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Fabrication-aware parametric design of segmented concrete shells

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Abstract

Research is underway to explore the potential of using structurally efficient non-prismatic geometries to substantially reduce the amount of concrete in building elements, thus reducing their carbon footprint. In particular, the benefits of using thin concrete shells for floor slabs are being quantified, by automating their production using computational design and digital fabrication methodologies. This paper presents the current development of a computational framework for the design of thin concrete shells, which incorporates existing solutions for parametric modelling, finite element analysis, isogeometric analysis and optimisation where appropriate. By incorporating fabrication constraints in the design optimisation, and by making it easy and quick to use, our approach aims to transform the construction industry towards a more sustainable future.

Keywords: concrete shells, sustainability, parametric modelling, finite element analysis, isogeometric analysis, segmentation, optimisation.

1. Introduction

The construction industry is responsible for nearly half of the UK's carbon emissions (Department for Business Innovation & Skills [1]), mainly due to the use of an extremely large volume of concrete, which is the world's most widely used man-made material, and accounts for more than 5% of global CO_2 emissions (J. Anderson and A. Moncaster [2]). Traditional formwork methods for concrete result in prismatic building elements (such as beams, floors slabs and columns), not because such shapes are needed for efficient load bearing, but because existing fabrication techniques rely on easy-to-construct prismatic moulds. Research has shown that up to 50% of the concrete in traditionally built elements is there only because of the prismatic formwork it was made in, and could be removed (J. J. Orr *et al.* [3]). For too long, the industry has used "ease of construction" as an excuse to waste material.

The authors are working on a research project, titled "Automating Concrete Construction" (ACORN) (P. Shepherd and J. Orr [4]), to explore the potential of using structurally efficient non-prismatic geometries to substantially reduce the amount of concrete in building elements, thus reducing their embodied carbon footprint (E. Costa *et al.* [5]). In particular, the benefits of using thin concrete shells for floor slabs are being further quantified, by automating their production using computational design and digital fabrication methodologies.

This paper documents how the ACORN project has focused on the articulation of structural design and fabrication constraints. However, for thin shells to be considered a viable construction solution, other functional requirements need to be addressed beyond structural, such as acoustic attenuation, waterproofing, thermal inertia and fireproofing. These issues, together with the impact of such structures on the quality of architectural space and the integration of MEP systems, have been discussed with industrial partners during the project, and are to be addressed as part of future research.

1.1 Thin shell floor slabs

Floor slabs represent more than half of the structural mass of a building (C. De Wolf *et al.* [6]). Previous research has shown that concrete thin shell slabs are a feasible alternative to flat plates, yielding considerable reductions above 50% in both embodied carbon and self-weight (P. Block *et al.* [7], W. Hawkins *et al.* [6]).

Plates rely on bending to carry loads, which requires thickness and reinforcement due to tensile forces. On the other hand, shells rely on both membrane and bending behaviour, thanks to their curvature and their supports admitting horizontal reaction, through external thrust or internal ties (Figure 1). Through form finding, a shell can follow a funicular shape, which guarantees a compression-only behaviour for a specified load case, usually the critical one. However, slabs experience a wide range of live loads, including asymmetrical surface loads and point loads, which induce deviation from the compression-only state. Therefore, a shell may perform only predominantly in compression, requiring local tensile reinforcement to carry higher tensile loads and enable a local bending capacity.

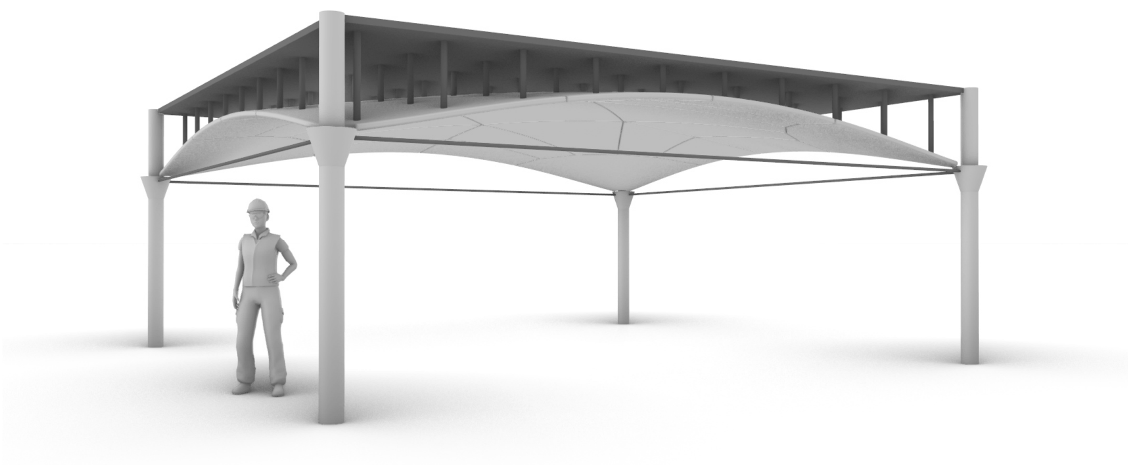

Figure 1: Rendering of assembled thin shell floor system (non-structural flat floor shown in dark grey)

