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Treatment of Reissner–Mindlin shells with kinks without the need for drilling rotation stabilization in an isogeometric framework

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Abstract

This work presents a framework for the computation of complex geometries containing intersections of multiple patches with Reissner–Mindlin shell elements. The main objective is to provide an isogeometric finite element implementation which neither requires drilling rotation stabilization, nor user interaction to quantify the number of rotational degrees of freedom for every node. For this purpose, the following set of methods is presented. Control points with corresponding physical location are assigned to one common node for the finite element solution. A nodal basis system in every control point is defined, which ensures an exact interpolation of the director vector throughout the whole domain. A distinction criterion for the automatic quantification of rotational degrees of freedom for every node is presented. An isogeometric Reissner–Mindlin shell formulation is enhanced to handle geometries with kinks and allowing for arbitrary intersections of patches. The parametrization of adjacent patches along the interface has to be conforming. The shell formulation is derived from the continuum theory and uses a rotational update scheme for the current director vector. The nonlinear kinematic allows the computation of large deformations and large rotations. Two concepts for the description of rotations are presented. The first one uses an interpolation which is commonly used in standard Lagrange-based shell element formulations. The second scheme uses a more elaborate concept proposed by the authors in prior work, which increases the accuracy for arbitrary curved geometries. Numerical examples show the high accuracy and robustness of both concepts. The applicability of the proposed framework is demonstrated.

Keywords: Isogeometric analysis; Geometrical nonlinear Reissner–Mindlin shell; NURBS; Interpolation of rotations; Treatment of kinks; Shell not requiring drilling rotation stabilization

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1. Introduction

Reissner–Mindlin shell elements are the prevailing discretization technique for the computation of complex surface-oriented structures. Most common finite element analysis packages provide shell formulations based on the Reissner–Mindlin shell theory. Several ways for the derivations of shell theories exist, see [1]. The well-known contributions of Simo et al. [2–5] introduce a Reissner–Mindlin shell formulation, which is derived from the continuum theory. These papers form the fundament of an earlier work by the authors [6] and of this contribution, which propose an isogeometric rotation-based Reissner–Mindlin shell formulation. In smooth areas the rotational state of Reissner–Mindlin shells is described by two rotations, which are aligned to the local geometry. No stiffness against rotations around the normal vector arises. All classical shell theories require C^1-continuous surfaces and thus strictly speaking do not cover geometries with kinks. Although precluded from a theoretical point of view, geometries with kinks and sharp folds are an important area of application in engineering practice. In [3] it is proposed to use two nodal rotations in smooth areas and three global rotations for nodes on kinks. Stiffness against three rotations arises merely from the intersection of surfaces, which is the case at kinks or for faceted surfaces. If stiffness against one rotation is very low or even zero, numerical problems arise. This can be prevented by a classification of nodes – located in smooth areas or on kinks. However, there is no general criterion for this distinction, which necessitates a manual classification. Alternatively, some kind of drilling rotation stabilization can be used. All kinds of shell formulations using C^0-continuous Lagrange basis functions – independent of the derivation of the shell theory – suffer from this problem. For an excellent overview of existing shell theories and details about the aforementioned numerical issues see [1].

The possibilities offered by the introduction of isogeometric analysis by Hughes et al. [7] have the potential to change this situation fundamentally. The exact description of the geometry with NURBS allows an automatic and appropriate treatment of both smooth regions and kinks. In the meantime several NURBS-based isogeometric shell formulations have been published. An isogeometric Kirchhoff–Love shell is proposed by Kiendl et al. [8]. Benson et al. [9] use a rotation-free shell [10] in regular regions and a Reissner–Mindlin shell [11] in regions with geometric discontinuities. The rotation-based Reissner–Mindlin shell formulation proposed by the authors [6] uses a new concept for the interpolation of the director vector adapted to the characteristics of NURBS surfaces. The computation of multi-patch geometries with kinks with a linearized version of this shell formulation is discussed in [12]. The work of Echter et al. [13] uses a difference vector formulation with transverse shear deformations instead of rotations as degrees of freedom. A solid-shell with two different methods to tackle locking phenomena is proposed in [14]. In addition to that, there are several isogeometric shell formulations which use other geometry descriptions, see e.g. [15,16].

Despite the presence of several shell formulations, until now, no parameter-free approach to treat shell models with kinks has been presented in an isogeometric framework. The works of Benson et al. [9,11] – implemented into the commercial FEA code LS-DYNA – rely on drilling rotation stabilization, which renders results dependent on drilling rotation stabilization factors. The Kirchhoff–Love shell formulation of Kiendl et al. [8] uses a penalty-like method to impede hinging behavior at C^0-continuous patch intersections, called bending strip method [17]. Its results depend on a penalty factor and in [9] it is shown, that the bending strip method needs aligned derivatives at intersections to work properly. To the authors' knowledge, currently no other isogeometric shell formulation does discuss the computation of geometries with kinks.

Based on the aforementioned the new aspects and the main contributions of this paper are the following.

(i) A nonlinear Reissner–Mindlin shell theory for large deformations and finite rotations is presented. The geometry is described with the shell mid-surface and an inextensible director vector. Thus, no thickness strains arise. Green–Lagrange strains are used as a measure for the strains and require the interpolation of the director vector, its derivatives and variations thereof. Basing on the previous publication [6] two methods for the interpolation of the current director vector and the other mentioned quantities are presented. The variation of the director vector is expressed as a function of the variation of nodal rotations.

(ii) Methods for the interpolation of the director vector and its variations in the presence of kinks are presented. The higher continuity of NURBS allows to neither hurt the orthogonality nor the continuity. Basically two sets of nodal basis systems are used. One set is defined patch wise and is able to interpolate