Structural stability of a Mitotic Spindle: parametric Finite element approach

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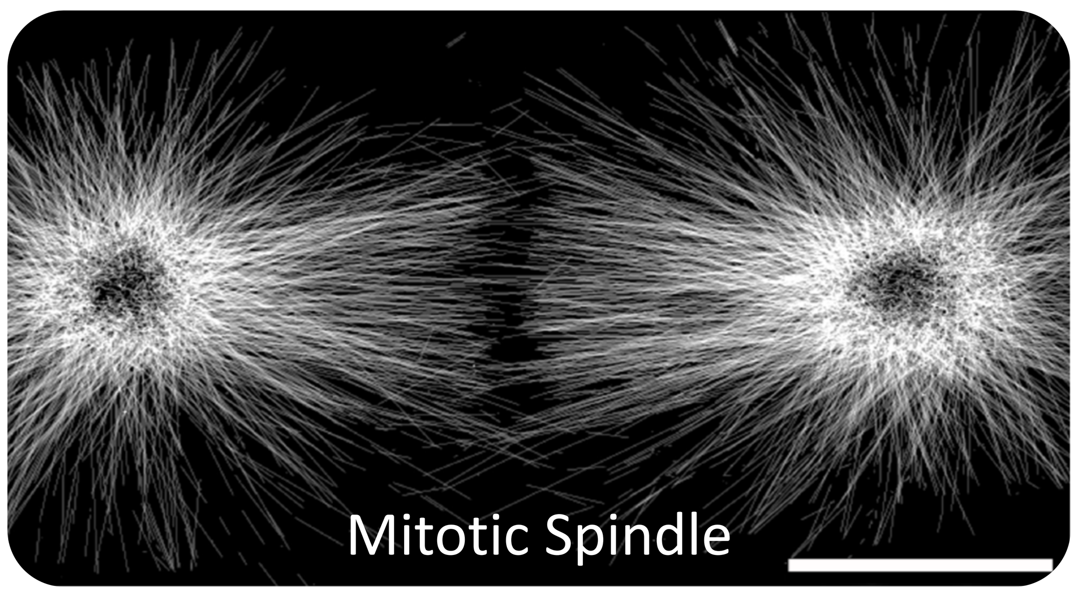
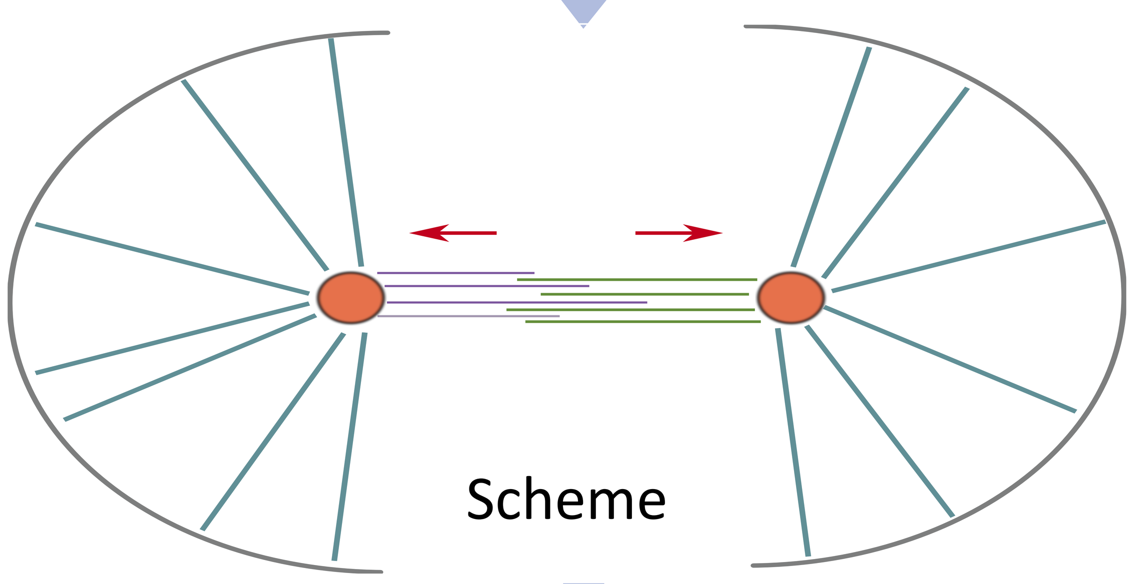
Spindle FEA workflow

