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Advances in the form-finding of structural membranes

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Abstract

The present contribution presents the application of the newly developed isogeometric B-Rep analysis to the form-finding and structural analysis of structural membranes. Therefore, the necessary basis of the model description is briefly outlined. The result of this approach is the possibility to perform mechanically accurate form-finding (and follow-up analyses) directly within a CAD-environment on a full NURBS-based CAD-model.
Selected benchmark examples show the accuracy and robustness of the developed method, assessed against analytical solutions if applicable. Two selected application examples that are entirely treated within the augmented CAD-environment highlight the potential of the method: Using one common model not only facilitates geometrical analysis and preparation of the model, but also allows for smooth and close interaction between design and analysis, which is of crucial importance in membrane design.

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1. Introduction and Motivation

Structural membranes provide minimal use of material combined with an attractive and impressive language of shapes. These shapes are directly mechanically motivated: based on the boundary conditions and the prescribed prestress field, form-finding analysis is used to determine the shape of equilibrium which allows the membrane to act in pure tension.

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This mechanical background usually leads to an iterative design procedure, where the mechanical form-finding and the modification of boundary conditions and prestress conditions as design handles mutually interact until a solution that is desirable from a structural as well as from an aesthetical point of view is found.

Classically the architectural part of the design of structural membranes is realized within a CAD (*computer-aided design*) environment, whereas the form-finding and subsequent analyses are performed within a CAE-environment (*computer-aided engineering*), usually a finite element-code. The separation of these models requires considerable amounts of time and is obviously rather error-prone.

Recently, the *isogeometric B-Rep analysis* (IBRA) has been proposed as a consequent generalization of the *isogeometric analysis* (IGA) with the aim of directly using the CAD-model – enriched by mechanical information – for the analysis of structures [3].

In the present contribution, the form-finding of structural membranes with IBRA will be presented, focusing on the form-finding directly on the basis of CAD models, and the potential of the applied method.

The contribution is outlined as follows: Section 2 gives a brief introduction to the *isogeometric B-Rep analysis* and sketches the development of an IBRA membrane and a cable element. Section 3 presents benchmark examples for the form-finding and points out the accuracy and robustness of the developed method. In Section 4 a prototypic full-scale application and a sculptural inflation example are presented in order to demonstrate the capability and potential of the derived methods for structural membranes. Finally Section 5 gives a conclusion and an outlook on future work.

2. Introduction to the isogeometric B-Rep analysis and the development of a membrane and a cable element

The *isogeometric B-Rep analysis* (IBRA), introduced by Breitenberger *et al.* in [3] is a relatively recent development in the field of finite element analysis: Its main objective is to allow for structural analyses on full CAD geometries, *i.e.* in general trimmed and coupled NURBS-surfaces, without the need for creating a separate analysis mesh. Hence the separation between a design model and a model for analysis shall be overcome since the gap between those is simply omitted.

This section introduces the *isogeometric B-Rep analysis* with some of its fundamentals as well as the elements required for structural membranes, *i.e.* mainly a prestressed membrane and cable element.

2.1. B-Rep description in CAD

In today's CAD systems, the *Boundary-Representation* (B-Rep) is a technique used to describe arbitrary geometrical entities by their boundaries. Following the B-Rep approach, for a three dimensional object a set of adjacent bounded surface elements called faces describes the "skin" of the object and thus the object itself. These faces at their turn are bounded by sets of edges which are curves lying on the surface of the faces. Several edges meet in points that are called vertices.

The B-Rep approach intrinsically incorporates trimmed surfaces, since the trimming curves become part of the boundaries in inner resp. outer trimming loops, see Figure 1.

As basis functions for the B-Rep description, commonly non-uniform rational B-splines (NURBS) are used [5]. The NURBS-based B-Rep description of geometries has become the standard for geometry description in modern CAD-systems.

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