1.2 Fabrication strategy

In order to benefit from the precision and controlled environment of a manufacturing plant, which provides the conditions to minimize waste and benefit from automation, and thus reducing the carbon footprint, the proposed shells are to be produced off-site. However, off-site production poses logistic constraints for a monolithic floor shell, the main one being transportation, given that the typical dimensions of a lorry are around 12m x 4m x 2m. Considering additional constraints related to fabrication and assembly, the shell must be subdivided into segments in order to benefit from off-site fabrication (Figure 2, left). The segments are connected through compression interfaces, as on-site grouting is excluded to allow disassembly and reassembly for a circular economy of construction.

Production of the segmented shells relies on the innovative articulation of fabrication technologies, which include a reconfigurable mould system for defining the shell's shape, robotic concrete spraying for producing the shell, and robotic filament winding for optimised reinforcement (R. Oval *et al.* [9]). The reconfigurable mould system provides a flexible formwork for shaping the concrete shell, and it consists of a set of four 1m x 1m modules, which can be laid out into larger 2m x 2m or 1m x 4m moulds (Figure 2, right).

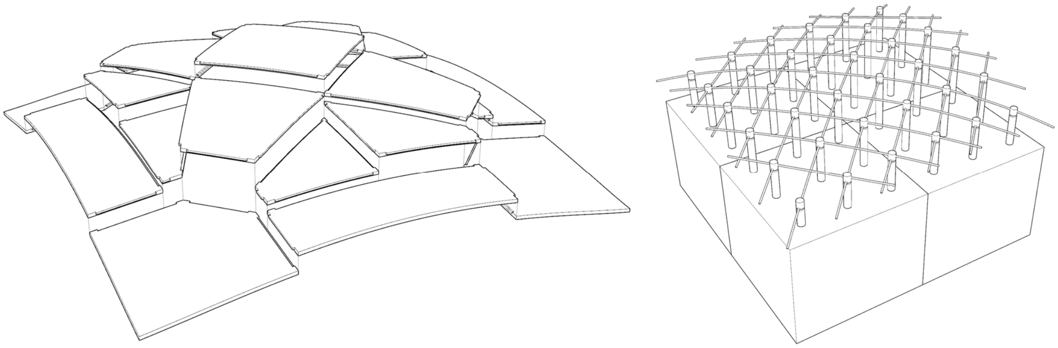

Figure 2: Assembly sequence of a segmented shell (left) and reconfigurable mould actuated by a set of vertical mechanically driven pins and connecting flexible formwork (right)

Each module consists of nine actuated pins with a maximum travel height of 40cm. A curved frame made of timber plates placed around the flexible formwork defines the segment's boundary. The interfaces between the segments are vertical to use simple flat timber plates, since following the normal direction of the shell's surface would generally require curved timber elements. The resulting risk of sliding failure between the segment is handled by boundary shear keys. These keys provide geometrical guides for partial interlocking during assembly (Figure 2, left). For the shell itself, concrete is placed within the formwork using a robotic spraying system. To tackle the need for a ductile behaviour, short fibres are added to the sprayed concrete. To increase the shell's resistance to tensile stresses, a network of reinforcement filaments is constructed using robotic winding (R. Oval *et al.* [10]) and placed within the mould prior to spraying (Figure 3). Presently, constraints related to the reconfigurable mould system have the most influence on the design workflow, in comparison with concrete spraying and wound reinforcement.

For the proposed solution to yield gains in terms of sustainability when compared to conventional reinforced concrete slabs, there is a need to consider not only the amount of concrete, but also the contributions of embodied carbon from the type of cement and reinforcement used, as well as the impact of off-site fabrication and transport when compared to on-site construction. The team is also looking at these implications, and those findings will be published elsewhere.

