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REVIEW

Knowledge Gap Analysis for Efficient Form-finding of Lightweight Structures

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Abstract

Historically, performance assessment of temporary structures' form was substantially dependent on how loads transfer along the geometry. Fortunately, the development of tools has enabled designers to explore more design variations as well as to test their feasibility. This study aims to address the knowledge gap between the design process, tool contributions, and feasibility requirements of temporary structures. This will be achieved through analyzing the evolution of temporary structures' design approaches including early form-finding approaches, geometrical properties dependencies, reflections of both bottom-top and top-bottom approaches as well as linking them to material innovations, structural contributions, and manual experiments.

As a result, the study ends with a conclusion of efficiency controllers of temporary structures which include geometry, material, and optimization processes in addition to feasibility-related requirements.

The study identifies potential future research regarding the possibility of scaling up the development strategies to be applicable to buildings, as temporary structures have simple architectural requirements, and it pushes the boundaries of constructable geometries.

Keywords: Computational design, Fabrication, Material properties, Performance-based design

1. Introduction

Numerically, several techniques for form-finding have been used to obtain ‘optimal’ geometry in static equilibrium under applied loads such as gravity loads, which represent the self-weight of temporary structure and have dominance over other loads Gabriele et al. (2018). Furthermore, the structural behavior can be substantially influenced by many factors such as plan geometry, material behavior (anisotropic or isotropic), fiber orientation, and prestressing forces; these factors control the force system and the way it flows along the structure. Pinto, Fonseca (Pinto and Fonseca, 2020) Dealing with multiobjectives to get the required optimal design is where the complexity of architecture exists (Ekici et al., 2019).

Geometry is substantially a representation of force; moreover, it is also related to its segmentation and the shape of panels (Fig. 1), so it is directly related to its constructability method (Adriaenssens et al., 2016).

1.1. Geometrical classification of shell structures

Lightweight structural forms have witnessed vast geometrical evolution over time, transitioning from mathematical, form-found shapes to free-form structures (Fig. 2). First, mathematical shells are commonly used as they guarantee easy analytical operations in addition to providing a precise description of the geometry for fabrication such as ellipsoids, catenaries, hyperboloids, and elliptic paraboloids. Second, form-found shells in which the shell is found through experimental methods to obtain the shape that the material tends to follow to reach an equilibrium state. Lastly, free-form shells are digitally sculpted using higher degree polynomials with no regard to structural performance

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Fig. 1. Topologies of lightweight constructions (Left) continuous shell (Right) discretized shell (Nejur, 2023).

and they can be represented computationally with NURBS geometry (Fouad et al., 2023).

1.2. Design approaches

The top-down approach represents a general vision to be followed across the design process from the overall shell shape design to the detailing of different parts. However, this approach fails for designs that require specific details. Contrarily, bottom-up approach allows exploring several forms using individual parts while considering that it may cause complex results after assembly so knowledge about the fabrication method is needed in the early stage of the design process. A combination of the two approaches will provide a good description of the design model (Fig. 3) Tellier et al. (2019).

1.3. Rationalization

Rationalization is the replacement of a designed surface into one that follows manufacturing constraints with simple fabrication requirements. Pottmann et al. (2015)I It can be classified according to the timing of its contribution into the design process. First, pre-rationalization means assessing the design according to certain fabrication constraints in the early design stage which is known as 'fabrication aware design' and then using computational tools to evaluate the design options. Second, co-rationalization is the strategy in which design parameters are controlled during design stages to adjust the surface according to fabrication aspects. Finally, in post-rationalization, information about the structure, materials, fabrication setup, and construction sequence gets involved to create a new informative digital model. The complexity of this process is to preserve the design intent (Fig. 4) Austern et al. (2018).

In early research about paneling, researchers had focused on planar quad panels and how they can cover free-form surfaces. This required the use of discrete differential geometry methods. These methods imposed new ways of beam layout and

a b c

Fig. 2. (a) Free form shell (b) Mathematical shell (c) from-found shells.

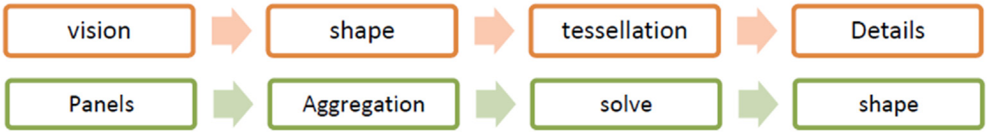

Fig. 3. Design approaches (Top) top-down steps flowchart (bottom) bottom-up steps flowchart.

