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An integrated framework for multi-criteria optimization of thin concrete shells at early design stages

Carlos Gomes[a], Manuel Parente[b], Miguel Azenha[c,*], José Carlos Lino[c]

[a] Shay Murtagh Precast Ltd, Raharney, Mullingar, Co. Westmeath N91 WY91, Ireland
[b] INESC TEC Institute for Systems and Computer Engineering, Technology and Science, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] ISISE – Institute for Sustainability and Innovation in Structural Engineering, University of Minho, School of Engineering, Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

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ABSTRACT

Thin shells are crucially dependent on their shape in order to obtain proper structural performance. In this context, the optimal shape will guarantee performance and safety requirements, while minimizing the use of materials, as well as construction/maintenance costs.

Thin shell design is a team-based, multidisciplinary, and iterative process, which requires a high level of interaction between the various parties involved, especially between the Architecture and Engineering teams. As a result of technological development, novel concepts and tools become available to support this process. On the one hand, concepts like Integrated Project Delivery (IPD) show the potential to have a high impact on multidisciplinary environments such as the one in question, supporting the early decision-making process with the availability of as much information as possible. On the other hand, optimization techniques and tools should be highlighted, as they fit the needs and requirements of both the shell shape definition process and the IPD concept. These can be used not only to support advanced design stages, but also to facilitate the initial formulation of shape during the early interactions between architect and structural engineer from an IPD point of view.

This paper proposes a methodology aimed at enhancing the interactive and iterative process associated with the early stages of thin shell design, supported by an integrated framework. The latter is based on several tools, namely Rhinoceros 3D, Grasshopper, and Robot Structural Analysis. In order to achieve full integration of the support tools, a custom devised module was developed, so as to allow interoperability between Grasshopper and Robot Structural Analysis. The system resorts to various technologies targeted at improving the shell shape definition process, such as formfinding techniques, parametric and generative models, as well as shape optimization techniques that leverage on multi criteria evolutionary algorithms. The proposed framework is implemented in a set of fictitious scenarios, in which the best thin reinforced concrete shell structures are sought according to given design requirements. Results stemming from this implementation emphasize its interoperability, flexibility, and capability to promote interaction between the elements of the design team, ultimately outputting a set of diverse and creative shell shapes, and thus supporting the pre-design process.

1. Introduction

A thin shell can be defined as a three-dimensional curved surface, in which one dimension (thickness) is significantly smaller than the other two. This type of structural element is crucially dependent on its shape in order to obtain proper structural performance [42,48,7], and only when a proper shape is defined will it be able to overcome large spans efficiently and economically, without compromising the aesthetic component. Thin shell design is generally a function of architectural and structural requirements. Architectural requirements regard mostly to aesthetics and functionality, whereas structural requirements regard to ensuring adequate performance in both service and ultimate limit states, evaluated by criteria such as internal stress states (the sought-after shape is expected to be exclusively subjected to compressive stresses) and displacements [12]. In this context, the optimal shape will guarantee performance and safety requirements, while minimizing the use of materials, as well as construction/maintenance costs [40].

* Corresponding author.
E-mail address: miguel.azenha@civil.uminho.pt (M. Azenha).

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Conventionally, this shape optimization concept has been subject of interest and thorough study. In fact, renowned authors such as Robert Hooke, Heinz Isler, Felix Candela and Antoni Gaudi are featured among the contributors to this field [15,6,7,1,13,14,22]. One of the main methodologies used by these notable shell builders is the concept of formfinding. In simple terms, the idea underlying this concept concerns the fact that inverting the shape of an object (in the aforementioned studies, this refers to objects such as a chain or a sheet of wet cloth) which has achieved stability under tension will result in a fully compressed, shell-shaped object [42]. As this is the most advantageous state for materials such as concrete (reasonably high compressive strength/cost ratio, as opposed to low tensile strength), not only does the process become simple from the analysis viewpoint, but it also provides the lowest cost structural solution [5].

