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ORICRETE: Modeling support for design and manufacturing of folded concrete structures

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ABSTRACT

The paper presents a flexible and efficient modeling approach to the simulation of the folding process of general crease patterns. The development of the model has been motivated by the need to provide support for targeted design and efficient manufacturing of shell structures inspired by the origami technique. This type of structures is becoming increasingly popular in many engineering disciplines and has been referred to as origamics. In the present work the folding technique is used to produce spatial structures from continuously reinforced thin-walled cementitious composite plates without the need to construct curved spatial formworks. In order to support the targetted design and manufacturing of folded concrete (oricrete) structures numerical model has been formulated as an optimization framework with several types of optimality conditions and equality constraints. The model is used both for form-finding of the spatial structure and for the realization of the manufacturing process.

1. Introduction

The folding technique inspired by the traditional japaneese art of origami has been used for ages to produce diverse shapes and forms out of a sheet of paper. The correspondence between the planar sheet of paper and the final shape of the product has attracted mathematicians and engineers since decades and is still a subject of an intensive ongoing research [1–4]. Applications of the origami concepts in engineering disciplines have been referred to as origamics. Exciting applications have been realized in architecture [5–7], medicine [8] and mechanical engineering [9].

In the present work the folding technique is used to produce spatial structures from continuously reinforced thin-walled cementitious plates without formwork. The especially appealing feature of the folding technique is in the ease of achieving different geometrical form of the product by modifying the crease pattern or by solely adjusting its parameters. An envisioned production process exploiting this feature is depicted in Fig. 1. The factory-produced preforms of the oricrete segments are transported to the construction site in a planar form. The segments with built-in crease patterns are then folded to their final shape and the crease lines are grouted. After the hardening the crease angles are fixed and the oricrete segments are installed to their destination.

The described production technology becomes particularly interesting in connection with flexible, continuous, high-performance reinforcement such as carbon and AR-glass textile fabrics. Textile reinforced concrete exhibits high strength and ductile behavior [10–12]. Due to the non-corrosiveness of the textile reinfocement, no extra cover is required for its protection. Consequently, its properties can be higly exploited in thin-walled spatial and shell structures [13–15]. This fact opens up the space for the shape optimization of light-weight shell structures [16].

Obviously, the described production technology can only be realized with the support for the computer-aided design and simulation of the construction process. This task falls into the discipline of *origami design* defined loosely by Demaine and Demaine [17] as

> *Given a piece of paper, fold it into the form with certain desired properties, e.g. a particular shape.*

Another domain of mathematical research of origami deals with the question of *foldability* addressing the general correspondence between the initial configuration of the crease pattern and the identification of the target form into which it can be folded.

Examples of models for origami design have been reported recently by several authors. Modeling strategy representing the folding process as a tree structure of folds has been proposed by Lang [18] and implemented in the `TreeMaker` software. This tool can be used to identify crease pattern with non-rigid facets leading to a desired form [19]. In the approach proposed by Tachi the crease

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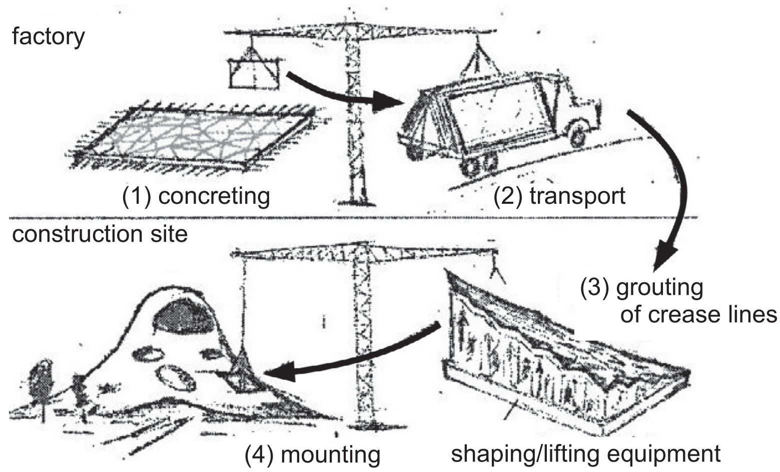

Fig. 1. Possible production method of folded concrete structures.

angles are used to represent the instantaneous configuration of the modeled structure [20,21]. Approaches to the design of cellular structures satisfying specific properties, such as density and mechanical performance have been presented by Klett in [22].