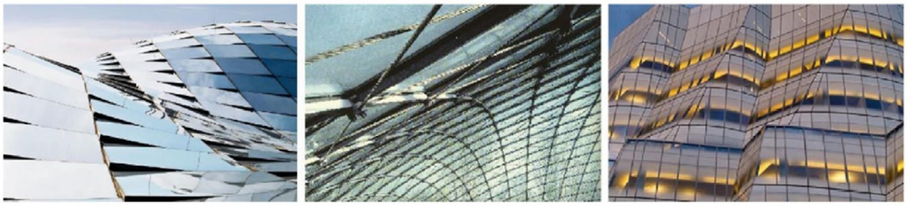

Fig. 4. Tolerance, hinges, and deformation criteria, respectively from left to right represent constructive criteria of built structures with repetitive elements (Schling and Barthel, 2020).

multilayer structure computation. Recently, researchers expanded an early approach to cover free-form surfaces using panels arranged along strips of surface known as developable surfaces. Other researchers attempted creating reusable prefabricated elements, so they tested the optimization approach using repeated elements (Lee et al., 2023).

2. Method

The method followed in this article (Fig. 5) is to analyze previous research projects and to define digital and cognitive correlation in several projects which set essential knowledge of recent constraints and possibilities for lightweight structure design, ending with approximation regarding the form generation and exploration, feasibility, materiality, and the required machinery to fabricate geometry.

2.1. Analysis method

The selected literature focuses on the form generation of temporary structures. Some works aim to innovate material usage, whether in formworks or in shell construction itself. Others depend on rationalizing building blocks through a bottom-top approach to facilitate constructing complex forms and the rest depend on structural performance analysis of the overall geometry And to facilitate turning digital vision into real constructions using different techniques and machinery that respect feasibility features. After stating the limitation in each case and analyzing feature correlations, we end up with a matrix to conclude the approximate general obstacles and limitations that affect the performance of a temporary structure design.

3. Literature review

3.1. Form finding paradigm

Over time, there was debate about the role of architects and engineers. The first thoughts were that engineers guarantee the stability of construction, and architects add aesthetic qualities to it. This argument conflicted with the thoughts of talented structural engineers in the 1950s and 1960s, who tended to include appearance along with efficiency and economy Adriaenssens et al. (2014). Between 1940 and 1960, architects and engineers extended the boundaries far beyond mathematical calculations and explored new spatial shapes based on testing theorized architectural solutions through experiments. This philosophy is known as the expressivity paradigm (Fig. 6) (Pone et al., 2013).

In Candela's view, shape should not be limited to stand for aesthetic elements nor should pure Math was the perfect way to design construction. Contrarily, he considered that the numerical analysis' target was to minimize and assort elements to aggregate them appropriately later. This view aligned with the form-finding approaches of Frei Otto and Heinz Isler. Their projects were based on validating the form through physical models in equilibrium. The former tended to analyze natural phenomena using a scientific approach and use it to have a correct description of design. The latter's experiments were concerned with traditional craftsmanship that is tied to physical laws or daily life observations for a better understanding of structures. Otto's most famous experiment is minimal surface applied using soap bubbles to represent tensioned surfaces, which tend to construct equilibrium geometry in which the tensile forces in two

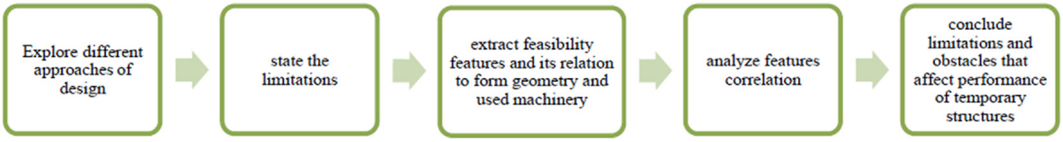

Fig. 5. General structure of the proposed method.

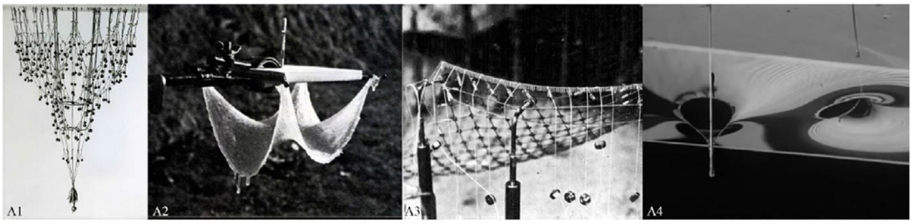

Fig. 6. (A1) Church of la Colonia Güell funicular model, (A2) Isler's hanging model, (A3) and (A4) hanging and soap film model respectively, made by Frei Otto (Baro et al., 2022).

directions are balanced between certain borders. Candela and Frei Otto had different approaches; however, they intrinsically agreed to shift from designing confined shapes to form-finding approach searching for optimal form design. (Boller and Schwartz, 2020; Pone et al., 2013b).