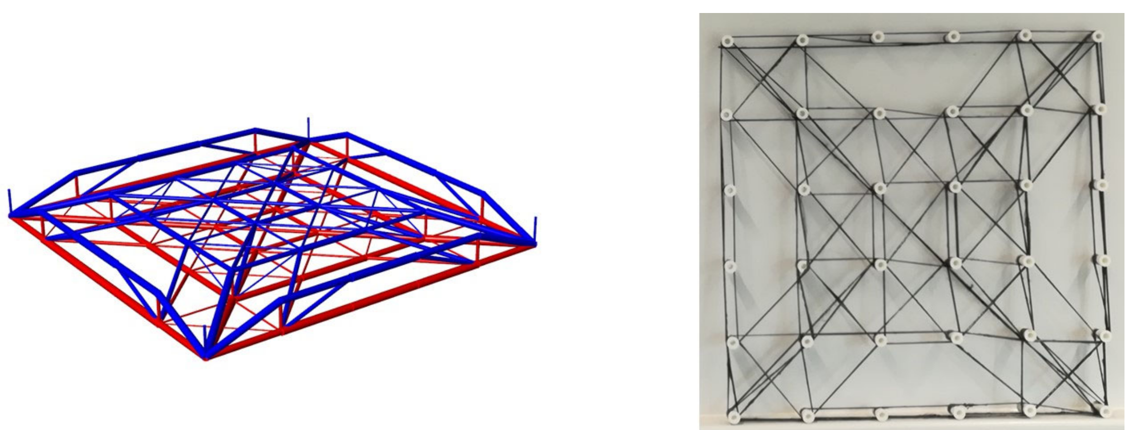

Figure 3: Tensile wound reinforcement – optimised strut-and-tie with compression in blue and tension in red (left) and wound reinforcement, based on layout optimisation (right) (R. Oval et al. [9]).

2. Design and analysis of segmented shells

This section presents the current development of a computational design tool whose ultimate goal is to assist designers in adopting non-prismatic concrete elements in their building designs. Focusing on thin concrete shells, the design tool is supported by a parametric modelling framework to generate efficient shapes through form-finding processes. Subsequent analysis of the performance of the concrete slab in near real-time enables the optimisation of shape, segmentation and cross-section parameters. The design of the segmented shell follows a workflow consisting of multiple stages, each responsible for a well-defined task (Figure 4). Presently, the design workflow is implemented using Grasshopper (GH), a visual programming interface for parametric modelling in CAD application Rhinoceros (Rhino). Additionally, two GH plugins are used for structural form finding and analysis, respectively Kiwi!3D (Kiwi), for Iso-Geometric Analysis (IGA) (P. Längst *et al.* [11]), and Karamba3D (Karamba), for Finite Element Analysis (FEA) (C. Preisinger [12]). The workflow implementation in GH comprises mostly custom components, meant to be later included in a plugin to facilitate the design of the structural elements being developed in ACORN.

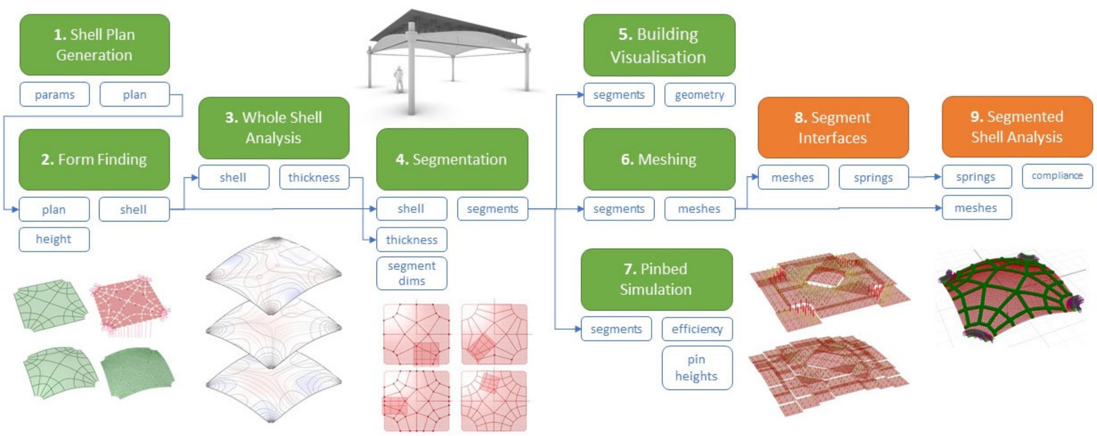

Figure 4: Design workflow stages (orange stages under development)

2.1 Input parameters and Shell Plan Generation

The design workflow starts from a set of initial parameters related to the geometry of the desired slab, namely the slab height and bay dimensions, in the case of rectangular slabs, or a closed curve, in the case of other geometries. Other initial inputs for the whole system include the type of concrete being used and its properties.

A shell plan is generated based on the geometry of the bay (Figure 5, green). While the project mostly focuses on rectangular slab footprints, the stage responsible for generating the shell plan was developed to allow for more generic geometries, namely irregular polygons. Besides generating the plan from its dimensions, the stage also determines the geometry of its corners at the column supports.

