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Three-dimensional isogeometrically enriched finite elements for frictional contact and mixed-mode debonding

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Highlights

- Extends isogeometric enrichment for finite elements to 3D mixed-mode contact.
- Produces at least C^1 continuity on the contact surface without smoothing techniques.
- Provides higher-order evaluation of surface integrals.
- Simplifies generation of volumetric meshes from IGA surface representations.
- Achieves high accuracy and increases robustness compared to Lagrangian finite elements.

Abstract

We present an isogeometric enrichment technique for three-dimensional finite element computations applied to frictional contact and mixed-mode debonding. This is an extension of previous work that focused on two-dimensional and frictionless problems. To offer a more complete view of the enriched element's performance, a comparison of the results to tri-variate isogeometric discretizations and standard Lagrangian elements is also included here. The enrichment is applied by discretizing parts of the surface that require higher accuracy with isogeometric basis functions, while the rest of the body uses Lagrangian shape functions. By using an isogeometric surface representation, the higher continuity across element boundaries and higher order of interpolation can be exploited. At the same time, the generation of tri-variate isogeometric meshes is avoided.

A convergence study without any surface effects, involving only volume integrals, shows that the enriched elements can also be beneficial for these problems. The major advantage of the isogeometric element enrichment over standard tri-linear elements is demonstrated in contact problems including normal and tangential tractions. For both, mixed-mode cohesive debonding and frictional contact, the enrichment increases robustness and leads to more accurate results than standard linear Lagrangian elements. All computations are also compared to results using tri-variate isogeometric discretizations to give a complete picture of the element's performance. It is also shown that the proposed enrichment formulation has advantages in mesh generation.

Keywords: Computational contact mechanics; Isogeometric analysis; Nonlinear finite element methods; Cohesive zone modeling; Peeling; Friction

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1. Introduction

The accurate description of surface effects and the computation of surface quantities can play a crucial role in engineering applications. In contact computations for instance, the contact pressure or quantities derived from contact forces are often of special interest. Besides accuracy and efficiency, also the robustness of such computations can be a critical aspect. This work aims at combining high surface accuracy with an efficient and simple bulk description. To achieve this goal, the surface or parts of the surface that require high accuracy are discretized using isogeometric basis functions, while the rest uses standard Lagrangian finite elements. Isogeometric basis functions, like NURBS or T-splines, offer a higher order of interpolation and in general continuity of C^1 or higher across element boundaries. By applying the isogeometric enrichment only locally where it is required, the overall computational cost is only increased slightly, while the advantages of the method are available at the same time.

This has been shown in 2D and for three-dimensional frictionless normal contact in [1] and for enrichments involving higher-order Lagrangian and Hermite interpolation on the surface in [2,3]. The isogeometric enrichment technique leads to major improvements in reaction forces and bending moments compared to standard linear Lagrange elements in sliding and peeling contact computations. In 2D, Hermite interpolation on the surface leads to solutions of comparable accuracy, but an extension to 3D does not exists. For the three-dimensional example considered in [1], the use of isogeometrically enriched elements leads to more accurate results while reducing the runtime by 35% compared to linear elements due to a reduction of the required number of Newton iteration steps.

Based on these promising results, this work extends the previous work by evaluating the general performance of the three-dimensional isogeometrically enriched elements in a convergence study. Also, the use of isogeometrically enriched elements in tangential contact is analyzed and discussed. The model problems are a debonding simulation using a mixed-mode exponential cohesive zone model and a frictional contact simulation using a stick–slip algorithm. A further novelty is the comparison of the enriched elements to tri-variate isogeometric finite elements. This extension offers a more complete picture of the performance of the enrichment technique, which has previously only been compared to tri-linear Lagrangian finite elements and other enrichment techniques. Furthermore, the enrichment of quadratic Lagrange element meshes is considered in addition to the linear Lagrange case considered so far.

A thorough discussion of finite element enrichment, isogeometric analysis, and computational contact mechanics can be found in [1] and references therein. The following gives a brief introduction and names some recent advancements.

The concept of isogeometric analysis (IGA) was introduced by Hughes et al. [4] and has since been adopted in many fields. Originally, isogeometric analysis was developed to bridge the gap between computer aided design (CAD) and finite element analysis (FEA) and has become popular due to its advantageous approximation properties. In computational contact mechanics the use of IGA offers advantages due to the continuous surface representation and its basis functions, which are greater or equal to zero.[1] Continuity of C^1 or higher restricts the need to treat edge and corner contact to truly geometric features as opposed to edges and corners appearing as the result of a faceted C^0 discretization. Recent advances in computational contact with IGA include multiscale thermomechanical contact [5], large deformation contact using T-splines [6], thermomechanical Mortar contact [7], isogeometric collocation for contact [8], and modeling of solid and liquid membrane contact [9,10].

The construction of volumetric spline meshes is challenging due to the tensor-product nature of the basis that requires hexahedral meshing. Current research explores the mapping to polycubes [11–13] or the use of immersed boundary meshes within the finite cell method [14]. The presented enrichment technique only requires an isogeometric surface representation and avoids the issue of volumetric IGA meshes. This is achieved by connecting the isogeometric surface mesh with a standard Lagrangian finite element volume mesh which can be generated using widely available and existing meshing tools.

Isogeometric analysis has been used with cohesive zone models by Verhoosel et al. [15] with NURBS and T-splines in 2D, by Corbett and Sauer [1] for 2D NURBS-enriched elements, and by Dimitri et al. [16] with NURBS and T-splines in 2D and 3D. Within this work, three-dimensional isogeometrically enriched elements will be analyzed and compared to NURBS and Lagrangian solutions.

[1] Quadratic Lagrange basis functions for example also have negative values. Interpolating a positive value at such a position leads to a negative nodal contribution and can lead to an unphysical solution.