Design-to-Fabrication Workflow for Bending-Active Gridshells as Stay-in-Place Falsework and Reinforcement for Ribbed Concrete Shell Structures

Lotte Scheder-Bieschin (Aldinger)[1(✉)], Kerstin Spiekermann[1], Mariana Popescu[2], Serban Bodea[1], Tom Van Mele[1], and Philippe Block[1]

[1] Institute of Technology in Architecture, Block Research Group, ETH Zurich, Stefano-Franscini-Platz 1, 8093 Zurich, Switzerland
aldinger@arch.ethz.ch

[2] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 Delft, The Netherlands

Abstract. Facing the challenges of our environmental crisis, the AEC sector must significantly lower its carbon footprint and use of first-use resources. A specific target is the reduction of the amount of concrete used. Funicular structures that base their strength on their structurally-informed geometry allow for material efficiency. However, a bottleneck for their construction lies in their costly and wasteful formworks and complex reinforcement placement.

This research presents an alternative flexible formwork system consisting of a bending-active gridshell falsework and fabric shuttering for ribbed funicular concrete shells. The falsework becomes structurally integrated as reinforcement and is designed as two connected layers offering shape control and sufficient stiffness to support the wet-concrete load.

The paper focuses on the development of a design-to-fabrication workflow and a graph-based data structure for gridshell falsework and reinforcement in the computational framework COMPAS. The implementation utilises, customises and creates packages for the form finding of the ribbed shell with TNA and the gridshell with FEA.

The research is based on a demonstrator realised in the context of the Technoscape exhibition at the Maxxi Museum in Rome, Italy. The computational workflow was used to design this system and translate it for materialisation. The demonstrator serves as proof-of-concept for the novel material-efficient construction system. Its key to efficiency lies in the structurally-informed geometry for both the formwork and the resulting ribbed concrete shell.

Keywords: Bending-active gridshell · Flexible formworks · Integrated formwork · Reinforcement · Ribbed concrete shell · COMPAS framework · FEA · Double-layered gridshell

C. Gengnagel et al. (Eds.): DMS 2022, *Towards Radical Regeneration*, pp. 501–515, 2023.
https://doi.org/10.1007/978-3-031-13249-0_40

1 Introduction

The critical impact of the construction sector on our environment demands a fundamental rethinking of design and construction practices towards more sustainable solutions. This is of particular relevance for reinforced concrete; as the most widely used construction material, a major contributor to global CO2 emissions and resource depletion (Lehne and Preston 2018). Conventional construction practices often rely on its excessive use to provide structural strength. In contrast, strength can be achieved through structurally-informed geometry like thin doubly-curved concrete shells with local stiffening articulations (Block et al. 2020). However, their complex shapes require bespoke formwork systems typically produced with CNC-milled foam or timber, which can be costly, wasteful, and limited to high-tech construction contexts (García de Soto et al. 2017). Additionally, the manufacturing and installation of custom reinforcement is cost- and labour-intensive (Waimer et al. 2019).

This paper presents an alternative flexible formwork solution employing geometric stiffness similar to tensile flexible formwork systems (Popescu et al. 2021). It utilises active bending, a deliberate-deformation method to elastically bend slender straight elements into curved geometries without formwork. It allows the construction of lightweight, material-efficient, self-contained and self-supporting structures that can be flat-packed for transport and easily deployed (Lienhard 2014). The presented construction system is a formwork system consisting of a bending-active gridshell falsework and fabric shuttering for ribbed funicular concrete shells. The strained gridshell is designed as a double-layered structure to ensure sufficient stiffness and shape control. This falsework becomes structurally integrated inside the ribbed concrete shell as reinforcement. Therefore, complex shell reinforcement does not have to be bent in and placed in an extra tedious construction step.

The focus of this paper is a design-to-fabrication workflow and data structure for gridshell falsework in the computational COMPAS framework (Van Mele et al. 2017–2022). This is required for the complex topology and geometry of the double-layered structure and for an integrative design approach. It enables the reconciliation of the form-finding geometry for the bending-active falsework and funicular shell, the simultaneous consideration of fabrication design for both, and the separate structural design with common focus on stiffness and shape control (Fig. 1).

The research is based on a demonstrator being built in the context of the Technoscape exhibition at the Maxxi Museum in Rome, Italy. Section 3 describes the system design; Sect. 4 presents the modelling workflow for such systems based on the case study, and, Sect. 5 touches on the materialisation and suitability assessment.