2.2 Form finding

The three-dimensional shape of the shell is defined by form finding using Iso-Geometric Analysis (IGA), through the Kiwi plugin for Grasshopper. Kiwi enables NURBS geometry as an input, as opposed to a polygonal mesh which is typically the geometry required by other GH plugins used for form finding, such as Kangaroo or Karamba (A. M. A. Bauer *et al.* [13]). Consequently, NURBS geometries can still be used in subsequent stages of the design process, which has proven particularly beneficial in the Segmentation and Pinbed Simulation stages.

The corner edges of the shell plan are divided into sets of points, and encoded into the structural model as pinned support points in which translation is restrained in all directions, while allowing rotation. The flat shell is then form found by incrementally applying an upward vertical uniformly distributed load, in a non-linear process. Finally, the deformation is adjusted to match the target shell height, which is defined as an initial parameter of the design workflow. The resulting 3D shape (Figure 5, red) is then used to represent the medial surface of the thin shell that supports the flat upper non-structural floor surface (in dark grey in Figure 1).

While in earlier prototypes of the design workflow deflection was calculated using Kiwi's Linear Analysis algorithm, the plugin's Formfinding component is currently being exploring, which is based on Updated Reference Strategy (URS) and suited to model the behaviour of tensile structures (K.-U. Bletzinger and E. Ramm [14]). Initial results show that this approach generates shell shapes with a more predominant compression behaviour of the shell.

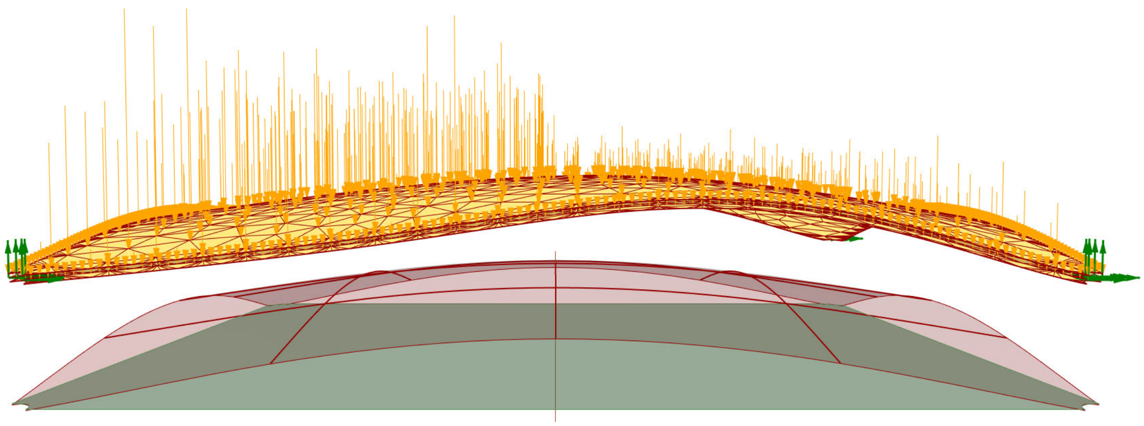

Figure 5: Initial shell plan (green), form-found shell as NURBS surface (red), and corresponding mesh deformed after FEA (yellow), showing asymmetrical live loads (amber arrows) and support points (green arrows).

2.3 Whole Shell Analysis

Having determined the shape of the shell, its thickness needs to be defined, which should be minimized according to the project's objective of reducing the amount of concrete. To determine an optimised value for shell thickness, a preliminary analysis is performed on the form-found shell to assess its structural performance, through Finite Element Analysis (FEA) using GH plugin Karamba (Figure 5, yellow). The objective is to minimize thickness while keeping critical parameters within acceptable ranges, namely compression stresses below a maximum value, and buckling factors above a minimum value. At this stage, the values for tension stress in the shell are not considered, since most of it should be absorbed by short fibres, providing ductility, and the wound reinforcement considered in the fabrication strategy (see Section 1.2). Nevertheless, tension stress would need to be re-evaluated should the wound reinforcement prove to be insufficient. Thanks to the compression-dominant behaviour, deflections are much lower than the standard maximum admissible values.

In this stage of the design workflow, a parametric structural model is assembled through Karamba using the form-found shell. Note that, throughout the design workflow, analysis tasks are performed using Karamba rather than Kiwi since the former provides a wider range of results than the latter. Similarly to the preceding Form Finding stage, the shell's corner curves are divided into pinned support points. In terms of loads, a combination of the shell's self-weight, superimposed dead loads (DL) and live loads (LL) were considered. Whereas DL correspond to a uniformly distributed load, for LL a number of symmetrical and asymmetrical load patterns are considered, similar to (W. Hawkins *et al.* [8]) (Figure 9, right). Such live load patterns, which are likely to occur on a building floor, confer the shell with its compression-dominant behaviour, rather than compression-only, and therefore generate tensile stresses in the shell.