Liddell (2015) Liddell explained that Otto's work often began with models of soap film and then turned it into robust stretch fabric models, which he used afterward to construct fabric patterns. Liddell *et al*. made a recapitulation of the construction of Mannheim grid-shell construction designed by Frei Otto (Fig. 7). Shell form was obtained using a hanging chain model. Using stereo photography, the grid-shell model was measured, and these photos were used to obtain the coordinates of nodes. These data were used by engineers to figure out the height of nodes using the force density method.

3.2. Literature focus on geometrical properties

Glymph *et al*. commenced using the term ‘rationalization’ in architecture involving mathematical considerations for design feasibility, while analyzing Gehry's complex design in the constructability aspect. Lee et al. (2023) Fischer explored rationalization in architectural view during the 2000s. Fischer (2012). Pottmman *et al*. wrote a detailed article that links architecture and rationalization from a mathematical aspect and argued about ‘architectural geometry’ as a research field that is concerned with differential geometry, discrete mathematics, numeric optimization, and computer graphics processing (Fig. 8). They classified algorithms by geometry type of skin construction to flat, developable, smooth double-curved paneling, and they tended to achieve repetitive elements, form patterns with torsion-free support, and get static-aware design (Pottmann et al., 2015).

Fig. 7. (Left): Mannheim gridshell, (right) Hanging chain model for Mannheim, source: (Liddell, 2015).

3.3. Bottom-top approach

Zimmer et al. (2012) tested rationalization by exploring the production of identical shapes and then modifying it (Fig. 9). They tried to exploit the form by cutting identical shapes with different angles and sizes by discretizing trihedron, which is cut with different angles while preserving centricity and preventing collisions of folding as construction constraints (Fig. 10).

Brancart et al. (2015) explored producing lightweight components with high geometrical stiffness using material sheets only. Deforming flat material by folding it across a curved crease pattern to turn

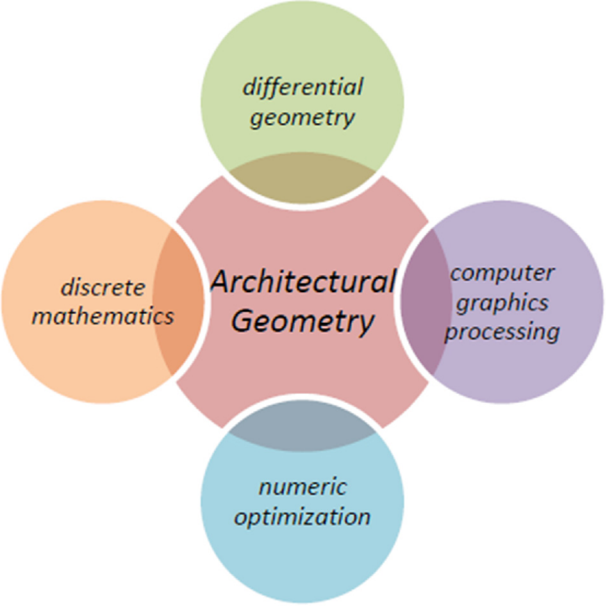

Fig. 8. Diagram show fields with collectively form Architectural geometry field, Reference: (Pottmann et al., 2015) processed by: Author.

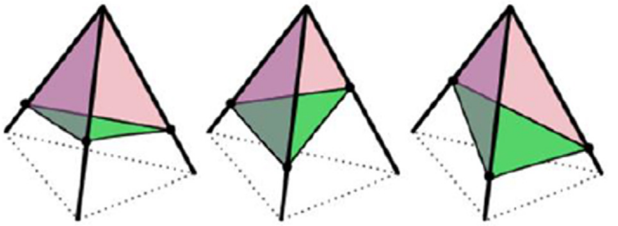

Fig. 9. Trihedron cut with different angles source: (Zimmer et al., 2012).

flat material into a three-dimensional shape. While fold lines are the deformation of the sheet and the rulings, Brancart *et al*. tested the parallel folding to get cylindrical curvature and symmetrical fold lines about the central axis with no torsion (Figs. 11 and 12).

3.4. Top-down approach

Pottmann (2013) showed the dependency on developable surfaces for free-form surface design approaches and stated the difficulty of approximating free-form surfaces using quad meshes as the process of optimizing that mesh to reach planarity is complex and mostly ends with failure or mesh distortion. Pottmann considered mesh quad representation to be closely related to conjugate direction field design as a discretized version.

Tang et al. (2014) tested new strategies for fabrication-aware design which depend on surface curvature and beam network while considering material's elastic behavior to form the grid (Fig. 13). Tang *et al*. chose grid shells for their structural efficiency. Depending on the elastic deformation of planar lamella grillage, the network of developable strips was modeled and connected orthogonally to the surface, which represents the ideal beams' center planes and finally the fabrication process was done without scaffolding.