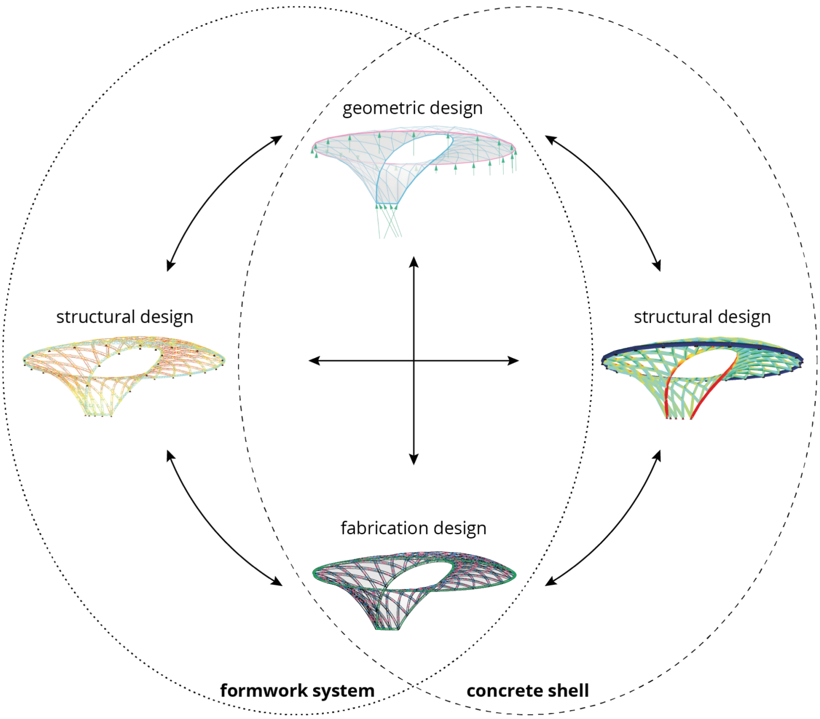

Fig. 1. Integrative design approach.

2 Background

2.1 Funnel-Shaped, Ribbed, Funicular Concrete Shells

Strength through geometry can be achieved with funicular compression-only structures through form finding with Thrust Network Analysis (TNA) (Block 2009). Van Mele et al. (2012) extended TNA to account for tensile members by lifting the necessary condition for compression-only TNA of convex, non-overlapping edges in the force diagram and allowing edges to flip orientation to close the force diagram. This enabled Rippmann and Block (2013) to explore a variety of efficient and expressive funnel shapes designed as funicular ribbed shells with tension rings.

2.2 Flexible Formwork Systems and Structurally-Integrated Falsework

Tensile flexible formworks are self-supporting, lightweight, waste-saving and compactly-packageable alternatives to conventional formworks for complex geometries (Hawkins et al. 2016). Mendez Echenagucia et al. (2019) and Popescu et al. (2021) utilised textile shuttering on cable-net falsework for expressive shells. However, these tensioned systems are limited to anticlastic curvature, and the tensile reaction forces necessitate large boundary structures.

Bending-active flexible formworks are self-contained, not needing extensive boundary support, and allow both syn- and anticlastic curvatures. Cuvilliers et al. (2017) demonstrated the use of a strained gridshell as falsework with a passive textile shuttering layer. Popescu et al. (2018) introduced stiffening articulation in both bending-active formwork and resulting shell. Both examples give the outlook to structurally integrate the gridshell falsework in hybrid composite action with the resulting concrete shell, whereas Hack et al. (2020) developed a construction system of passively bent rebar that serves as formwork and reinforcement for non-standard geometries. Already the pioneer Nervi (1956) had combined formwork and reinforcement in his Ferro-cement invention to overcome their bottleneck for complex geometries.

2.3 Bending-Active Structures

Bending-active structures suffer the dilemma of requiring low stiffness for the elastic forming process and sufficient stiffness to withstand external loads. Thus, gridshells such as the Multihalle Mannheim are often designed as double-layered systems with shear connectors (Adriaenssens et al. 2014) – then the splines' minimum bending radius is small due to small spline sections with nevertheless, larger structural height.

The form finding of strained gridshells is commonly performed with dynamic relaxation for fast simulation or with finite element analysis (FEA) for accurate numerical modelling and analysis. Bellmann (2017) implemented a built-in function into the commercial FEA-software SOFISTIK (2020) that computes internal bending stresses based on curved input splines' initially straight, unstressed states.

2.4 Computational Frameworks

The modelling of gridshells with complex topology and geometry is challenging with visual programming software that typically stores the data in tree structures without their connectivity. Instead, the Python-based, open-source framework COMPAS for research in computational architecture, engineering and construction (Van Mele et al. 2017–2022) provides a versatile graph-based data structure that can be customised and interface with various COMPAS packages, as in Mendez Echenagucia et al. (2019).

