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Christoph Meier, Alexander Popp, Wolfgang A. Wall

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A Finite Element Approach for the Line-to-Line Contact Interaction of Thin Beams with Arbitrary Orientation

Christoph Meier[a], Alexander Popp[a,*], Wolfgang A. Wall[a]

[a] Institute for Computational Mechanics, Technische Universität München, Boltzmannstrasse 15, D–85748 Garching b. München, Germany

Abstract

The objective of this work is the development of a novel finite element formulation describing the contact interaction of slender beams in complex 3D configurations involving arbitrary beam-to-beam orientations. It is shown in a mathematically concise manner that standard beam contact models based on a point-wise contact force fail to describe a considerable range of configurations, which are, however, likely to occur in practical applications. On the contrary, the formulation proposed here models beam-to-beam contact by means of distributed line forces, a procedure that is shown to be applicable for arbitrary geometrical configurations. The proposed formulation is based on a Gauss-point-to-segment type contact discretization and a penalty regularization of the contact constraint. By means of detailed theoretical and numerical investigations, it is shown that this approach is more suitable for beam contact than possible alternatives based on mortar type contact discretizations or constraint enforcement by means of Lagrange multipliers. The proposed formulation is enhanced by a consistently linearized integration interval segmentation avoiding numerical integration across strong discontinuities. In combination with a smoothed contact force law and the employed C^1-continuous beam elements, this procedure drastically reduces the numerical integration error, an essential prerequisite for optimal spatial convergence rates. The resulting line-to-line contact algorithm is supplemented by contact contributions of the beam endpoints, which represent boundary minima of the underlying minimal distance problem. Finally, a series of numerical test cases is analyzed in order to investigate the accuracy and consistency of the proposed formulation regarding integration error, spatial convergence behavior and resulting contact force distributions. For one of these test cases, an analytical solution based on the Kirchhoff theory of thin rods is derived, which can serve as valuable benchmark for the proposed model but also for future beam-to-beam contact formulations. [...]

Keywords:
Beam contact, Line-to-line contact, Thin fibers, Finite elements, C^1-continuous Kirchhoff beams

1. Introduction

There exist many fields of application, where mechanical system behavior is crucially determined by slender fiber- or rod-like components. In technical applications, such fibers occur for example in industrial webbings, high-tensile ropes and cables, fiber-reinforced composite materials or synthetic polymer materials. Furthermore, also the fibers in biological systems such as muscles and biological tissue or the filaments in biopolymer networks [5] can be identified as slender mechanical components of this type. In most cases, these fibers can be modeled with sufficient accuracy by applying a 1D beam theory. In the last three decades, many different types of beam element formulations have been proposed in order to discretize such beam models by means of the finite element method. In his recent contribution [31], Romero points out the excellent performance of one specific category of beam elements denoted as geometrically exact beam formulations. While most of the geometrically exact beam formulations available in the literature are of Simo-Reissner type (see e.g. [4, 10, 12, 30, 32, 33, 34, 35, 41]), thus incorporating the modes of axial tension, shear, torsion and bending, in our recent contributions [23] and [24], a shear-free formulation based

*Corresponding author
Email address: popp@lnm.mw.tum.de (Alexander Popp)