In the present work we apply the concepts of numerical mechanics to reflect kinematics of a rigid foldable crease pattern with triangluar facets. For this simple facet shapes, the model can be regarded as a pin-jointed framework of rigid trusses. However, the approach is general as other types of constraints can be easily introduced in order to enforce developability of a folded structure to a sheet form or to include quadrilateral and polygonal facets. The model development has been stimulated by the envisioned practical industrial applications. We will try to document that the achieved efficiency and flexibility of the modeling framework turns out to be able to cover several use cases included in the design cycle based on the envisioned technology.

The numerical model has been formulated as an optimization framework with several types of optimality conditions and equality constraints. Except of the simulation of the folding process the modeling framework also includes the assessment of the mechanical behavior of the produced structure. To our knowledge, this issue is not included in the existing models of *origami design*.

The simulation steps included in the design cycle are indicated in Fig. 2 showing the parameterized specification of initial the crease pattern configuration (1), specification of fold constraints and optimality criteria (2), simulation of the folding process to achieve the target configuration (3), fixing of the crease lines and introduction of supports (4), simulation of the load-bearing behavior (5), assessment of the mechanical response and adaptations of the planar configuration of the crease pattern (6).

An important feature of the tool is the transparent and open implementation of the model using the scripting high-level scientific computing tools based on the Python language combined with the numerical libraries NumPy and SciPy. The ongoing development of the package is managed using the open-source management platform on `github.com` [23].

The paper is organized as follows: In Section 2 a production of a realized prototype of an oricrete shell is described in order to visualize the shaping and production process of a thin cementitious element. After that, the implementation framework, formulation of the optimiality criteria and equality constraints is presented in Section 3 and demonstrated on an example of a folded vault element. Then, in Section 4 the application of the model to the simulation of the manufacturing is exemplified.

2. Prototype of an oricrete structure

In order to demonstrate the manufacturing concept and to test its feasibility a prototype of a folded cementitious shell has been produced using the Yoshimura crease pattern. Fig. 3 shows the production steps starting from the formwork with installed linear

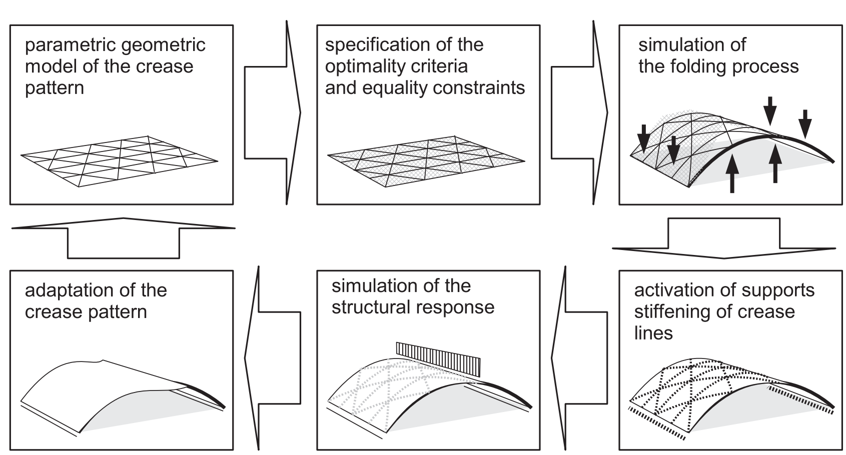

Fig. 2. Simulation steps involved in the design process of oricrete elements.