3 System Design

The presented construction system undergoes three main construction stages: the assembly of the bending-active gridshell falsework, the mounting of the fabric formwork and the in-situ concreting of the ribs of the ribbed funicular concrete shell structure (Fig. 2). The falsework stays in place after casting and is structurally integrated into the concrete as reinforcement. The textile of the faces in between the ribs that stabilises the shuttering during casting can either be removed or remains as an architectural feature. Alternatively, it could also be used as shuttering for casting a thin continuous shell layer. The demonstrator will not include the in-situ concreting step for logistical and sustainability reasons.

The geometry of the case study exhibits a funicular funnel shape with a droplet-shaped opening inspired by soap film explorations by Otto (1988). The ribbed concrete shell structure is a design descendent and homage of the funicular rib vaults by Rippmann and Block (2013), using a pattern reminiscent of Pier Luigi Nervi's Palazzetto dello Sport, which is in close vicinity. The rib pattern is key to the structure's aesthetics as it highlights the force flow and is informed by the funicular structural logic. The rib's cross-sections are equilateral triangles with sectional dimensions of 18 cm (Fig. 2 – right). The cross-section is consistently translated along the rib curves, following the normal orientation of the surface into torsional triangular prisms. The global structure's circular outer diameter and maximum height measure 9 m and 3.5 m, respectively. It is supported by conventional scaffolding props along its perimeter.

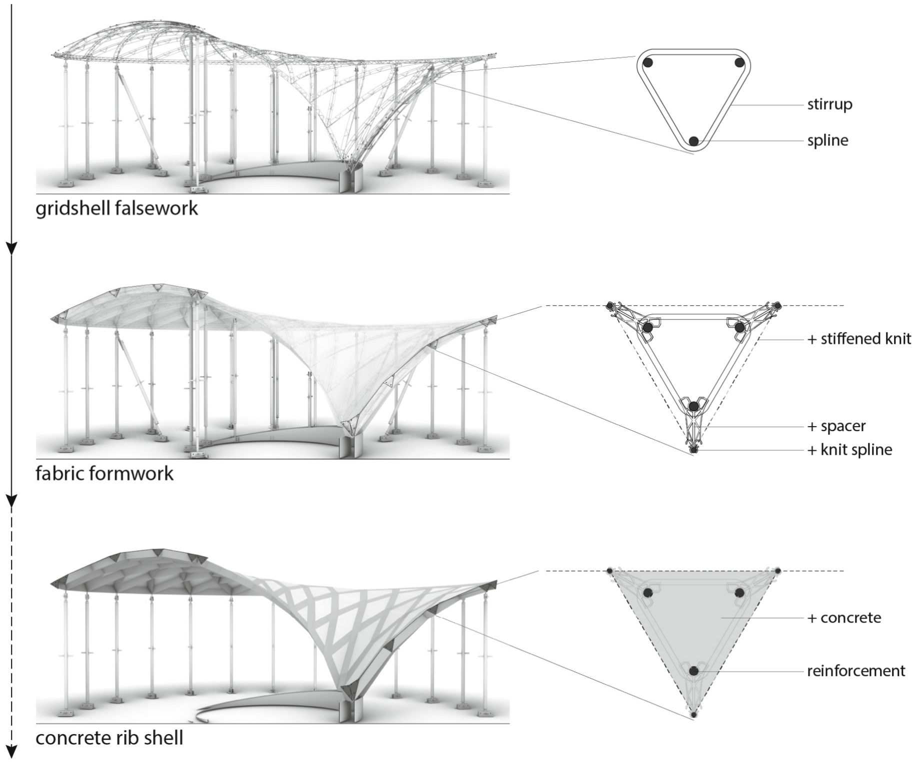

Fig. 2. The systems' three main construction stages.

3.1 Falsework Plus Reinforcement: Bending-Active Double-Layered Gridshell

The gridshell falsework (Fig. 2 – top) is the support structure for the wet-concrete load and defines the global shape. It is a double-layered system to ensure sufficient stiffness and shape control and subsequently serves as reinforcement. The falsework is materialised using conventional steel rebar, and constructed using typical techniques of the concrete industry. The mechanical properties of reinforcement steel are just within the range of suitable materials for bending-active structures that must offer a high ratio of flexural strength to stiffness (Lienhard 2014). However, compared to typical materials for strained gridshells like timber or fibre-reinforced polymers, steel offers workability with a high plasticity that permits the irreversible bending of stirrups.

A trio of continuous 10 mm rebar splines form a rib and cross another rib's splines with hinged conditions. To allow for the required minimum curvature of the global geometry the spline's highly slender sizing of 10 mm is at its maximum. Consequently, the structural height must be provided by the double-layered system. The three splines are connected with 6 mm rebar stirrups to space the splines and with a pair of inclined 6 mm stirrups as shear connectors to stiffen and lock the gridshell into its doubly-curved shape (Fig. 12). The crossing connections in between the splines are made using wire twist-ties. These crossing locations and the splines' overall lengths are extremely important as they dictate the global geometry.