Nevertheless, in contemporary design, and especially in its early phases, the definition of the shape that best fits the architectural and structural requirements is achieved through the interaction between architect and structural engineer [22]. Yet, even with the modern advances in computational applications, this is still a relatively slow process that includes a large time gap between the conceptual discussion of the structure geometry and the definition of solutions for discussions [37]. Alternatively, owing to the development of new technologies, novel concepts and tools become available to support this process. On the one hand, concepts like Integrated Project Delivery (IPD) [2] are under exhaustive study and discussion on account of the potential of their application in multidisciplinary environments such as the one at issue. The main drive behind this concept is to support the early decision-making process with the availability of as much information as possible, so as to maximize the impact of decisions made in the initial stages of a project. In a world where a company's success is in no small measure marked by a design team's efficiency and quality of response to the client's needs as early and as optimally as possible, methodologies like IPD emerge as fundamental competitive advantages. The recent increase in research and successful applications may be seen as an indication of the elevated potential of IPD in design and construction [34,35,24,30]. On the other hand, optimization techniques and tools should be highlighted, as they fit the needs and requirements of both the formfinding process and the IPD concept. Tools such as evolutionary algorithms and/or parametric/generative models can be used not only to support advanced design stages, but also to facilitate the initial formulation of shape during the early interactions between architect and structural engineer from an IPD point of view. Indeed, the ability to promptly generate and assess a given shape in these stages provides the design team with a significant amount of information that would not have been available early on otherwise, thus allowing for more impactful decisions to be made straight away. In general, early applications in the field of support of architectural-structural design were focused on enhancing the interactions between architects and engineers, mainly by means of 3D modelling techniques [29,25,19], often complemented by the establishment of shape grammars [52,36,20] or knowledge-based systems [45,27,46] to support it. Yet, with the rapid growth of advanced artificial intelligence tools, studies evolved towards automatic generation of design solution, especially through the implementation of evolutionary optimization [28,16,49,21]. Specifically in the field of shell design, successful applications include the use of genetic algorithms for the optimization of axisymmetric and free form shells, [4,51,41], as well as in the optimization of other structural elements, such as trusses [47].

These applications use powerful design systems allied to robust methods to generate several options from a set of given assumptions and priorities. However, the design of unique iconic structures has a strong artistic component, and, as such, is an organic and sometimes stochastic process in which the initial assumptions and priorities are constantly evolving or changing. For this reason, the methodology presented in this paper is, unlike those found in the literature, meant to allow for maximum flexibility in the context of the interaction between Architecture and Engineering teams to freely change these priorities, assumptions and concepts as they deem necessary. To achieve this, this paper addresses the challenges and opportunities posed by structural design of thin concrete shells by the availability of current computing power and modelling/analysis software, capable of modeling arbitrary geometries, as well as their interoperability. It is remarked that such interoperability is achieved through a custom-devised application, and supported by the use of shape optimization techniques, such as formfinding and the use of numerical solvers. Additionally, this work proposes a framework for early pre-design stages of a thin shell structure, recalling its capacity to obtain an optimized structure by resorting to real time interoperability between a modelling software and structural analysis software, while facilitating and promoting interaction between Architecture and Engineering teams. The proposed framework is implemented in a set of fictitious scenarios, in which the best thin reinforced concrete shell structures are sought according to the given design requirements. Ultimately, this work is intended to address the research gap associated with the application of the IPD concept to shell design, by leveraging on the development of current design methodologies, design software interoperability, and multi-criteria optimization techniques.

The paper is organized as follows. Section 2 introduces the proposed framework in the context of a team-based formfinding optimization process, while Section 3 discriminates the tools that are used in each stage of the same process. Section 4 details how this framework was used in order to solve the problem presented by a case study. Finally, some conclusions pertaining to the advantages of resorting to this methodology are drawn in Section 5, supported by the results achieved in the previous section.

2. Proposed framework

The aforementioned goals could be translated into an optimization problem centered on finding the best form or shape for a thin shell element subjected to specific restrictions, which are a function of project specifications. In other words, a simplified objective function for the general optimization problem associated with thin shell design could be to find the shape that minimizes the maximum displacement of the structure. This would be directly related to minimizing compressive stresses, as well as the risk of buckling failure, while guaranteeing that tensile stresses and bending moment are null [23].

However, this definition neither manages to capture the outstanding complexity of the problem, nor does it take into account its multidisciplinary and multi-criteria nature. In fact, thin shell design is a team-based iterative process, as opposed to a simple optimization problem. For that reason, rather than simply presenting an optimization method/algorithm, this work proposes a methodology, which, by leveraging on a decision support optimization tool, is capable of assisting the Architecture and Engineering teams throughout an IPD-compliant pre-design process for thin shells. The presented methodology was implemented together with several architects, and their feedback was taken into account in order to adjust it accordingly. The overall flow of the proposed framework is summarized in 3 processes and depicted in Fig. 1, accompanied by a simplified illustrative example of a bridge structure, which is not necessarily structurally viable.

In order to start this interactive and iterative methodology, a number of key design specifications should be known, namely implantation area architectural requirements (e.g. height of the structure, solar exposition). This allows the Architecture/Engineering teams to build a model of the implantation area (Process 1 as depicted in Fig. 1), while defining potential support conditions and initial structural requirements. At this point, a numerical formfinding process can be carried out, aiming to attain an initial shell geometry or shape. Numerical formfinding allows for the simulation of the physical formfinding process within virtual environments, comprising a fast and inexpensive method when compared to the latter. Moreover, the

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