Efficient mixed rod finite elements for rockfall protection ring-net barriers with frictional contact

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The protection of human infrastructure against natural hazards has become a major engineering challenge, particularly under the increasing impact of climate change. Among these hazards, rockfall poses severe risks to settlements, transportation routes, and critical infrastructure. Consequently, substantial effort is devoted to improving rockfall protection systems, including flexible ring-net barriers. To satisfy economic constraints and support optimal design, reliable numerical predictions of ring-net behavior have become indispensable, as illustrated in Figure 1.

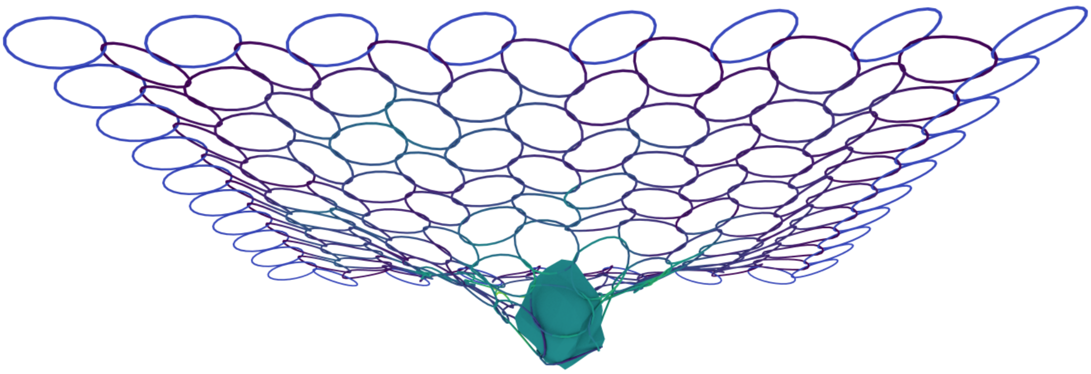

Figure 1: Numerical simulation of a rock impacting a rockfall protection ring net.

For the efficient numerical simulation of such highly deformable structures, we employ nonlinear rod finite elements as proposed in [1]. The formulation is based on a mixed finite element method [2] derived from the Hellinger–Reissner principle. A particularly efficient discretization is obtained using linear Lagrange interpolation with one-point quadrature for the internal forces, combined with a trapezoidal rule for dynamic and external contributions. To enhance performance further, the generally nonlinear internal force laws are differentiated in time, yielding an evolutionary system of equations. This allows the kinematics, dynamics, and internal forces to be integrated within a unified framework.

A complete description of the net-rock interaction requires an accurate treatment of frictional contact. For this purpose, the rod finite elements are embedded into the nonsmooth dynamics framework, resulting in a measure differential inclusion. The latter is discretized using a variant of Moreau's mid-point rule [3], adapted to the mixed rod finite element formulation with frictional contact and impacts.

Numerical experiments confirm the efficiency, robustness, and conceptual simplicity of the proposed method, demonstrating its suitability for large-scale simulations of ring-net rockfall protection systems.

References

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[2] F. Brezzi and M. Fortin. *Mixed and Hybrid Finite Element Methods*. Springer New York, New York, NY, 1991.

[3] J. J. Moreau. Unilateral Contact and Dry Friction in Finite Freedom Dynamics. 1988.