3.2 Formwork Shuttering: Knitted Textile

The falsework supports and defines the shape of the fabric formwork shuttering into the prismatic profiles (Fig. 2 – middle). To ensure minimum concrete coverage, custom spacers are clipped onto the splines and hold thin rods at their extremities to shape the fabric. The fabric formwork is made of a CNC-knitted textile that provides custom features and pockets for the rods as in Popescu et al. (2021). Alternatively, the shuttering could be made of woven textiles with sewn pockets, which would demand more manual operations and no high technology. For both, the non-prestressed fabric must be stiffened with a resin or cement paste prior to concrete casting.

3.3 Concrete Shell Structure: Ribbed Funicular Shell

Each trio of splines with fabric wrapping is cast into a reinforced-concrete (RC) rib of the funicular ribbed shell structure (Fig. 2 – bottom). The geometry is designed as a compression-only vault with a continuous tension ring along the perimeter balancing the thrusts under self-weight (Fig. 7). However, for the non-funicular live loading cases, the concrete ribs and nodes must withstand bending moments, especially because the topology lacks bracing triangulation. The rebar splines and stirrups provide the required bending-stiff, non-discrete RC ribs. Thus, the dual role of the gridshell as falsework and reinforcement is critically important.

4 Computational Design Modelling Methods

The integrative design of all construction stages and design constraints for both the formwork system and the concrete shell demands an elaborate computational modelling workflow from geometric to structural to fabrication design (Fig. 3). The implementation therefore employs existing COMPAS packages, customises them, and develops new packages.

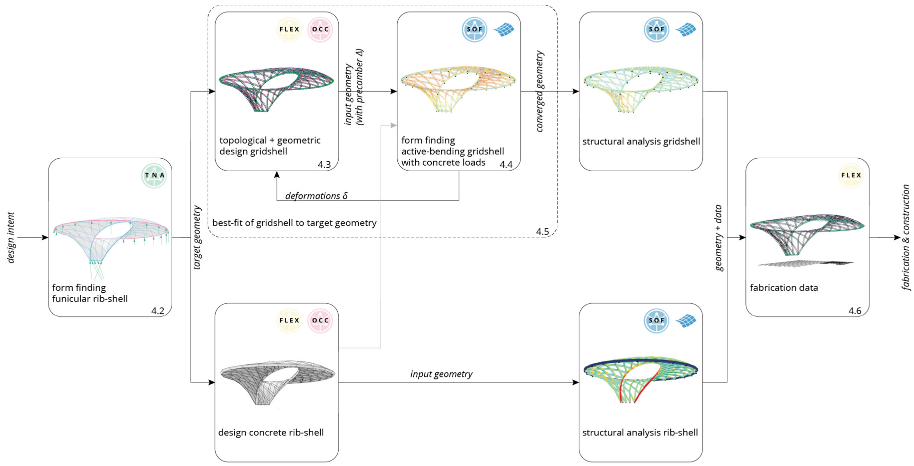

Fig. 3. Computational design-to-fabrication workflow.

4.1 Assembly Graph Data Structure

A custom package named compas_flex was developed for versatile data handling of such flexible formworks and reinforcement of complex geometry and topology with numerous different parts and connections. It inherits and customises the assembly graph data structure from the COMPAS library and stores a unique network, mesh or curve in each graph node and their respective connectivity in its edges. All parts and edges of the assembly have a unique identifier key and can be called by their attributes such as position, size, or type (Fig. 4). Separate networks guarantee spline continuity, and the graph edges store the hinge conditions in their attributes (Fig. 5). Furthermore, virtual connections between spline networks and the ribbed shell mesh store how different construction stages relate.

