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Active control of a rod-net formwork system prototype

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A B S T R A C T

A prototype rod-net for a fabric formwork system is described, including the fabrication, control of the geometry via turnbuckles, and the measurement of nodal co-ordinates via an image-based theodolite system. Such a net and fabric formwork system consists of a network of tie elements, either discrete or continuous, forming the main falsework structure, onto which is placed a fabric membrane acting as the flexible formwork for the pouring of wet concrete for the forming of a concrete shell. The fabrication of the plastic and steel net components of the prototype is described in detail, including the arrangement of the nodes, rods and boundary conditions. A control system was developed to determine the necessary adjustments at the boundary elements to move the rod-net to a target geometry to eliminate deviations that may arise from fabrication and construction tolerances. This control system showed that with minimal adjustments the rod-net could be directed effectively, resulting in deviations from the target surface reduced from up to 3–9 mm to below 1–2 mm for a 3D rod-net of approximate dimension 2.5 m × 4.5 m × 2.0 m. Additionally, the algorithm provided a more symmetric distribution of deviations around the target. The control system was coupled with 3D point-cloud measurements of markers placed on and around the rod-net by using a motorised image-assisted theodolite and specialised software for spherical and circular targets. This semi-automated process proved to be both efficient and accurate for determining the spatial co-ordinates of the markers and hence the node locations.

1. Introduction

Concrete shells are an efficient structural form, able to cover large spans with minimal structural depth, gaining stiffness through the structure's curvature. Loads can be carried effectively via membrane stresses (in-plane axial stresses) rather than flexural stresses, when the curved geometry is form-found and is resistant to out-of-plane instability. However, it is the curved geometry of many concrete shells that have been built in the past that lead to extensive material use and high labour costs when constructing shells through traditional single-use timber or milled foam formwork. In addition, the structural form can be limited to hypar sections allowing the use of linear falsework and formwork elements in place of more expensive and not reusable milled timber or foam solutions for curved surfaces.

An alternative fabrication method can be found in a net and fabric formwork system consisting of a network of tie elements, either discrete or continuous, forming the main falsework structure, onto which a fabric membrane, acting as the flexible formwork, is placed. The wet concrete is subsequently poured directly onto the fabric, for which the weight of the wet concrete is supported by the net until it has cured into the desired form. Textiles such as Geo-textiles may be used, with a surface finish that can give no adherence of the concrete to the sheet after striking. The net and any supporting falsework and framing may then be removed after the concrete structure is load bearing and then reused to recreate the same structural form.

A history of fabric formwork use for thin concrete shell structures can be found in [1] and [2], including other hyperbolic-paraboloid based cable-net investigations such as [3] and [4], which also described a computational and construction workflow. The prospect of using cable-net formwork for hypar-based bridge crossings can be found in [5]. The use of tensioned formwork alternatives in concrete shell construction could offer a variety of benefits such as 1) a reduced demand on the foundations due to a lower mass of formwork and falsework, 2) promote usable and unobstructed internal space under the system during construction thus avoiding space vacation, 3) encourage formwork re-use for projects with repeated elements, 4) eliminates the material waste experienced with traditional timber formwork and falsework, and 5) open up a more expressive set of double-curved structural forms. Cable-net and fabric based solutions can offer advantages over purely fabric solutions, as the cable elements can be constructed of steel, capable of both spanning greater distances, supporting extra loads, and acting as discrete pre-stressing and control elements. Additionally, a cable-net allows the application of a non-uniform pre-stress state; in a membrane, stresses equalise rapidly after tensioning.

A net formwork system, such as that presented in this research, has great potential in influencing how formwork systems are considered in the construction industry, for the following reasons. All components of the system can be reused either to construct an identical structure or a sub-set of the parts to create a different structure, which leads to effectively zero formwork and falsework material waste. Consequently,

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there is great economy for fabricating multiple repetitive elements. This is ideal when compared to the material waste involved with milled foam and timber solutions that have heavy carpentry costs. For various structures, especially bridges or construction projects in built-up urban areas, keeping an unoccupied space under the structure can be critical to minimise disturbance. In certain situations, accessibility and logistics would warrant complicated falsework solutions, for example spanning over a river or road

This research project investigates the fabrication, control and measurement of a prototype rod-net formwork system, needed to define a geometrically accurate net such that it will non-uniformly displace under the wet concrete self-weight to cure into the correct final shape.

2. Research methodology

The rod-net's control system comprises of two main components: 1) a control algorithm that calculates which length adjustments are needed to the net in order to keep stresses within safe material limits, and to direct the geometry to a target shape, and 2) a physical system of changing the lengths of prescribed elements, for which threaded turnbuckles have been used in this prototype. This combined algorithmic and physical control system is then applied to make fine adjustments to the geometry of the rod-net, from spatial deviations that may arise from both fabrication and construction tolerances. Such deviations must be corrected before the pouring of the concrete so that the as-built geometry is as close as possible to the design intent.

