ICCCM 2023

VII International Conference on Computational Contact Mechanics

July 5 - 7, 2023 - Torino, Italy

Book of abstracts

Virtual element methods and higher order penalty-based Node-to-Segment contact

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Keywords: Virtual element method, node-to-segment contact.

The virtual element method is a generalization of the finite element method for polytopal shapes and arbitrary convergence order. Almost a decade has passed since its first introduction [1], and it has been used for many applications where finite element methods dominated, especially those where geometrical versatility of the elements was welcome. One such case is contact, where a whole novel approach for Node-to-Node contact has been proposed based on this method for both 2D [2] and 3D [3].

Whereas new approaches are certainly valuable contributions to the state-of-art, investigating the use of new tools for approaches that, despite their flaws, have stood up to the test of time, can also lead to unexpected results and insights.

In this case, by approaches the authors refer to the penalty-based Node-to-Segment (NTS) method. This contact scheme can be found in literature as early as 1976 [4], representing a departure from Node-to-Node schemes where the contact location was required *a priori*. Although more modern (and mathematically sounder) approaches are now available (*e.g.*, Mortar methods), the Node-to-Segment is still widely found in commercial finite element analysis software and employed by the industry due to its low computational cost and sufficient accuracy for the intended purposes, justifying the interest in penalty-based formulations, which does not add degrees of freedom to the system.

A modern detailed formulation of NTS can be found in [5]. The method is inherently flawed by its asymmetrical treatment of the contact surfaces, this affects its capacity to provide a discrete contact contribution to the problem's weak formulation consistent with the adjacent continuum discretization, which becomes evident in its patch test performance [6]. In the last years, some modifications of the method have been proposed such that the patch test is passed for first-order interpolations, *e.g.*, virtual node schemes [7] and, more recently, an improved area regularization scheme [8]. Nevertheless, these approaches focus only on first order elements and guarantee consistency of the contribution only for uniform contact pressure, on other cases (*e.g.*, Hertz contact) the solution is still inconsistent. For quadratic polynomial onward, a new source of incompatibility on the treatment of the surfaces comes into play: the different weights associated with extremities and in-edge nodes when computing the equivalent nodal load for a distributed load over the segment.

This work presents another outlook on improving the stresses from Node-to-Segment contact schemes, for first and higher order elements. Assuming the method's incompatibility as something cannot not be fixed without losing the simplicity which makes it attractive, the authors aim at reducing the consequent oscillations in the stresses at element scale. This is done not by changing the contact scheme, but the formulation of contact-adjacent elements from finite to virtual.

The reduction of intra-element oscillations in the stresses is a consequence on how stress results are visualized with the virtual element methods, *i.e.*, by taking the polynomial projection of the solution. This projection effectively acts as a filter on these oscillations. This filtering effect may vary with the characteristics of the element used in the contact region, polygonal elements with over 5 sides have shown the best results.

In Figure 1, one can see a detail of the minimum principal stress on contacting cylinders in a plane-strain linear elastic model, such that the minimum stress according to Hertz's theory should be -669.

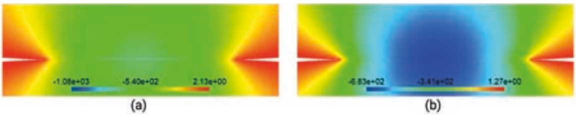

Figure 1: Minimum principal stress (σ_3) for contacting cylinders in plane strain linear elasticity with (a) quadratic triangular finite elements and (b) quadratic polygonal virtual elements

In the conference, a discussion and more examples of this filtering behavior will be provided, showing its potential benefits while post-processing stresses stemming from contact interactions.

This work was funded in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, and supported by Vale S.A. through the Wheel-Rail Chair project.

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