the post tensioning (PT) cables are assigned the steel material properties shown in Table 1.

Table 1
Material properties.

Material	Young's Modulus (GPa)	Poisson's ratio	Mass density (kg/m³)	f_{yk} (MPa)	f_{ck} (MPa)	f_{ctd} (MPa)	Partial safety factor (γ)
Concrete	30	0.2	2500	-	30	1.35	1.5
Steel	200	0.3	7700	450	-	-	1.15

The PT cables have an anchor force of 40kN applied, with zero wobble factor and zero Coulomb friction coefficient. It is assumed that prestress losses are low and have been taken into account in the 40kN. For the sake of simplification, the only load accounted for during construction is the self-weight. The wind and snow loads are checked after construction once the temporary supports have been removed (stages 142 and 143 respectively) as shown in Figure 5.

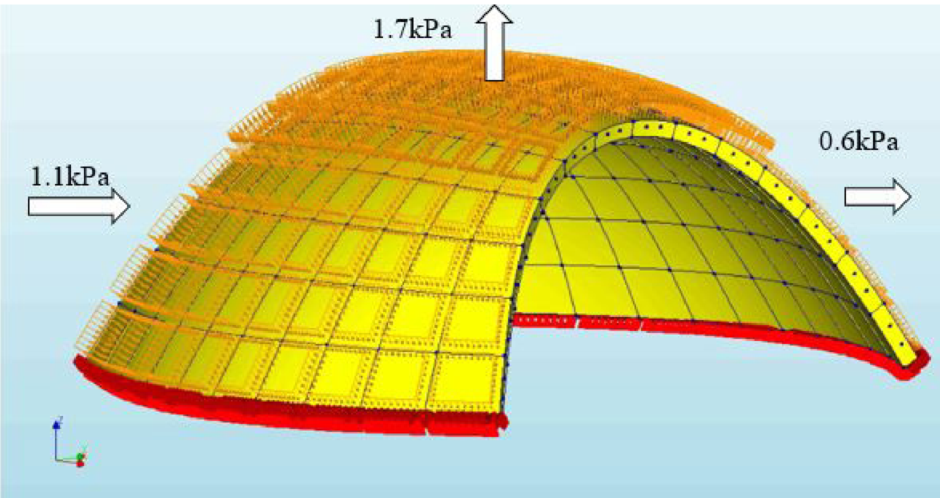

Figure 5
Permanent supports and wind loading conditions in DIANA FEA.

In the FEA conducted, the structural materials are assumed to be linearly elastic, and a staged construction analysis is performed. Equilibrium should be maintained throughout the construction stages. A simplified model is used rather than having anchor plates for the prestressing cables or interface elements to observe the stresses between the panels. However, there should be no tensile stresses at the interfaces to guarantee construction stability. With more sophisticated models (e.g., with interface elements added), tension could be acceptable if less than the design tensile strength and the equilibrium is maintained. Consequently, the results were focussed on the tensile stresses and whether the stresses would lead to concrete cracking and secondly whether the interface stresses would cause instability and loss of equilibrium during construction.

Generally, the tensile forces at the interface increase with the subsequent construction stage. Multiplying the tension stresses and their percentage of area on the interface results in the tensile force at the given interface for that construction stage. The highest tensile force is 58 kN which is less than the force provided by the PT cables (2×40 kN = 80kN) at each interface. Therefore, the PT cables provide a counter force that is more than the tension at the interface and so no loss of equilibrium would be expected during construction. Additionally, the tensile stresses (Figure 6) are less than the design tensile strength of concrete (refer to Table 1).

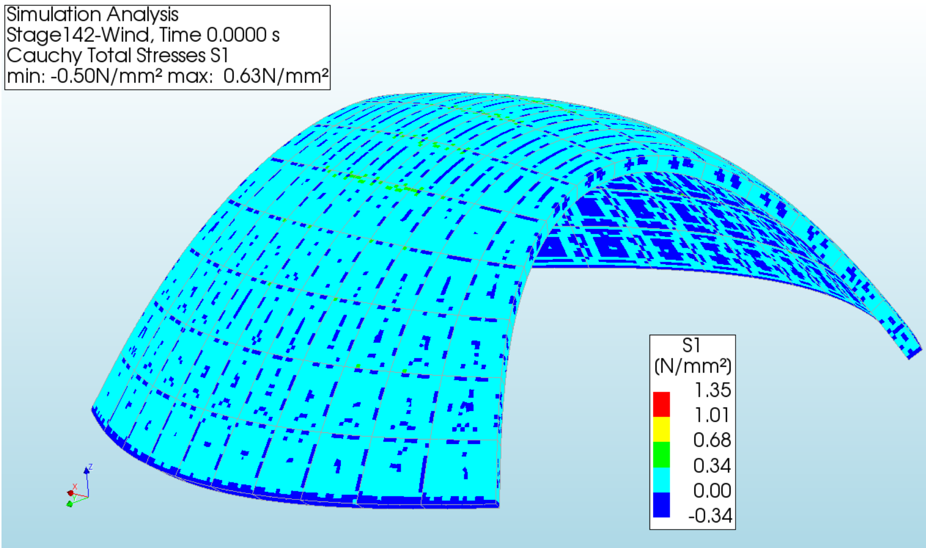

Figure 6
Results in DIANA FEA for S1 Principal stresses at Construction Stage 142.

6. Conclusions

A BIM framework based on parametric modelling and computational design to achieve interoperability and collaboration between engineers and architects was presented. The framework works for varying shapes and sizes and therefore can be used for a variety of structures and applications. For further work, more disciplines could be included in the framework such as the MEP engineers and contractor. In addition, a more in depth look at the BIM modelling in Process 2 can be investigated including preparation of the documents for construction and how these would be linked to a factory for modular construction.

Additionally, it would be prudent to include earthquake loading as well as more load combinations to evaluate robustness of the structural shapes produced. Although the resulting stresses at the interfaces were relatively low, there were not expected at all due to the addition of the prestress. For this reason, further investigation into the connection or interface between panels would be required to ensure stability. Moreover, it would also be worth investigating if increasing the number of cables in each direction may reduce the tension at the interface. Furthermore, there is the need for technological developments to make the proposed system really viable especially related to the challenges in terms of the moulds and cable positioning in the prefabrication plant.

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