To optimise the shell's thickness, a set of individual structural models can be generated by varying values for thickness and iterating the loading patterns, and values for compression stress and buckling load factors are obtained by Linear Analysis through Karamba. The resulting data can be processed using a custom developed Design Space Visualisation system that generates two- and three-dimensional charts, which help identify best and worst case scenarios in which multi-objective trade-offs can be explored and, ultimately, identify minimum thickness values.

2.4 Segmentation

According to the fabrication strategy, the shell is decomposed into smaller segments due to logistic constraints. An important fabrication constraint is that segments fit the dimensions of the reconfigurable mould's envelope, requiring the automated generation of segmentation patterns. Currently, the segmentation pattern is determined by the intersection of the shell's principal stress lines generated by Karamba (Figure 6), so that the interfaces between segments are orthogonal to principal stress directions, thus aligning the segments with the flow of compression forces, and preventing sliding failure in the in-plane direction.

The segmentation pattern includes a segment acting as a keystone at the shell's apex, and segments acting as cornerstones where the shell interfaces with its supporting columns. The network of principal stress lines is determined by parameters related to target dimensions for the generic segments, as well as for the keystone and the cornerstones. Such target dimensions mainly depend on factors such as the number of pinbed modules available and their aggregated dimensions.

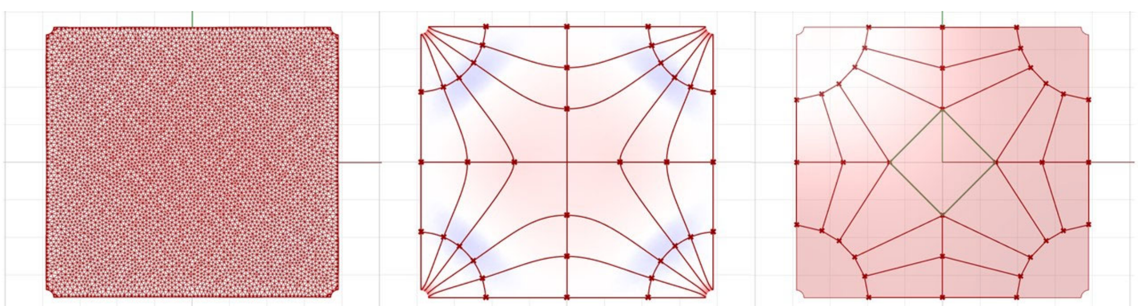

Figure 6: Segmentation process: the mesh corresponding to the form-found surface (left) is used to calculate the principal stress lines through FEA (middle), whose intersection points inform the segmentation (right).

2.5 Pinbed Simulation

In order to assess if the resulting segments fit the maximum pin height of the reconfigurable mould, it was necessary to develop a design stage responsible for simulating the pinbed modules. After determining the number of pinbed modules needed for each segment and the most suitable layout, the required pin heights are determined by vertically projecting the points corresponding to the pin's position within the module onto the segment's surface (Figure 7).

In the eventuality that some of the required pin heights are larger than the actual maximum pin height, three strategies are considered. The first strategy consists of lifting the pinbed modules at different heights relative to each other (Figure 7, right). However, this might not be viable at an industrial scale. The second strategy consists of rotating the segment's orientation in three dimensions relative to the pinbed module's top plane. While this strategy creates an additional challenge regarding the orientation of the frame plates that define the segment's boundary, it reduces the needed pin height considerably, and therefore is currently being explored. The third strategy consists of applying local adjustments to the segmentation pattern.

The final output of the pinbed simulation stage is a set of pin height values that can be fed into the reconfigurable mould controller to drive the physical pins. A useful intermediate output is area efficiency, which corresponds to the ratio between the area of a segment's projected boundary curve and the total area of the modules being considered for producing that segment. Trying to maximize area efficiency is a natural step into future optimisation of the segmentation process, which would also consider the maximum pin height as a constraint.