3.5. Material-driven approaches

Schinegger et al. (2020) analyzed the interconnection of material effect and global predefined geometry considering material as a form generator of the surface. They used a robotic set to explore shotcrete technology and ended with a number of limitations for the research trial, which can be concluded as the limitations of robotic set rotation, material properties study like studying the flow rate of material while considering structure hardening as

Fig. 10. (13, 9, 32) molds, respectively, from left to right the insets show the corresponding validity volumes. Canonical representatives of the used element classes (randomly color-coded) are depicted alongside (Zimmer et al., 2012).

Fig. 11. The assembly process of Undulatus pavilion hanging at the IASS2015 expo (Brancart et al., 2015).

Fig. 12. *Grid Modelling, assigning components with curved line folding and extraction of component's fabrication data in flat state are the steps applied in digital tools* (Brancart et al., 2015).

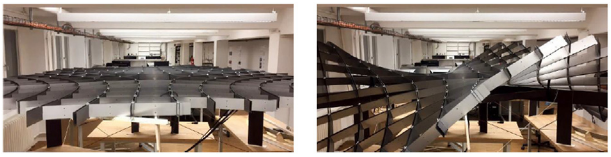

Fig. 13. *Beam network from elastic deformation of a grid which respects asymptotic directions of the surface* (Tang et al., 2014).

the roving passes through resin first, and then fed to the effector (Fig. 14).

Bodea et al. (2021) considered the excessive cost and the small numbers of experts' involvement are the main reasons for the slow adoption of composites in construction and declared the need for new automated solutions to address upscaling, customization, and cost reduction. Composites can operate as a tailoring material for surfaces depending on performance requirements to achieve stiffness of the form. Prefabrication strategies for complex geometries are presented by Bodea et al. (2021); for formwork elimination, they focused on robotic coreless filament winding. The research proposed upscaling strategies using updated robotic programming (Figs. 15 and 16).

Hyperbolic paraboloids are doubly ruled surfaces that denote the geometry that can be formed by lines following certain cross sections. Historically, Candela took advantage of this property to rationalize and exploit double-curved concrete structures as it made construction easier. This construction process has limited geometrical varieties and requires vast scaffolding. Popescu et al. (2021) explored the capabilities of KnitCrete formwork and computational design methods through many design iterations targeting to enhance the design aesthetically and structurally. The experimental design did not follow a hyperbolic paraboloid shape or minimal surface, but it had nonuniform force density distribution over the

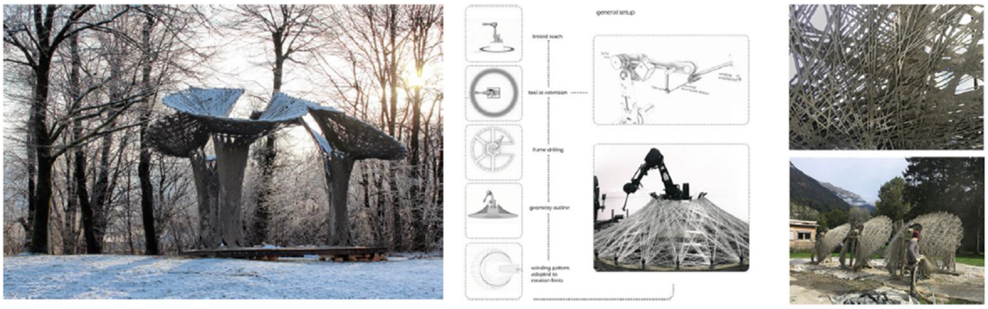

Fig. 14. *Prototype at the campus of the University of Innsbruck, Robotic fabrication, shotcrete application process respectively* (Tang et al., 2014).

Fig. 15. *Fibrous morphology research pavilions by ICD/ITKE* (Bodea et al., 2021).

