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Fully isogeometric modeling and analysis of nonlinear 3D beams with spatially varying geometric and material parameters

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Abstract

We present a fully isogeometric modeling and simulation method for geometrically exact, nonlinear 3D beams with spatially varying geometric and material distributions, both along the beam axis and through its cross-section. The approach is based on the modeling of 3D beams using the Cosserat rod theory and the numerical discretization using B-Spline and NURBS parameterizations in an isogeometric collocation method. Transversally varying material constitutions are represented using non-homogeneous, functionally graded beam cross-section definitions such as laminates and continuously graded cross-sections. Furthermore, to model the axial variation of material and geometry, we introduce the parameterization of cross-section properties as spline curves along the beam centerlines. This fully isogeometric modeling and analysis concept, which is based on spline parameterizations of initial beam centerline curves, kinematic unknowns and axially varying material and geometric parameters, has various practical applications enabled by advances in manufacturing technology, including multi-material 3D printing and advanced manufacturing of composites with automated fiber placement. We verify and demonstrate the modeling and simulation approach using several numerical studies and highlight its practical applicability.

Keywords: Isogeometric analysis, 3D beams, Spatially varying materials, Functionally graded beams, Collocation method

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1. Introduction

In recent years, many new possibilities for design and manufacturing of slender and light-weight structures have emerged through the advancement of additive manufacturing technologies [1]. Existing and potential applications range from three-dimensionally (3D) printed micro-structures, which can be used to create meta-materials with high strength-to-weight ratios [2, 3], to multi-functional and composite materials with locally defined material properties [4–6] (see Fig. 1a), to active, smart and self-assembling materials and structures, soft robots, and deployable composite space structures, where compliant components need to be designed with tailored large deformation behavior [7–12] (see Fig. 1b). In particular, multi-method and multi-material 3D printing now enable the fabrication of freeform structures with arbitrarily varying material compositions, thus opening new perspectives for design and application of spatially varying and composite materials.

Modeling and design of these structures, especially when they are made from soft materials and subject to large deformations, calls for advanced simulation methods and computer-aided engineering tools that can efficiently incorporate the complex material constituency. Thus, there is a demand for nonlinear modeling

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