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dynLattice: A finite element environment for dynamic simulation of beam networks and lattice metamaterials

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Software

- Review
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Summary

Beams and beam structures undergoing fast deformation often experience large strains and inelastic material behavior. Understanding this behavior enables engineers and designers to design beam networks resulting in so-called mechanical metamaterials. Metamaterials offer unique properties not found in naturally occurring materials. Harnessing these properties presents new possibilities for a wide range of fields (Davies et al., 2025; Jiao et al., 2023). In order to enable engineers to design mechanical metamaterials, the relation between the geometry of the beam network and the resulting properties needs to be understood. For large deformations at high rates, this usually requires destructive testing, limiting the speed of developments. This limitation can be overcome using efficient numerical tools, allowing for both the accurate and fast description of the inelastic deformation at high rates (Bonfanti et al., 2024).

Software Description

In order to design metamaterials undergoing large deformations at high rates, dynLattice provides both researchers and engineers in the field a toolkit for numerical experiments. dynLattice is built on top of the openly available C++ `JIVE` finite element toolkit (Dynaflow Research Group, 2021; Nguyen-Thanh et al., 2020). This toolkit allows for the implementation of original methods through the development of custom *modules*, for parts of the program flow in the simulation framework, and of custom *models*, for anything related to the numerical representation of the system of partial differential equations. In the present addition to the `JIVE` framework, the *models* further contain a separate *materials* class, representing the constitutive models considered in the problem. This separation allows both the easy and user-friendly extension of the frameworks by simple inheritance of the provided classes as well as usability by structuring the inputs needed for the program flow and the problem description. dynLattice additionally uses `GMSH` (Geuzaine & Remacle, 2009) to mesh the imported geometries efficiently.

Statement of need

There is a wide plethora of existing finite element toolkits available in the market, such as MOOSE (Lindsay et al., 2022), FEniCS (Baratta et al., 2023), or deal.II (Arndt et al., 2023), to name several prominent ones. The usage of these libraries for explicit dynamics with inelastic beams however, would require substantial alteration of their code, as for example in FEniCS explicit dynamics is only available using lumped mass matrices, which would be nonphysical for the rotational inertia contributions of the beams, in deal.II neither beam elements nor explicit solves are available and in MOOSE only a limited Timoshenko-Ehrenfest beam is implemented with only elastic behavior. Other finite element toolkits having built in beam-elements and explicit dynamics include Kratos (Dadvand et al., 2010; Ferrándiz et al., 2025) and Akantu (Richart et al., 2024). For Kratos similar problems as for MOOSE can be seen in only a limited set of beam elements being available and none supporting inelastic behavior in the cross-sectional strain measures. Akantu, focusing on fracture mechanics and providing a solid representation of contact, on the other hand only provides Euler-Bernoulli beam elements, neglecting all shear deformation within the elements.

Background

The following is a short description of the beam kinematics and cross-sectional kinetics implemented in this software, with a more detailed description given in (Gärtner, 2025).

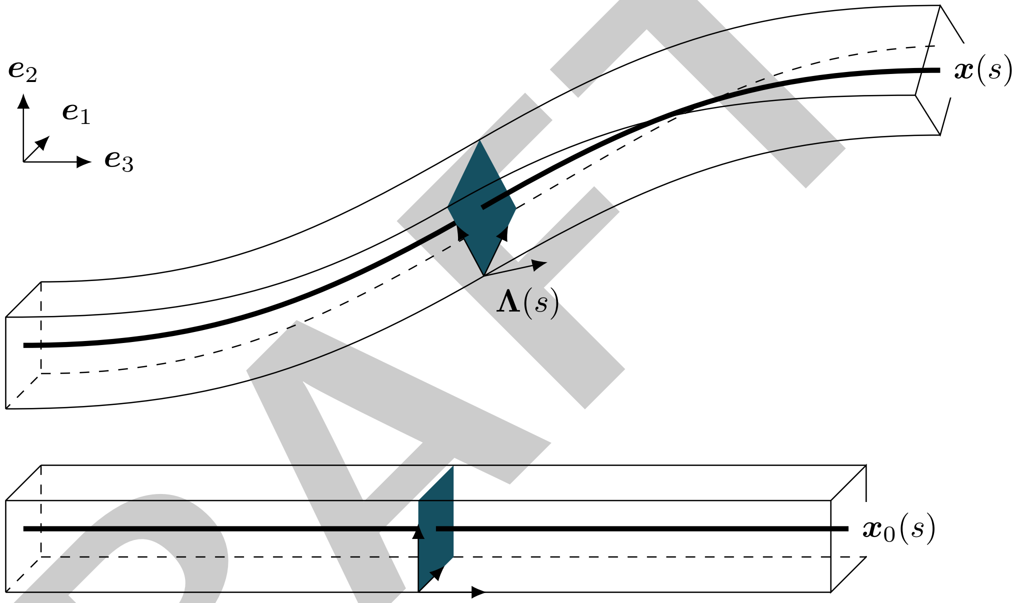

Figure 1: A beam undergoing large deformation.

In Figure 1, a beam undergoing large deformation is shown. A beam is described with the centerline $\mathbf{x}(s)$, where $s \in [s_0, s_1]$ is the measure along the length of the beam, with two orthonormal directors attached to it $\mathbf{d}_1(s), \mathbf{d}_2(s)$. Together with a third orthonormal director $\mathbf{d}_3(s) = \mathbf{d}_1(s) \times \mathbf{d}_2(s)$, these are the column vectors of the rotation matrix between the global reference frame and the local coordinate frame of the beam:

$$\Lambda(s) = \mathbf{d}_i(s) \otimes \mathbf{e}_i = \begin{bmatrix} \mathbf{d}_1(s) & \mathbf{d}_2(s) & \mathbf{d}_3(s) \end{bmatrix}.$$

From these measures, strain prescriptors, describing stretching, shearing, bending, and twisting of the beam can be derived. These strain prescriptors are then used together with the material model of the beam, be it elastic (cf. (Eugster, 2015; Simo & Vu-Quoc, 1986)) or elasto-plastic (cf. (Gärtner, van den Boom, et al., 2025a; Herrnböck et al., 2022; Smriti et al., 2021)), to assemble the global force vector and—in the static, implicit case—the tangent stiffness matrix using standard finite element procedures.

Publications

dynLattice has already been used in a series of publications (Gärtner et al., 2024, 2025a, 2025b; Gärtner, Dekker, et al., 2025) and laid the foundation for several student theses (IJzendoorn, 2024; Niessen, 2022; Smit, 2024). During these efforts it was used both on big computational clusters ((DHPC), 2024) and on various local machines using the provided `apptainer`.

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