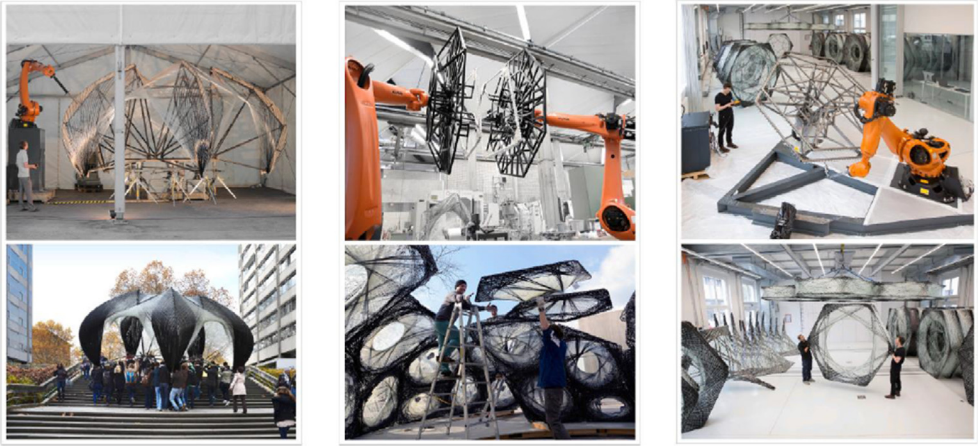

Fig. 16. Research Pavilion of Coreless Filament Winding in construction by ICD- (Top) setup, (Bottom) Installation (Bodea et al., 2021).

surface. They used knitted formwork and sprayed concrete for thin form-active structures. Formwork depends on two elements: Cable-net falsework which is represented by the knitted textile and cable inserted into its channel in the textile (Figs. 17 and 18). The final shell can be described as a waffle shell, with 3 cm-thickness and 4 cm-deep stiffeners in principal directions (Fig. 19).

3.6. Literature focus on structural aspects

Another research approach by the Block Research Group (BRG) (Rippmann et al., 2016) used computational tools to explore forms and study their structural performance and find construction methods that suit associated forms. Their research intent was to graphically represent the design of a complex shell in an equilibrium state. BRG and ZHCODE made computational tools and methods that are force-driven. Therefore, the awareness of structural requirements and performance related to geometry can help in solving manufacturing constraints (Bhooshan, 2017). (Figs. 20 and 21)

3.7. Manual fabrication experiment (craft)

Shinohara and Chan (2024) was inspired by the traditional weaving style 'Kagome', which is a traditional basketry weaving craft usually made of bamboo using a tri-hexagonal pattern; the weaving pattern results in a self-bracing object with no need for fasteners thanks to the entwined lattices.

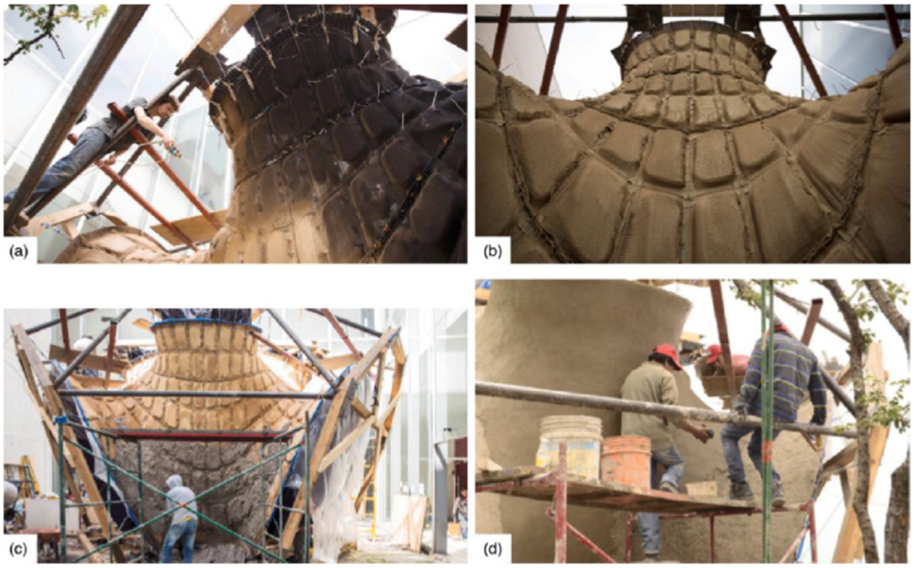

Fig. 17. Concreting steps: (a) spraying consolidation material on the textile; (b) coated structure after consolidation; (c) concrete layer; (d), finishing (Popescu et al., 2021).

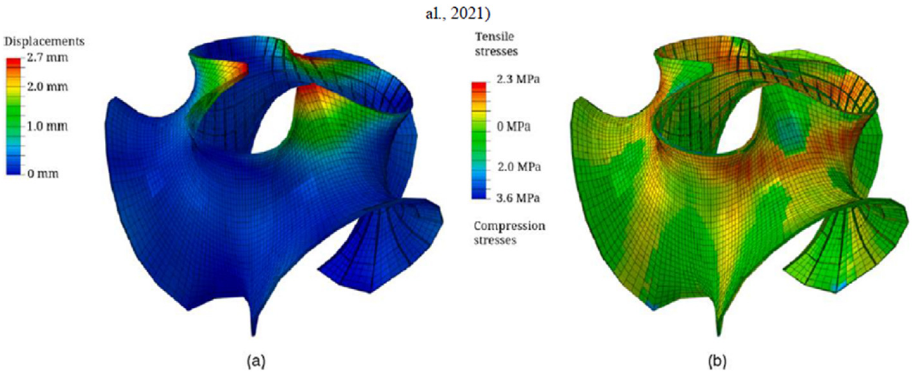

Fig. 18. Deflections and Tensile stresses: (a) deflections below 3 mm (b) tensile stresses below material stress limit of 4 MPa (Popescu et al., 2021).