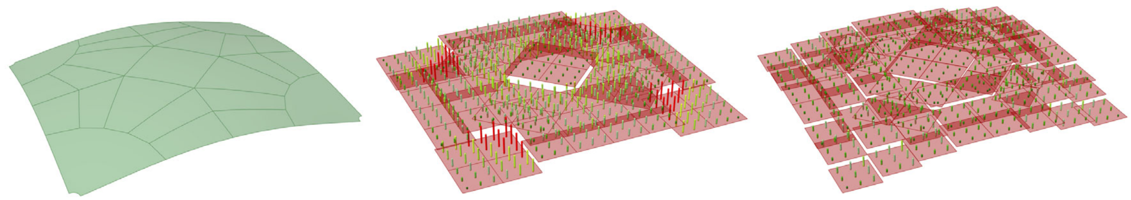

Figure 7: Simulation of the reconfigurable mould for the segmented shell (left), with constant module heights within the same segment (middle), and varying module heights (right) (red-coloured pins above maximum pin height)

2.6 Segmented Shell Analysis

The Segmented Shell Analysis stage models how segments interact with each other. The interface between any pair of segments is modelled in Karamba as a set of springs connecting the adjacent edge of each segment orthogonally (Figure 8). In the current fabrication strategy, shell segments are interlocked using boundary shear keys. Therefore, the modelled springs must be non-elastic to take into account the lack of tensile capacity and the unidirectional behaviour of the shear key. Simplified, linear interfaces in the Karamba model will depend on values for translation and rotation stiffness, which have been specified with the intent of simulating the shell segments' behaviour at the shear keys. Through parametric studies, sensible intervals were defined for these values, which will be tested on physical prototypes of the segmented shell. One of the challenges in modelling such interfaces is related to converting the segment surfaces into meshes. For the springs to align correctly, the meshes need to match between adjacent segments (Figure 8, right).

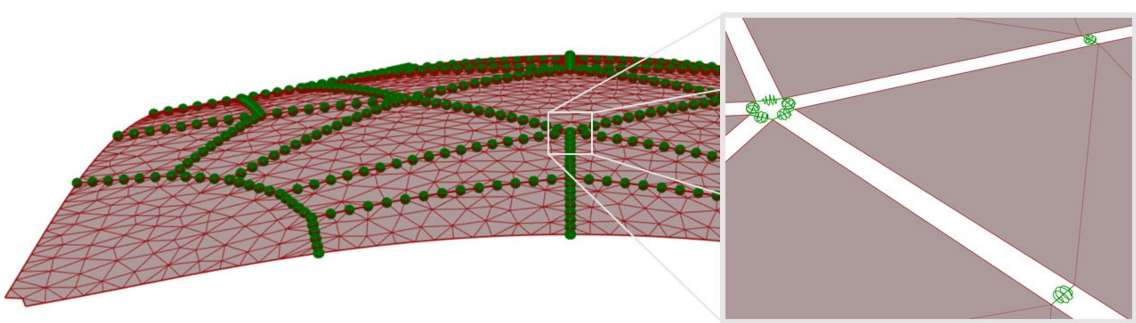

Figure 8: Setup for segmented shell analysis (springs in green; segment surfaces converted into coarse mesh for illustration purposes); detail (right): artificially separating the segments ensures the correct orientation of springs

3. Results

The design workflow was partially tested in the scope of a study whose main goal was to estimate two key parameters for the construction of the reconfigurable pinbed equipment: the shell's thickness, which determines the weight that the pins would have to withstand, and the pins' maximum height. This study tested the Form Finding, Whole Shell Analysis and Pinbed Simulation stages, while it also provided insights for some of the remaining stages such as Segmentation and Building Visualisation. In this study, segmentation patterns were pre-defined, rather than generated within the Segmentation stage, which was still being developed at the time. The design workflow stage responsible for Building Visualisation (Figure 1) was also developed in the scope of the study.

In this study, two different shell plans were used: a square bay (6 x 6m), and a rectangular bay (7.8 x 7.2m). For each floor plan, a corresponding form-found shell was generated using Kiwi's Linear Analysis algorithm, and input into a structural model in Karamba for analysis, in which supports were situated along the edges at the shell's bottom corners and the external loads were applied on the shell's top surface. Loads included the shell's self-weight, a dead load value of 1.0 kN/m^2 and a live load value of 1.5 kN/m^2.

Both shell designs were analysed for a range of thickness values between 40 and 100mm, and for the range of live load patterns mentioned earlier. Analysis results related to critical parameters were sampled for each combination shell design / thickness / live load pattern, and laid out into charts for comparison using the customised Design Space Visualisation system. Such comparison determined the least favourable loading pattern for each critical parameter, which was consistent throughout all sampled results. Regarding the thresholds for critical parameters, maximum compression stress was set to 20 MPa, equivalent to the design compressive strength of a C30/37 concrete ($f_{cd} = \alpha_{cc} f_{ck} / \gamma c$), using a partial safety factor $\gamma c = 1.5$ (E. C. for Standardization [15]), while minimum buckling load factor was set to 10, to anticipate for the influence of the shape imperfections due the use of a flexible formwork. Deflection values were also considered, and deemed acceptable for a span/deflection ratio greater than 200.