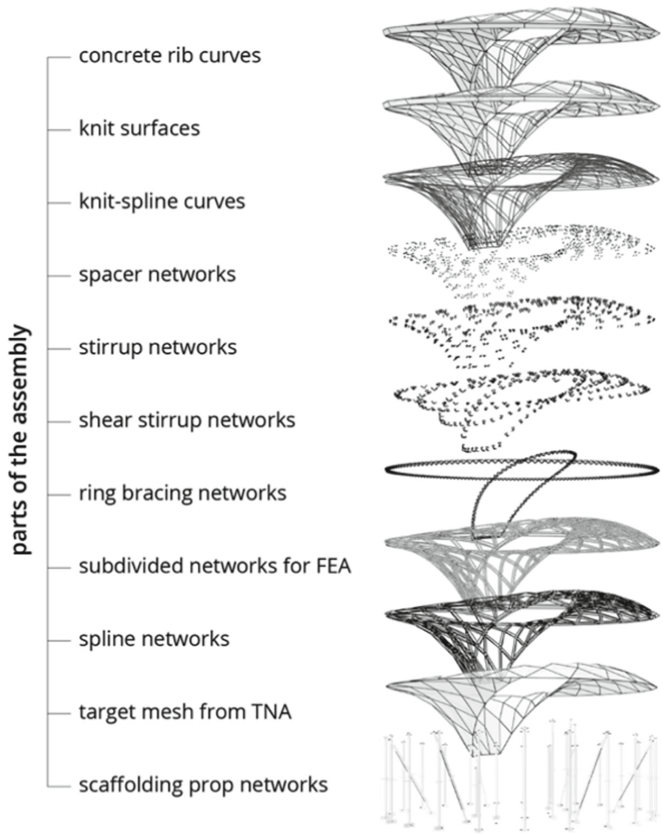

Fig. 4. Parts of the assembly graph by type.

4.2 Form Finding of Ribbed Concrete Shell

The workflow initiates with the form finding of the funicular shell using the compas_tna package. For the case study, the input pattern is generated from 48 radial splines that cross along five equally spaced hoops (Fig. 5 – left). In the form diagram, the tensile outer ring's edge attributes are set to tension (Fig. 5 – middle). Tension causes flipping edges to close the force diagram (Fig. 5 – right). Five vertices of the inner ring and all vertices of the outer ring are designated as supports after the horizontal equilibrium is found to ensure exclusively vertical reaction forces under the design loads. The resulting thrust network finds vertical equilibrium in the desired funnel with a droplet-shaped opening (Fig. 6 – left).

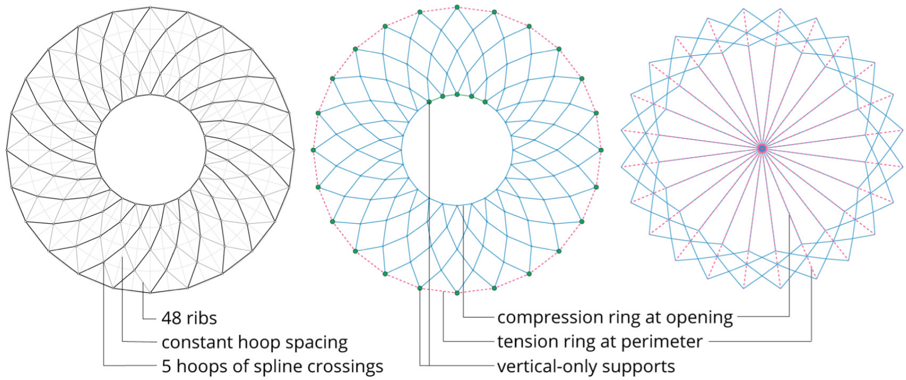

Fig. 5. Input pattern, form diagram, and force diagram.

Even though the equilibrium shape is independent of the shell's material density, the loading distribution is decisive for the funicular geometry, differing from a continuous shell to a ribbed shell by up to 8 cm (Fig. 6 – left). This is due to the varying ratio of ribbed shell openings to tributary vertex area, as the size of the faces and the skewness vary. Compas_tna is implemented for continuous shells, and thus its function to update loads in each iteration for finding vertical equilibrium is retrofit for ribbed shells. All mesh face-edge polygons are offset. Then, for each vertex, the tributary area of the offset edges is computed using the cross vector of the face centroid and adjacent half-edges, and thereafter subtracted from the sum of vertex area of the continuous shell (Fig. 6 – right).

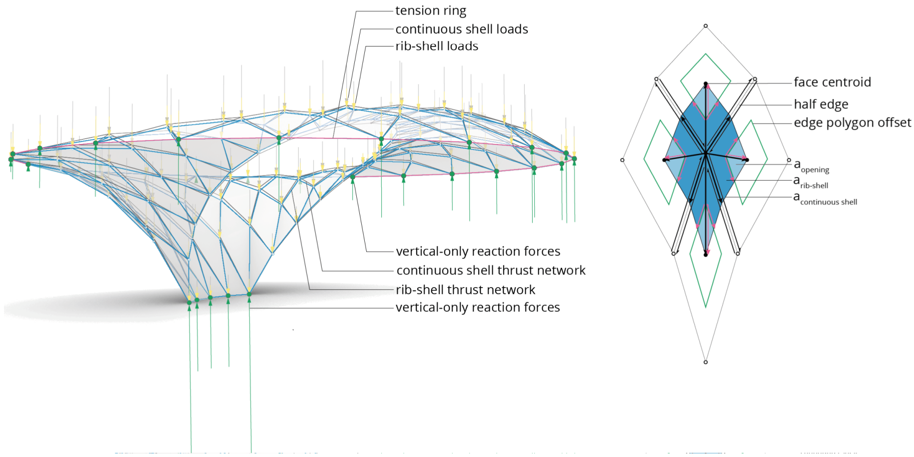

Fig. 6. Thrust networks of continuous versus ribbed shell (left) due to difference of tributary area distribution (right).

