Engineering Structures 75 (2014) 39–50

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Design process for prototype concrete shells using a hybrid cable-net and fabric formwork

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ARTICLE INFO

Article history:
Received 3 November 2013
Revised 20 May 2014
Accepted 21 May 2014
Available online 13 June 2014

Keywords:
Shell structure
Cable net
Fabric formwork
Flexible formwork
Form finding
Shape optimization

ABSTRACT

This paper sets out to explore the potential of combining a cable net with a fabric, in particular to scale the concept of flexible formworks to the size of large-span roofs and bridges, especially when applying a thin coat of concrete or mortar to form a shell structure. By carefully designing the cable net and its topology, and calculating and controlling the prestressing forces, it is possible to form a wide range of anticlastic shapes, beyond those of the hyperbolic paraboloid.

A complete workflow for the computational design of a shell shape and its corresponding flexible formwork are presented as a proof-of-concept for future work. Two prototype shell structures were built based on this workflow to validate the overall approach, to compare the built geometry with that of the design model and to identify further challenges when developing and scaling up the concept. In addition, a comprehensive overview of flexible formworks for anticlastic shells is presented to frame the present research.

1. Introduction

Concrete shell structures, if properly designed and constructed, are able to cover large spaces at minimal material cost through efficient membrane action.

However, they are challenging to construct, traditionally requiring full and generally rigid formworks, which are both material- and labor-intensive. The materials are often used only once, since they are customized for a specific doubly curved geometry. Due to the amount of work involved, these structures are generally not competitive in a contemporary building environment where labor is expensive.

It is possible to reduce the amount of material, especially of the falsework, by introducing a flexible formwork. In this case, the shuttering is replaced by a fabric, and the falsework by a cable net, supported by an external frame at its boundaries. The challenge is then to design the flexible formwork such that the resulting shape matches the designed geometry.

After summarizing the wider context and the specific objectives of this research project, Section 2 presents a review of historical and recent construction methods for anticlastic (negatively doubly curved) shell structures with an emphasis on flexible formworks. This review is intended to illustrate some of the differences between the combined cable-net and fabric formwork discussed here and flexible formworks in precedent work. In addition, it is used to frame some of the design choices made for two built prototypes. Section 3 presents a complete workflow for the design, optimization and form finding of these cable-net and fabric-formed, anticlastic shell prototypes, before discussing their actual construction in Section 4.

1.1. Context of research project

The workflow and prototype structures, presented in this paper, are intended to further inform and develop the design of the HiLo roof. HiLo is a research and innovation unit for NEST demonstrating ultra-lightweight construction. It is planned as a 16 m × 9 m duplex penthouse apartment for visiting faculty of Empa and Eawag. NEST is a flagship project of Empa and Eawag in collaboration with the ETH Domain. It is a dynamic, modular research and demonstration platform for advanced and innovative building technologies on the Empa–Eawag campus in Dübendorf, Switzerland, to be completed in 2015 (Fig. 1). As a “future living and working lab”, NEST consists of a central backbone and a basic grid to accommodate exchangeable living and office modules, such as HiLo, allowing novel materials and components, and innovative systems to be tested, demonstrated and optimized under real-world conditions. HiLo is a collaborative effort of the BLOCK Research Group and the Assistant Professorship of Architecture

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http://dx.doi.org/10.1016/j.engstruct.2014.05.036

Fig. 1. Visualization of the preliminary design for NEST, with HiLo constructed at the top corner. ©EMPA and Gramazio & Kohler.

and Sustainable Technologies (SuAT), both at the Institute of Technology in Architecture, ETH Zurich, joined by Supermanoeuvre in Sydney as well as Zwarts & Jansma Architects (ZJA) in Amsterdam.

HiLo introduces several innovations, and this paper relates in particular to the development of a reusable and lightweight cable-net and fabric formwork system to construct the anticlastic, thin shell roof, with no internal falsework. Van Mele and Block [1,2] presented a method for finding the distribution of forces required in such a cable-net or membrane formwork to obtain a particular shape, after it has been loaded with concrete. This control allows a range of pre-defined, non-analytical, anticlastic shapes to be designed and constructed, thus offering room for shape optimization. In 2010, the first author provided consultancy to ZJA for a competition to design an interstate wildlife crossing. In this context, ZJA proposed to use a cable-net supported fabric to push the concept of a flexible formwork to the scale of long-span bridges emphasizing its qualities and constructional advantages [3]. The present paper is a continuation of these earlier ideas.

1.2. Objectives

The objectives of this paper are twofold. First, to establish, as a proof of concept, a complete workflow for the structural design of an anticlastic thin concrete shell taking into account the fabrication constraints of a hybrid cable-net and fabric formwork. Second, to construct prototype shells based on this workflow in order to identify challenges in both computational and constructional aspects. The results of this paper are then used to inform future research and development of the workflow and construction method for full-scale structures in general, and the roof structure of HiLo in particular.

2. Historical overview of related work

The innovations in this and future work are rooted in the longer history of using (prestressed) fabrics as a flexible formwork to construct thin-shell concrete structures. This section serves as a first comprehensive overview of flexible formworks for anticlastic shells. The overview is meant to frame the present research and highlight some of the similarities and differences with our particular approach.

2.1. Fabric-formed shells

The British engineer, James Hardress de Warenne Waller (1884–1968), was the first to apply fabrics to the construction of thin shells. He developed the 'Ctesiphon' system, which started from reusable, lightweight falsework arches, made of steel or timber, catenary in profile, and placed in parallel. A slightly prestressed hessian fabric was tacked to the arches and, under the weight of the applied cement mortar, sagged in between the falsework arches to form corrugations, acting as a lost formwork. The thickness of the first thin coat of cement, the prestress in the fabric and the spacing between the arches would determine the depth of the corrugations, and thus the stiffness of the shell. The system was competitive as it reduced the cost of molds and scaffolding, and required no skilled labor [4].

Waller patented a specific system in 1955 for spans of up to 150 m using prefabricated, external trussed arches from which to suspend the fabric. By the end of the 1970s, the Ctesiphon system had been used around the world for the construction of over 500 shell structures. Two of Waller's last and largest were the Chivas Distillery Warehouses in Paisley, Scotland. The two structures, 100 ft (30.5 m) and 150 ft (45.7 m) long, each featuring three 100 ft (30.5 m) spans, have a thickness of 2.5 in. (6.4 cm), with the fabric spanning 2.54 m between the arches [5] (Fig. 2). The success of the system was partially attributed to the rising demand for unobstructed covered spaces with increased clearances in addition to global shortages at the time of the "modern wonder material, steel", as well as timber [6].

The renowned shell builder Félix Candela Outeriño (1910–1997) used the Ctesiphon system for his first shell, an experimental

Fig. 2. Formwork [5] (top) and current state in 2013 (bottom) of the shell of the Chivas Distillery Warehouse, now Chivas Central Bottling Hall and despatch warehouse, Scotland, ca. 1959, by James Waller et al., with 30.5 m spans and thickness of 6.4 cm. Photo (bottom) courtesy of Chivas Brother Ltd.