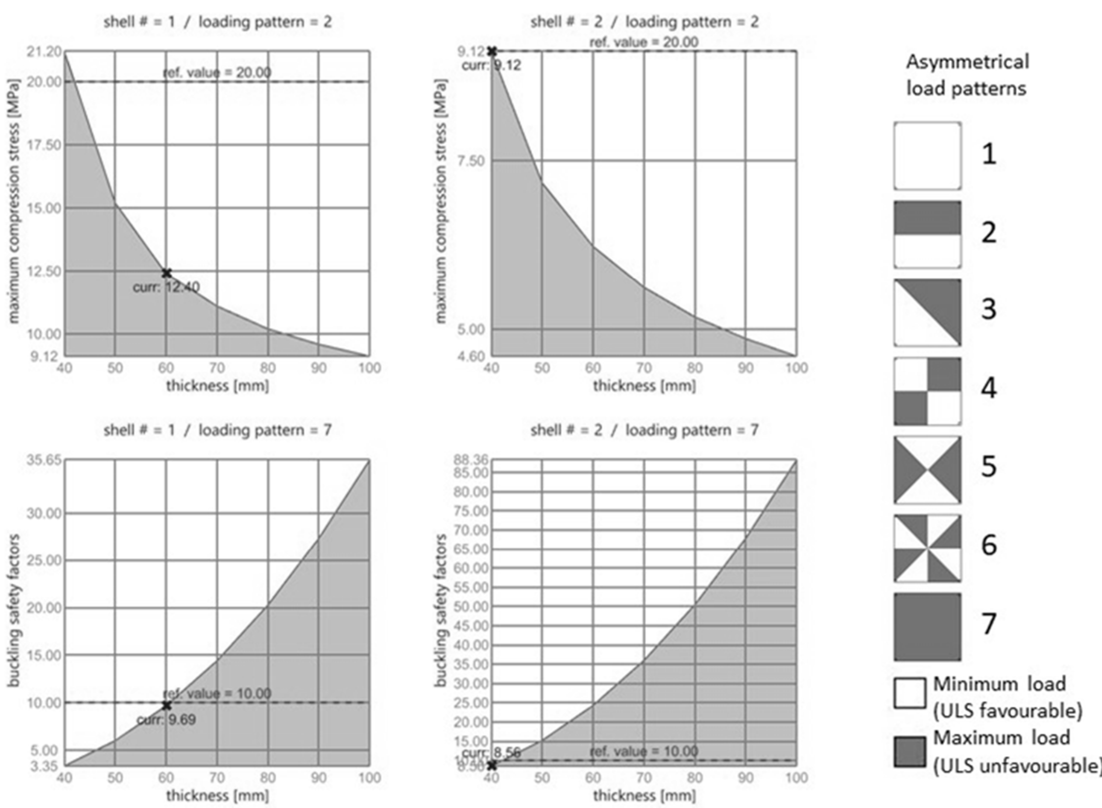

Figure 9: Left: Analysis result charts for defining the shell thickness while respecting the structural requirements on strength and stability; right: symmetrical and asymmetrical load patterns, adapted from W. Hawkins et al. [8]

Analysis of the results showed that the buckling load factor drove thickness selection in both designs, prescribing larger thicknesses than those prescribed by maximum compressive stress and deflection values. Final values for thickness, corresponding to 46mm for the 6x6m shell, and 61mm for the 7.8x7.2m shell, were extrapolated from the chart's sample points to obtain a minimum buckling load set to 10 (Figure 9, left), and running a final analysis for cross-checking. While thickness was determined by "manual tuning", this case study suggests potential for automating the optimisation process, for example using available tools for Grasshopper, such as Galapagos or Goat.

Further development of the Form Finding stage, subsequent to this study, explored Kiwi's Formfinding algorithm as an alternative to Linear Analysis. As a preliminary test, shell designs form found using the same initial parameters were analysed for comparing results, which suggest that the new shapes yield better results for the critical parameters, thus allowing for smaller thickness values. Considering that the shell's thickness is proportional to the amount of concrete and therefore related to its embodied carbon, the benefits of further optimising thickness – for example, by exploring thickness variation along the shell – become evident.

4. Conclusion

The presented design workflow is still under development. Efforts are now directed at the final stages, related to analysis of the segmented shell. The main objective is to have the whole design workflow operational in time for the construction of a demonstration building featuring the segmented shells as a solution for building concrete slabs. Such shells are scheduled for production during the second half of 2021. This production exercise, as well as preliminary physical experiments, are expected to provide multiple insights on how to improve the design tool.