4.3 Modelling of Double-Layered Gridshell

The resulting funicular shell is the target geometry for the topological and geometric modelling of the double-layered, bending-active gridshell (Fig. 7). First, the assembly data structure stores the separate ribs as networks (generated from the mesh edges) with main attributes {direction, is_ring, at_base} and connectivity to each other and the mesh. Second, with the compas_occ package, a Python-based COMPAS binding for OpenCascade3D (2022), the NURBS curves defining the ribs are modelled to generate tangential frames that are normal to the target geometry to generate the spline trios. Third, the resulting networks are added as nodes to the assembly graph with their complex connectivity, especially on the upper layer where four splines cross per node. The spline geometry is corrected such that the splines intersect at their closest midpoint, and the networks are updated accordingly. Finally, the splines are subdivided into dense networks along reconstructed NURBS curves for the FEA input, preserving the initial coarse network nodes for connectivity. Stirrups (in blue) and inclined shear stirrup pairs (in pink) are modelled along frames and added to the assembly graph with their specifics in attributes and connectivity to the splines.

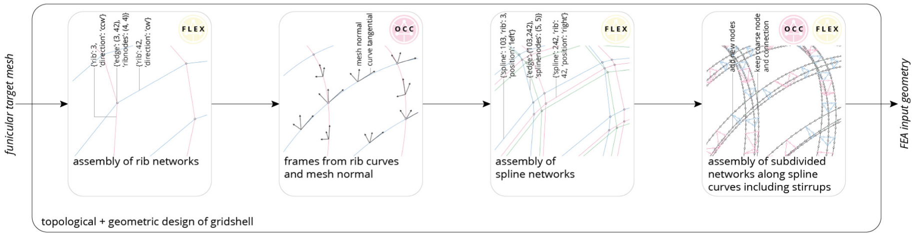

Fig. 7. Modelling of gridshell.

4.4 Form Finding and Structural Simulation of Gridshell

The spline's lengths and crossing positions are the shape-decisive input for the form finding of the bending-active structure. The form finding is performed with SOFISTIK through a direct interface from a custom package named compas_sof to the commercial FEA software (Fig. 8). Compas_sof translates the attributes of the subdivided networks into input parameters of sectional values, geometry and connectivity (with hinged or stiff couplings) into the.dat-file format for the SOFISTIK input (Fig. 8 – left).

In the SOFISTIK procedure, internal active-bending stresses are introduced with the built-in function such that the system equilibrates with non-linear, third-order analysis into its deformed form-found shape. This step is computed without the shear stirrups; they are added in a second step with wet-concrete load to match the physical assembly process (Fig. 8 – middle).

The FEA results are read out directly from the SOFISTIK.cdb-database by the compas_sof package and stored in the attributes of the parts and connections. The geometry in COMPAS is then updated with the deflections, and the shape difference (Fig. 8 – right) is evaluated and minimised prior to computing the fabrication data (Sect. 4.5). The same procedure allows setting specific loading distributions for concreting sequences and wind loads for the structural analysis (Aldinger et al. in preparation).

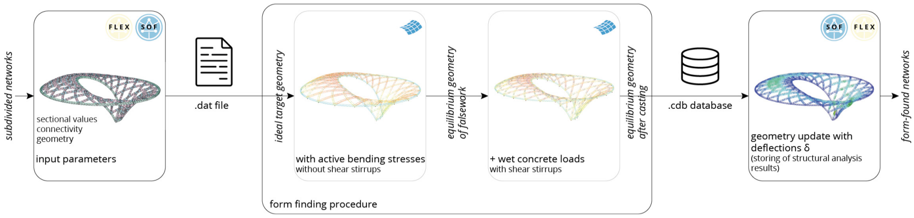

Fig. 8. Form finding of gridshell.

4.5 Translation to Fabrication Data

The fabrication data is generated from the geometry of compas_flex. From the assembly nodes, it exports the splines' unstressed lengths with their key and naming convention for cutting; from the assembly edges, the crossing locations and connecting element's key for marking (Fig. 9). Further, the surfaces of the textile shuttering are generated with compas_occ and numbered based on the connectivity of the half-edge mesh data structure. Subsequently, these serve for the knit pattern generation (Popescu et al. in preparation).