The control system is coupled with 3D point-cloud measurements of markers placed on and around the rod-net by using expertise and specialist equipment. The measurement of the 3D point-cloud is realised at the sub-millimetre level by the deployment and combination of several QDaedalus systems (using multiple theodolites for improved coverage), taking measurements from underneath the rod-net. The QDaedalus system is based on a motorised image-assisted theodolite and specialised software, allowing precise spatial measurements of spherical or circular targets. The 3D co-ordinates are obtained by a geodetic network adjustment, based on the spatial directions carried out at different locations. The combination of efficient control and measurement systems allows for quick and precise adjustments of a net on-site before pouring.

The rod-net used to demonstrate the formwork system is based on the roof structure of the NEST-HiLo research and innovation unit [6] for the Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland (see the conceptual image of Fig. 1). The project will feature a full construction-scale net and fabric-formed, thin-shell concrete roof structure. The NEST-HiLo unit is a collaboration between the Institute of Technology in Architecture, represented by the Professorships of Architecture and Structure (Block Research Group BRG) and Architecture and Building Systems (AIS), architectural office supermanoeuvre and engineering firm Bollinger + Grohmann. HiLo is in the domains of lightweight construction and smart, integrated and adaptive building systems [7-10]. On top of the steel cable-net will be placed a geo-textile fabric formwork, CNC cut and positioned accurately with cut-outs at each node and locked-in with a shear connector. The textile will be taut and strong to support the weight of the concrete within each bay, spanning between the ties without excessive sagging (pillowing) as this leads to additional self-weight. As the geo-textile does not stick to the concrete, even without surface treatment, it can be used many times over without loss of performance, and provides a watertight cover on one side of the concrete during curing and gives the soffit a quality finish after striking.

Extending the prototype cable-net formwork systems for anti-clastic shells developed by the Block Research Group, a 1:4-scale prototype system of the NEST-HiLo roof has been under investigation, as part of formalising the control and measurement protocol for the system, as well as investigating the use of a novel rod and ring network instead of continuous cables. Previous research on cable-net and fabric formwork prototypes can be found in [1] and [11] where information can be found on the calculation of the cable-net forces and pre-stress levels needed for such systems, while the computational form-finding methods can be found in [12]. A variety of steps are needed to design a complete net and fabric formwork system including 1) boundary condition considerations, 2) target shell shapes, 3) the mapping of the cable-net to the shell surface, 4) fabric cutting patterns, 5) tributary nodal load allocations and load combination calculations, 6) best-fit optimisation of cable forces during wet concrete loading, and 7) element sizing of the net and the supporting frame. These steps have been performed previously for the scale model prototype, with this paper focusing on the fabrication and control–measurement process.

Difficulties that arise in utilising such a formwork system, and how they have been tackled in this research, can be summarised as follows:

- The model that has been set up to tackle the computational modelling of a tension-only network with a high degree of statical indeterminacy is described in Section 5.2. This model is characterised by an efficient energy minimisation algorithm for finding static equilibrium using the coordinates of the free nodes as variables. This solves for the high indeterminacy of the rod-net, the tension-only condition via appropriate optimisation constraints, and makes the

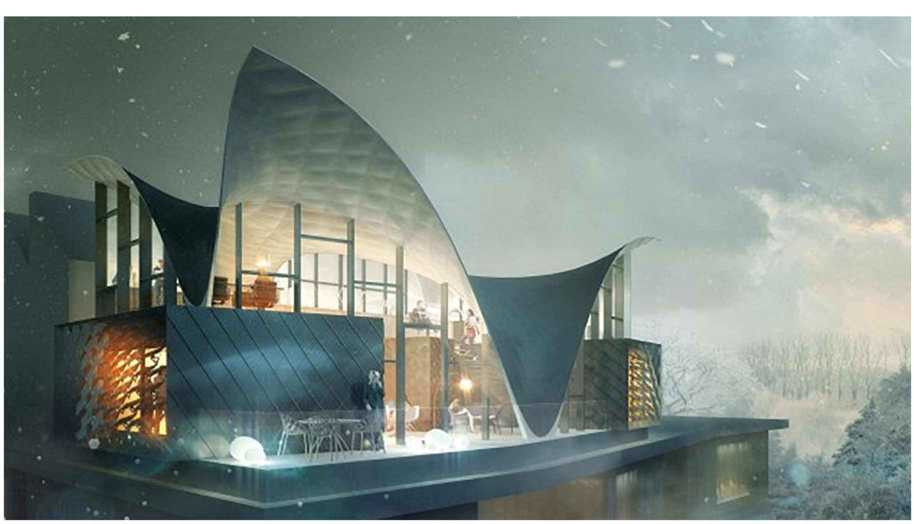

Fig. 1. The NEST-HiLo research and innovation unit at Empa, Dübendorf, CH. Source: Image: supermanoeuvre/Doug & Wolf.