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Assembling Freeform Buildings in Precast Concrete

Zaha Hadid Architects - Heydar Aliyev Cultural Centre - Baku

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Fabric Formwork:
The State-of-the-Art and Future Endeavors

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***Abstract*— This document gives a brief overview of what fabric formwork technology entails, as well as an overview of current applications and research efforts. Furthermore, it discusses research that has been carried out at the Delft University of Technology as part of the author's Master's thesis. The topic was evolutionary optimisation of fabric formed structural elements. Further proposed research based on the results is discussed.**

I. Introduction

Traditionally concrete structures are thought to be generally rectangular in appearance, and perceived as crude in nature. This public image of concrete sharply contrasts the fact that it is a cast material with all the geometric freedom that implies. On a large scale this property is more often fully utilized, illustrated by seminal work of shell builders such as Heinz Isler, or by more contemporary free form architecture by the likes of Santiago Calatrava and Zaha Hadid. However, free form architecture is often capital and labor intensive, and only comes to fruition under specific socio-economic circumstances.

Fig. 1 Contrasting orthogonal, rectangular prefabrication with free form architecture and prevailing esthetics

On a smaller scale, on the level of structural elements, applying free form to concrete implies intricate formworks or complex computer-driven production methods. Fabric formwork technology, as it is now envisioned, addresses this apparent contradiction (Fig. 1) of concrete's inherent fluidity, yet angular application. It can offer relatively simple production for economically feasible and esthetically pleasing designs.

II. Fabric Formwork Technology

Fabric formwork is characterized by the use of coated fabrics or geotextiles as the main material for a concrete mold. One or more layers of fabric are filled or injected with fresh concrete. The fabric can be either prestressed or slack, as the hydrostatic pressure of the fresh concrete ultimately stresses the formwork. The design considerations for these formworks is similar to those in the design and engineering of tensioned membrane structures, involving the interaction of prestress, non-linear material behavior and the support conditions. Additionally, fabric formwork has concrete pressures and fluid structure interaction as complicating factors. There are two aspects that distinguish the design of fabric formwork from that of membrane structures, caused by its short term use. Firstly, the formwork invites the designer to apply not only fixed, but also supports along which the fabric may slide during stressing and casting, normally leading to long-term wear and tear. Secondly, the stress distribution within the fabric may be highly uneven. One result of these possibilities is shown in Fig. 2.

Fig. 2 Concrete truss cast at the University of Manitoba, with the timber and fabric formwork shown below in two seperated parts

Practical applications of fabric formwork are commonly found in the construction of foundations, especially for hydraulic structures. Other examples are mostly confined to simple columns or walls, or non-structural applications.

Research into more geometrically pronounced structural elements, such as shells or non-prismatic beams [1], has yet to lead to widespread use of this technology. The lack of sufficient engineering understanding of these elements is one of the contributing causes. Computational research at the Delft University of Technology focused on this issue.

III. EVOLUTIONARY OPTIMISATION OF FABRIC FORMWORK

The design of structurally efficient non-prismatic shapes has been investigated for the last few decades with Evolutionary Structural Optimisation (ESO) as one of the most prominent methods of finding optimal forms [2]. This and similar algorithms remove inefficiently used material and produce results that are often described as organic or skeletal (Fig. 3). However, resulting shapes are difficult to manufacture economically by conventional means and also do not take constraints posed by fabric formwork into account.

Fig. 3 Simply supported beam optimized with ESO

A new computational framework was devised in which three steps necessary in fabric formwork design were integrated, the form finding of the fabric, the analysis of the resulting beam and finally, the optimisation of the beam shape. The entire framework was written in Java and interfaced with ANSYS for finite element analysis of the concrete beam. There are a few form finding algorithms available for the design and engineering tensioned membrane structures. One commonly used and well defined algorithm, dynamic relaxation [3], was chosen and adapted to use for fabric formwork (Fig. 4).

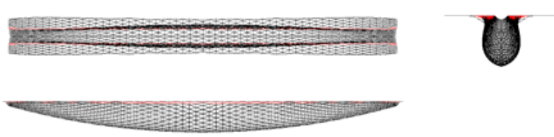

Fig. 4 Example of beam shape developed with dynamic relaxation

The fabric mesh was then translated to a three dimensional concrete mesh in ANSYS and then analyzed to determine the volume and overall stiffness in terms of strain energy. These properties were then used to evaluate the beam. Optimisation of the beam shape was performed by using a genetic algorithm, differential evolution [4]. Genetic algorithms use an analogy with biological evolution by continuously generating and evaluating a certain number of solutions, then combining their properties based on the evaluation to form a new generation of solutions. In this case a set of beams was continuously generated by form finding and subsequently analyzed and rated using the finite element analysis in ANSYS (Fig. 5). The entire process is fully automated and produced optimized, manufacturable fabric formed beams.

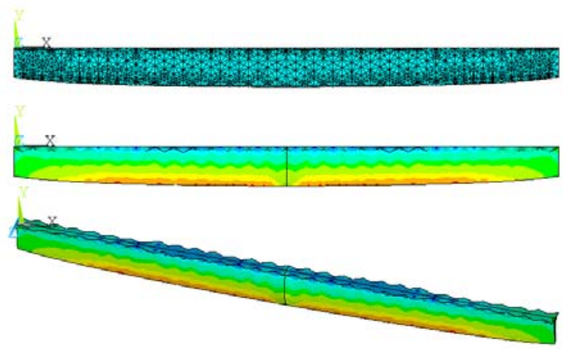

Fig. 5 Example of meshing and analysis of optimised result

It has been shown that constraints posed by fabric formwork can be integrated in a single functional design tool, thereby bridging the gap between computational optimisation and manufacturability [5]. A linear elastic comparison between the resulting beam shapes and rectangular beams shows that significant material reductions can be realised (Fig.6, Table I).

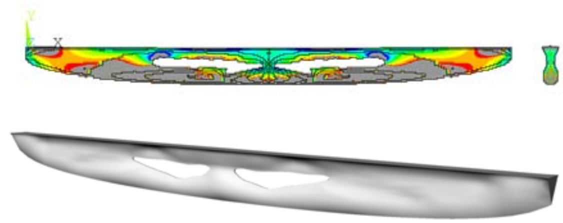

Fig. 6 One of the final results obtained from optimization, used for comparison in Table I.

TABLE I
LINEAR ELASTIC COMPARISONS OF FABRIC FORMED BEAM WITH RECTANGULAR BEAM

Beam	**volume**	**height**	**deflection**
reference beam	100%	100%	100%
fabric formed beam, equal volume, equal slenderness	100%	>100%	9%
fabric formed, equal volume equal construction height	100%	100%	22%
fabric formed, equal deflection equal construction height	42%	100%	100%

IV. FUTURE RESEARCH

Several recommendations were made that form the basis for future research at the ETH Zurich. The automated evolutionary optimisation will be (partially) abandoned due to its high computational demands in favor of more user interaction and engineering judgement. The scope of the research will also be broadened to include entire structural systems, whilst investigating reinforcement strategies, the role of fabric patterning (sewing or welding fabric together) as well as implications of the design on the supporting frame of the fabric. Parallel to this computational work, quantitative information will be collected on completed projects and prototypes to gain further insight into the true economy and value of the technique. This should offer better understanding of the full potential of fabric formwork and work towards handing both architects and engineers better tools to design, analyze and ultimately realize fabric formed structures.

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