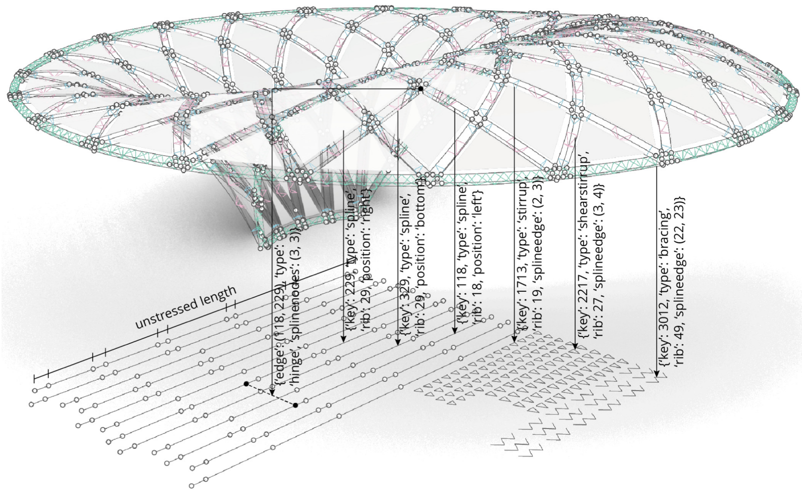

Fig. 9. Fabrication data with assembly graph.

5 Results

5.1 Materialisation and Construction

A pavilion demonstrator validates the materialisation of the falsework and reinforcement system (Fig. 10). The handling is labour-intensive but feasible for unskilled labour. The complexity lies in the correct assembly order and precise positioning of crossings, labelled and marked based on the fabrication data of unstressed segment lengths (Sect. 4.5).

Fig. 10. Demonstrator in the construction stage of the completed gridshell made of bending-active splines.

5.2 Suitability of Double-Layered Gridshells as Concrete Falsework

The shear stirrups (Fig. 11) dramatically improve the stiffness and restrain the shape in both the physical prototype (where it was strongly noticeable) and in the simulation. Their distribution and shape result from a sensitivity study. Figure 12 shows that in an FE-analysis with wet-concrete load, deformations are approximately half and buckling load factors are approximately double for a gridshell with shear connectors instead of normal stirrups only. While the separate-layer model only converges with a third of the wet-concrete load.

Fig. 11. Stirrup and shear stirrups of the gridshell.

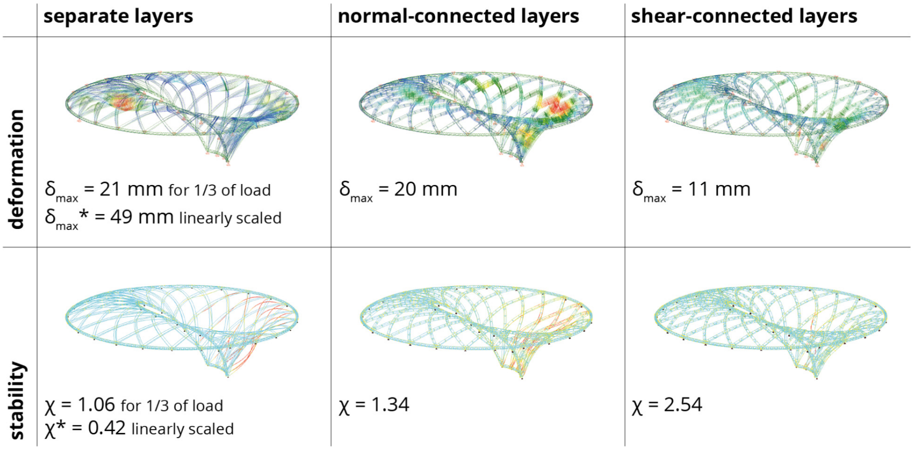

Fig. 12. Comparison of deformation and buckling load factors of double-layered gridshell under wet-concrete load.

6 Discussion and Outlook

Activating the structural height of the double-layered gridshell with shear connectors makes the proposed system a valid falsework solution. However, the sensitivity lies in the global shape accuracy toward spline lengths and crossing positions.

Further research will investigate the structural analysis with sensitivity studies and concrete loading sequence, the physical assembly logistics, and the demonstrator's construction, quantifying tolerances and stiffening (Aldinger et al. in preparation). The demonstrator validates the system design (Bodea et al. in preparation) with the knit (Popescu et al. in preparation) and the design-to-fabrication workflow as well as demonstrates the potential of the construction system for the efficient shaping of syn- and anticlastic-curved ribbed shells.

The computational development with COMPAS allows the use and customisation of existing packages as well as the creation of new packages resulting in a reproducible, comprehensible and generalisable workflow for such construction systems. The assembly data structure offers high control of the geometric, structural and fabrication design with complex topology and geometry.

The computational workflow allowed the form finding and design of a structural and construction system so that the key to efficiency for both the flexible formwork and the funicular concrete shell lies in their structurally-informed geometry. Thus, unlike the conventional CNC-milled moulds, the formwork system is less wasteful and not limited to high-tech construction contexts. Even though it is labour-intensive, no additional reinforcement installation step is required. As an outlook, such a construction system could find application in bridges, vaulted roofs or vaulted rib-stiffened floors with an additional continuous shell layer. All this could make the system applicable to a wide range of construction contexts and mitigate the environmental crisis by reducing the material consumption of both formwork and concrete structure.