The main issues to be addressed will include the proper simulation of the segment interfaces, but also the suitability of the optimised thickness values. This includes considering different thickness values across segments, such as having thicker shell segments adjacent to the supports. Segmentation is therefore expected to be revised as a result of those insights. Sensitivity analyses to creep, shrinkage, thermal loads, and support displacements should also be addressed, since these could greatly impact the stability of the segmented, non-monolithic shell. Having an operational version of the ACORN design tool, we expect to be in the position to make it available to designers for testing, which will provide valuable feedback for its further development.

Acknowledgements

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References

[1] Department for Business Innovation & Skills, "Estimating the amount of CO2 emissions that the construction industry can influence - Supporting material for the Low Carbon Construction IGT Report," 2010. Accessed: Dec. 20, 2019. [Online]. Available: https://www.gov.uk/government/publications/low-carbon-construction-igt-report-co2-emissions-influenced-by-the-construction-industry.

[2] J. Anderson and A. Moncaster, "Embodied carbon of concrete in buildings, Part 1: analysis of published EPD," *Buildings and Cities*, vol. 1, no. 1, pp. 198–217, Jun. 2020, doi: 10.5334/bc.59.

[3] J. J. Orr, A. P. Darby, T. J. Ibell, M. C. Evernden, and M. Otlet, "Concrete structures using fabric formwork," *The Structural Engineer*, vol. 89, no. 8, pp. 20–26, Apr. 2011, Accessed: Jun. 21, 2019. [Online]. Available: https://researchportal.bath.ac.uk/en/publications/concrete-structures-using-fabric-formwork.

[4] P. Shepherd and J. Orr, "ACORN: Automating Concrete Construction," 2019.

https://automated.construction/ (accessed Apr. 13, 2021).

[5] E. Costa, P. Shepherd, J. Orr, T. Ibell, and R. Oval, "Automating Concrete Construction: Digital Design of Non-prismatic Reinforced Concrete Beams," in *Second RILEM International Conference on Concrete and Digital Fabrication*, Springer, Cham, 2020, pp. 863–872.

[6] C. De Wolf, M. Ramage, and J. Ochsendorf, "Low carbon vaulted masonry structures," *Journal of the International Association for Shell and Spatial Structures*, vol. 57, no. 4, pp. 275–284, Dec. 2016, doi: 10.20898/j.iass.2016.190.854.

[7] P. Block, C. Calvo Barentin, F. Ranaudo, and N. Paulson, "Imposing Challenges, Disruptive Changes: Rethinking the floor slab," in *The Materials Book*, I. Ruby and A. Ruby, Eds. Ruby Press, 2020, pp. 214–219.

[8] W. Hawkins, J. Orr, T. Ibell, and P. Shepherd, "A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors," *Engineering Structures*, vol. 207, p. 110195, Mar. 2020, doi: 10.1016/j.engstruct.2020.110195.

[9] R. Oval, E. Costa, M. Nuh, D. Thomas-McEwen, J. Orr, and P. Shepherd, "A path towards the off-site automated fabrication of segmented concrete shells for building floors," in *Proceedings of the IASS Annual Symposium 2020/21 and the 7th International Conference on Spatial Structures: Inspiring the Next Generation*, 2021.

[10] R. Oval, E. Costa, D. Thomas-Mcewen, S. Spadea, J. Orr, and P. Shepherd, "Automated Framework for the Optimisation of Spatial Layouts for Concrete Structures Reinforced with Robotic Filament Winding," *Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC)*, pp. 1541–1548, 2020, doi: 10.22260/isarc2020/0214.

[11] P. Längst, A. M. Bauer, A. Michalski, and J. Lienhard, "The Potentials of Isogeometric Analysis Methods in Integrated Design Processes."

[12] C. Preisinger, "Linking Structure and Parametric Geometry," *Architectural Design*, vol. 83, no. 2, pp. 110–113, Mar. 2013, doi: 10.1002/ad.1564.

[13] A. M. A. Bauer, P. Längst, R. Wüchner, and K.-U. K.-U. Bletzinger, "Isogeometric Analysis for Modeling and Simulation of Building Processes," *International Association for Shell and Spatial Structures (IASS) Symposium*, no. September, p. 1, 2017, Accessed: Oct. 16, 2020. [Online]. Available: https://structurae.net/en/literature/conference-paper/isogeometric-analysis-for-modeling-and-simulation-of-building-processes.

[14] K.-U. Bletzinger and E. Ramm, "A General Finite Element Approach to the form Finding of Tensile Structures by the Updated Reference Strategy," *International Journal of Space Structures*, vol. 14, no. 2, pp. 131–145, Jun. 1999, doi: 10.1260/0266351991494759.

[15] E. C. for Standardization, "EN 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-1: General ruels and rules for buildings," 2005.