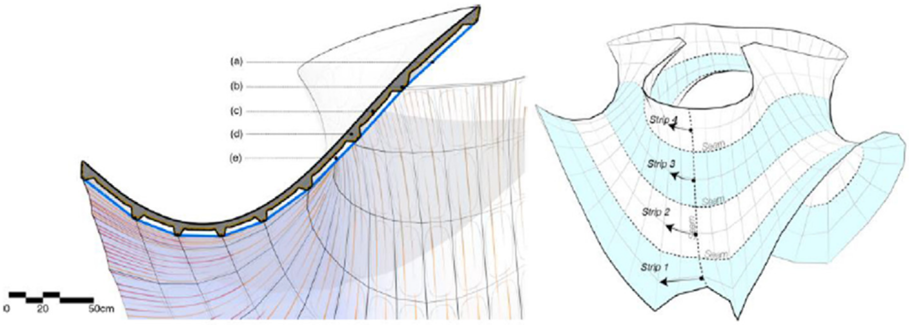

Fig. 19. (Left) Detail section showing: (a) knitted textile; (b) cable net; (c) cement-paste coating; (d) waffle shell; and (e) voids (right) shell's surface strip division for fabrication (Popescu et al., 2021).

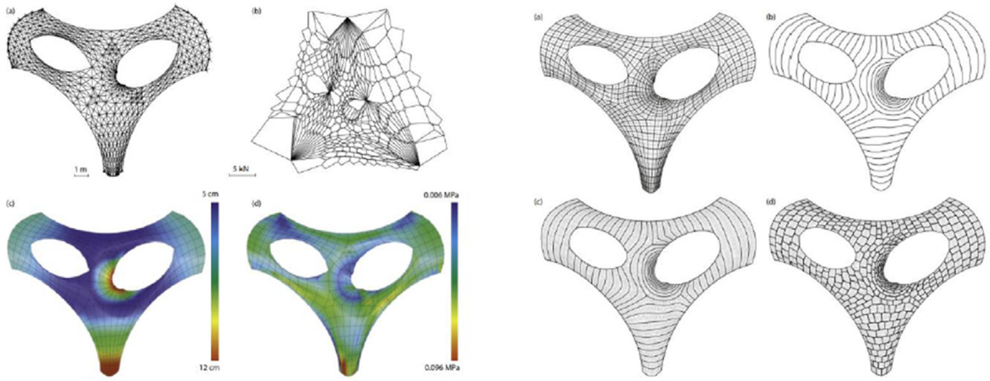

Fig. 20. (Left) Force-flow analysis (right) funicular shell tessellation Images from (Adriaenssens et al., 2014; Bhooshan, 2017).

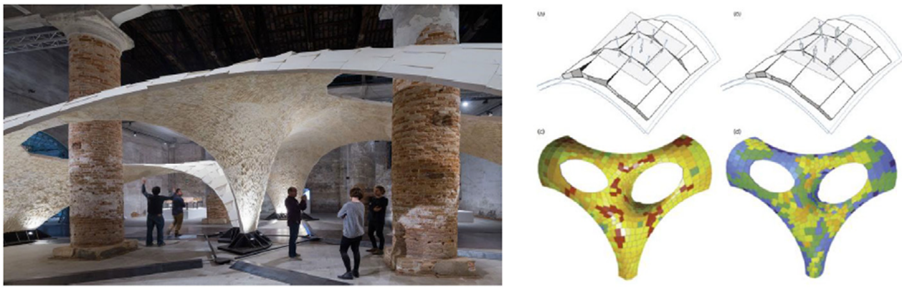

Fig. 21. (Left) The Armadillo Vault, Venice, Italia, 2016 (Right) tradeoff between planarity/tolerance and surface fairness (Photo: Iwan Baan) (Rippmann et al., 2016).