Acknowledgements. The authors would like to express their gratitude to their industry supporters Debrunner Acifer Bewehrungen, Gisler Bewehrungen and Doka Schalungstechnik. The research was supported by an ETH Architecture & Technology fellowship and by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (Agreement # 51NF40-141853).

References

Adriaenssens, S., Block, P., Veenendaal, D., Williams, C.: Shell Structures for Architecture: Form Finding and Optimization. Routledge Taylor & Francis Group, Abingdon (2014)

Aldinger, L., Popescu, M., Bodea, S., Spiekermann, K., Van Mele, T., Block, P. (in preparation)

Bellmann, J.: Active bending starting on curved architectural shape. In: Bletzinger, K.-U., Onate, E., Kröplin, B. (eds.) 8th International Conference on Textile Composites and Inflatable Structures - Structural Membranes 2017 (2017)

Block, P.: Thrust network analysis: exploring three-dimensional equilibrium. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, USA (2009)

Block, P., Van Mele, T., Rippmann, M., Ranaudo, F., Calvo Barentin, C., Paulson, N.: Redefining structural art: Strategies, necessities and opportunities. Struct. Eng. **98**(1), 66–72 (2020)

Bodea, S., Popescu, M., Aldinger, L., Spiekermann, K., Van Mele, T., Block, P. (in preparation)

Cuvilliers, P., Douthe, C., Du Peloux, L., Le Roy, R.: Hybrid structural skin: prototype of a GFRP elastic gridshell braced by a fiber-reinforced concrete envelope. IASS J. **58**(1), 65–78 (2017)

García de Soto, B., et al.: Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall. Autom. Constr. **2018**, 297–311 (2017)

Hack, N., et al.: Structural stay-in-place formwork for robotic in situ fabrication of non-standard concrete structures: A real scale architectural demonstrator. Autom. Constr. **115**, 103197 (2020). https://doi.org/10.1016/j.autcon.2020.103197

Hawkins, W.J., et al.: Flexible formwork technologies - a state of the art review. Struct. Concr. **17**(6), 911–935 (2016). https://doi.org/10.1002/suco.201600117

Lehne, J., Preston, F.: Making concrete change; innovation in low-carbon cement and concrete. Technical report, Energy Environment and Resources Department, London (2018)

Lienhard, J.: Bending-Active Structures: form-finding strategies using elastic deformation in static and kinematic systems and the structural potentials therein. Ph.D. dissertation, Universität Stuttgart (2014)

Mendez Echenagucia, T., Pigram, D., Liew, A., Van Mele, T., Block, P.: A cable-net and fabric formwork system for the construction of concrete shells: design, fabrication and construction of a full scale prototype. Structures **18**, 72–82 (2019)

Nervi, P.L.: Structures. F.W. Dodge Corp., New York (1956)

OpenCascade3D: Open Cascade 3D Technology (2022). https://dev.opencascade.org/doc/overview/html/

Otto, F.: IL 18. Seifenblasen, Stuttgart (1988)

Popescu, M., Reiter, L., Liew, A., Van Mele, T., Flatt, R., Block, P.: Building in concrete with an ultra-lightweight knitted stay-in-place formwork: prototype of a concrete shell bridge. Structures **14**, 322–332 (2018)

Popescu, M., et al.: Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. Structures **31**, 1287–1299 (2021)

Popescu, M., Aldinger, L., Bodea, S., Spiekermann, K., Van Mele, T., Block, P. (in prepartion)

Rutten, D., McNeel, R.: Grasshopper3D. Seattle, Robert McNeel & Associates (2007)

Sofistik: Sofistik: structural engineering software (2020). https://www.sofistik.com

Rippmann, M., Block, P.: Funicular funnel shells. In: Gengnagel, C., Kilian, A., Nembrini, J., Scheurer, F. (eds.) Proceedings of the Design Modeling Symposium Berlin 2013, Berlin, pp. 75–89 (2013)

Van Mele, T., Lachauer, L., Rippmann, M., Block, P.: Geometry-based understanding of structures. J. Int. Assoc. Shell Spat. Struct. **53**(4), 285–295 (2012)

Van Mele, T., et al.: COMPAS: a framework for computational research in architecture and structures (2017–2020). http://compas.dev

Waimer, F., Noack, T., Schmid, A., Bechmann, R.: From informed parametric design to fabrication: the complex reinforced concrete shell of the railway station Stuttgart 21. In: Design Modelling Symposium Berlin, pp. 390–400 (2019)