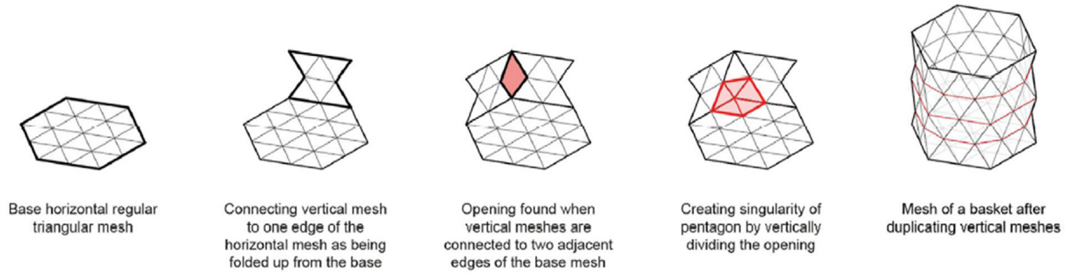

Fig. 22. Digital model creation of Kagome basket weaving pattern. Shinohara, Chan (Shinohara and Chan, 2024).

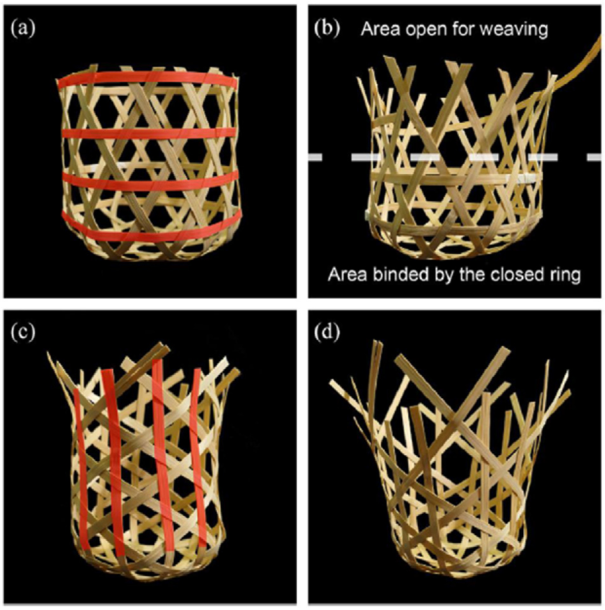

Fig. 23. (a) Ring strips; (b) closed continuous strips; (c) strips parallel to tube orientation; d) loosened strips (Shinohara and Chan, 2024).

Researchers used computational tools to explore and represent different design configurations using triangulated tessellation of the surface (Fig. 22). They tried to scale the craft theory up into an artifact and then evaluated the reflections on the performance of the method through a full-scale mockup (Fig. 23).

4. Results and discussion

According to the reviewed literature, both weight and performance can be optimal in several ways developed over time. Clearly, every period has its qualities such as the expressivity movement in the 60 s and its reflections on developing innovative forms by engineers as Frei Otto (Liddell, 2015), who used the concept of minimal surface design through physical form modeling. However, fabricating these forms required further analysis and study of the geometry of forms by mathematicians indicated in (Pottmann et al., 2015; Pottmann, 2013). Moreover, the innovations in computer and computational tools facilitate modeling forms and interdisciplinary

Table 1. Main innovation aspect of literature.

Classifications	Literature	Year	Main innovation aspect				Commentary
			Material	Shape/ Geometry	Machinery	Structural performance	
Form finding paradigm	Frei Otto (Liddell, 2015)	2015		*			New forms exploration during expressivity movement
Literature focus on geometrical properties	Pottmann (Pottmann et al., 2015; Pottmann, 2013)	2015, 2013		*			Mathematicians' involvement in detailing process
Bottom-top approach.	Zimmer *et al.*, (Zimmer et al., 2012)	2012		*	*		Innovations in computational
	Brancart *et al.*, (Brancart et al., 2015)	2015		*	*	*	
Top-down approach.	Tang *et al.*, (Tang et al., 2014)	2014	*	*		*	Fabrication-aware approach
Material-driven approaches	Schinegger *et al.*, (Schinegger et al., 2020)	2020	*		*	*	Resource depletion problem.

(*continued on next page*)

Table 1. (continued)

Classifications	Literature	Year	Main innovation aspect				Commentary
			Material	Shape/ Geometry	Machinery	Structural performance	
	Bodea *et al.*, (Bodea et al., 2021)	2021	*		*	*	
	Popescu *et al.*, (Popescu et al., 2021)	2021	*		*	*	
Literature focus on structural aspects	Rippmann *et al.*, (Rippmann et al., 2016)	2016	*	*	*	*	Computational software development
Manual Fabrication experiment (Craft)	H.Shinohara *et al.* Shinohara, Chan (Shinohara and Chan, 2024)	2024	*	*		*	

approaches. Recently, researchers concentrated on testing new materials and assemblies for environmental purposes. Summary of the reviewed literature is indicated in Table 1.

5. Conclusion

For lightweight structures, designers' way of thinking had shifted from form-making of specific, predefined forms to finding form under certain circumstances and boundary conditions. Consequently, new media for testing novel theories was required. For example, both Candela and Otto relied on experiments and physical models. Alternatively, novel computational tools enabled designers to explore several design options and to simulate various boundary conditions.

New fabrication techniques such as sectioning, folding, tessellation, forming, and contouring are being used with digital tools for three-dimensional printing, CNC, and robotic fabrication for assembly and composition in the computer-aided design-computer-aided manufacturing chain. However, the applicability of new techniques depends on the local construction, engineers, and builders. Therefore, designers, material scientists, and structural engineers need to contribute to the design process to achieve optimal designs.

Despite having distinct problem-solving strategies, each studied literature mainly faced the same issues indicated as follows:

Form geometry

The fabrication of the double-curved geometry has always been a source of engineering challenges during the past decades. Therefore, new fields of research emerged such as fabrication-aware design, construction-aware design, shape rationalization, and architectural geometry.

Material use

According to Achim Menges in Ref (Menges et al., 2018), the material system does not only represent the material used for construction, but it refers to the complexity and interrelation between materiality, structure, space, form, production, and assembly process as well as the effect of interaction between form and forces on performance. Therefore, the material's rule can represent a substantial innovative design aspect. For example, some recent approaches used a composite material and knitted formwork intents, whereas others tested different material configurations of local material following contemporary concepts.

Optimization

Material use, structural efficiency as well as fabrication cost and time are interconnected; therefore, adjustment in each aspect has further reflections on others such as waste reduction of the panel fabrication process and assembly complexity minimization.

In conclusion, both novel manufacturing tools and form-finding methods extended design possibilities toward lightweight materials use, structurally informed designs as well as connection and assembly innovative strategies. A summary of the design problems explained in the literature to turn an initial design into feasible projects is provided in Table 2. Further research is needed to test the applicability of implementing novel notions on a large-scale building.

Table 2. Design problems of temporary structures.

Problem/requirement	Objective	Method/parameters	Potentials	Limitation
Fabrication efficiency (Cost/time)	Minimum number of panel sets	Molds reuse	Using tolerances and structural flexibility allows getting the original shape. Panel waste reduction	In large-scale constructions, it is hard to get small sets of panels. Extracting identical or approximated elements has certain limitations.
		Optimize (rationalize) panels	Optimizes positioning process and guarantees tangential continuity at panel boundaries	Not effective for handling architectural designs with large nonrepetitive sections
	Material-induced geometric constraints	Material selection and innovation	Low material consumption and high stiffness	Material lifetime
	Time-efficient production	Discretization is based on the method of fabrication as being planar/developable.	Use tolerance range in surfaces to modify surface paneling trying to find the best exchange between skin smoothness and cost.	Surface fairness and design intent preservation using discretized elements
Required machinery features	Sectioning	Edge profiles	Have immense potential to fabricate structures with a wide range of topological configuration and geometric complexity	The limited number of feedstock materials, weak mechanical properties, poor surface quality
	Folding	Increasing stiffness and rigidity by folding a flat material.		
	Tessellation	Placing sets of pieces with no gaps to form a surface.		
	Contouring	CNC machinery tools		
	Forming	Molds' generation		
Design execution	Tolerances	Provide clearance between parts	Allow for repetitive façade panels	Tolerance range
	Hinges	Allow a variation of a specific angle parameter to lower node complexity	Enable a specific structural behavior without restraints and avoid undesired bending moments in beams	Rationalize hinges
	Deformation	Elastic bending of a beam or panel	Panel reuse	Deflections caused by overloading element
	Loads and Structural constraints	Funicular shape	Self-supporting structure, low material consumption, integrate different aspects in the design process	Calculating the stresses produced by secondary effects (temperature contraction for setting of the concrete − differential subsidence of the ground) is a complex task
	Load on or masses of the nodes	The length and strength of the structural support		
	Force distribution	The topology of the network and related discretization of load		
Aesthetic	Topology	Architecture design	Integrate different aspects in the design process	Multidisciplinary design complexity
	User experience requirements			
	Spatial configuration			
	Free-form surface fairness			

Author contribution

Study conception or design of the work: Shorouk M. Khedr. **Data collection and tools:** Shorouk M. Khedr, Mohamed E. ElAttar. **Data analysis and interpretation:** Shorouk M. Khedr, Ahmed ElTantawy. **Methodology:** Ahmed ElTantawy. **Supervision:** Mohamed E. ElAttar, Esraa Elazab. **Drafting the article:** Shorouk M. Khedr. **Critical revision of the article:** Ahmed ElTantawy, Esraa Elazab. **Final approval of the version to be published:** Shorouk M. Khedr, Mohamed E. ElAttar, Ahmed ElTantawy, Esraa Elazab.

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Conflict of interest

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