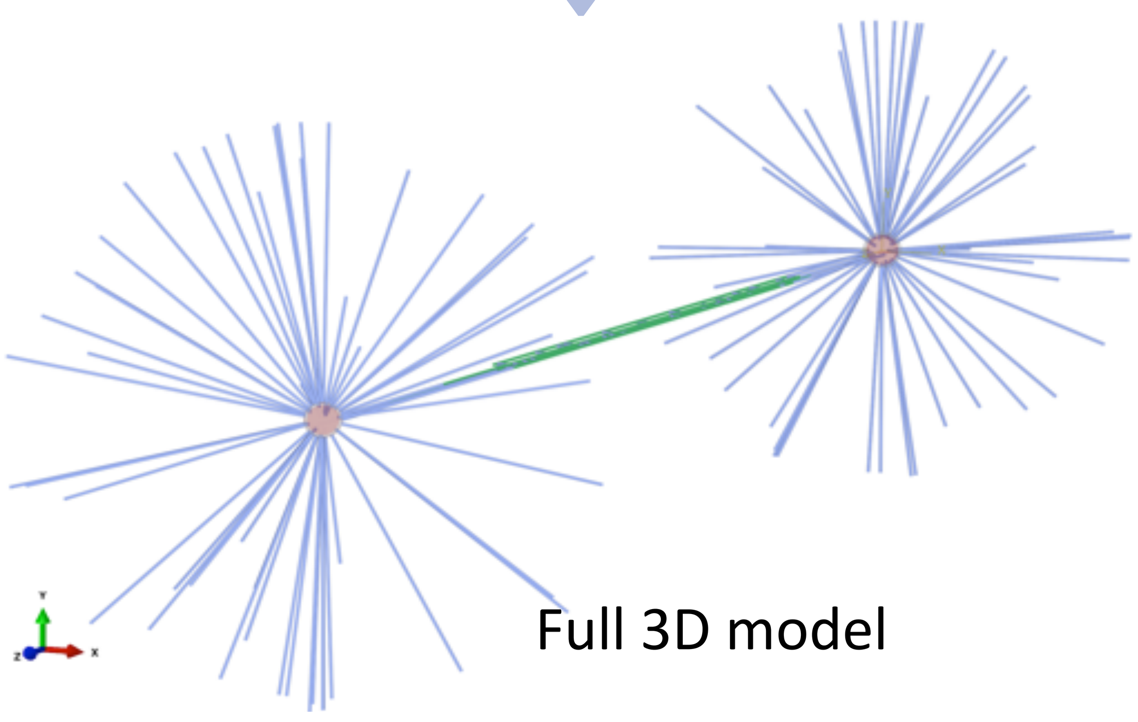
A



B

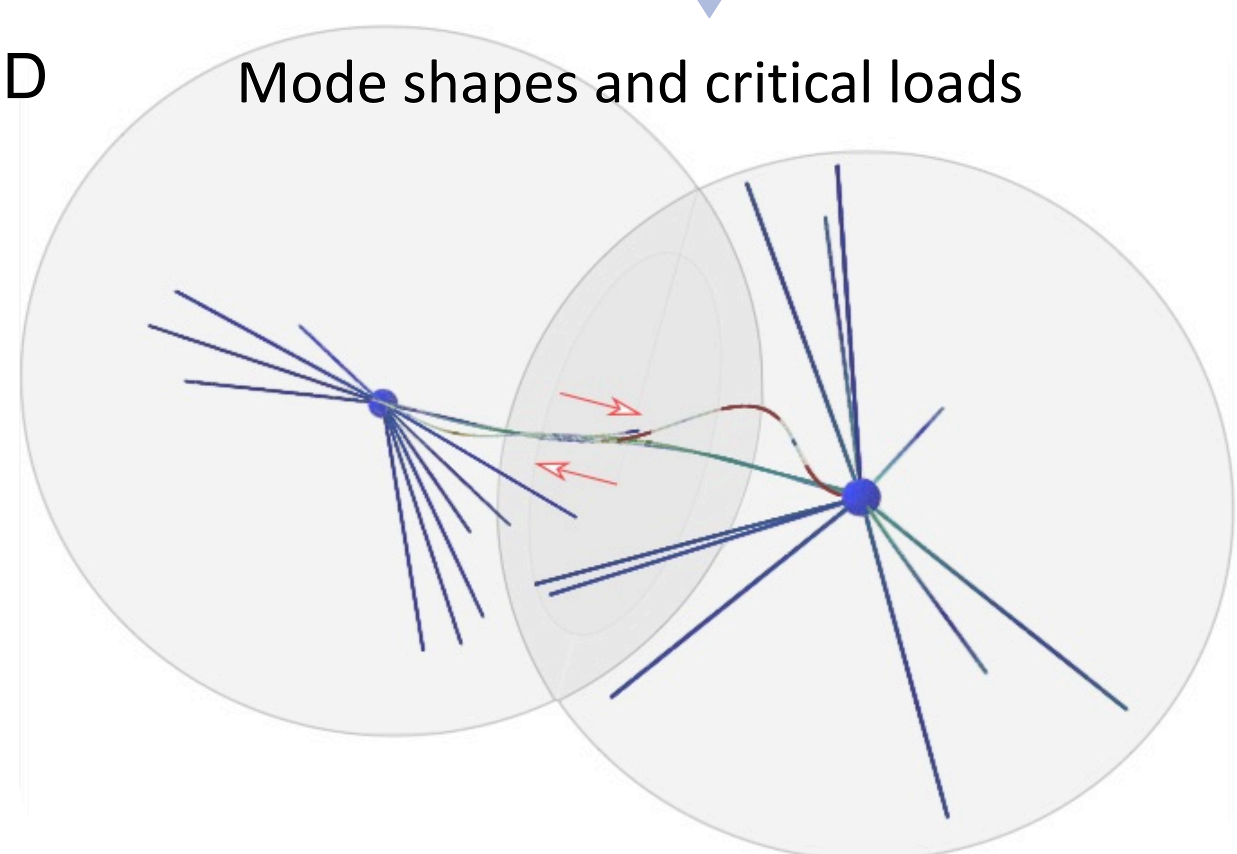


C



Linear buckling analysis

D



The main workflow of the Spindle FEA application. The spindle architecture (A) is adapted from [1]. It is schematically presented in (B). Based on the hierarchical scheme, a 3D model of the spindle (C) is generated by Spindle FEA. Material properties, coupling between members, loading and boundary conditions are specified. The analysis input file is created and submitted to Abaqus FE solver for linear buckling analysis. The critical buckling loads with associated spindle deformed configurations (D) are computed during the analysis step.

Spindle FEA application

Spindle FEA is a software developed by the authors based on the principles of continuum mechanics and finite element analysis (FEA) to perform parametric modelling of the elastic stability of mitotic spindles for various cell types in different stages of mitosis.

The application is capable of studying the mitotic spindle as a whole taking into account the structure and properties of spindles and their parts.

Structural assumptions

1. Centrosomes, MTs and MT connectors are modelled as elastic bodies.
2. Microtubules (MTs) are modelled as long slender hollow filaments. Inter-polar MTs are connected using a large number of randomly distributed cross-linkers to form an assembly.
3. Astral MTs connect poles to the membrane and support them within a cell. Growing ends of aMTs are fixed when connecting to the membrane.

Physical assumptions

1. The mitosis is assumed to develop slowly in time supporting a quasi-static loading assumption.
2. The model of the MTs and connectors is based on linearly elastic isotropic Bernoulli-Euler beam.
3. All parts of the spindle are elastically coupled.
4. Linear or modal buckling analysis is performed and critical buckling loads, as well as the associated modes, are obtained. Any post-buckling is ignored.

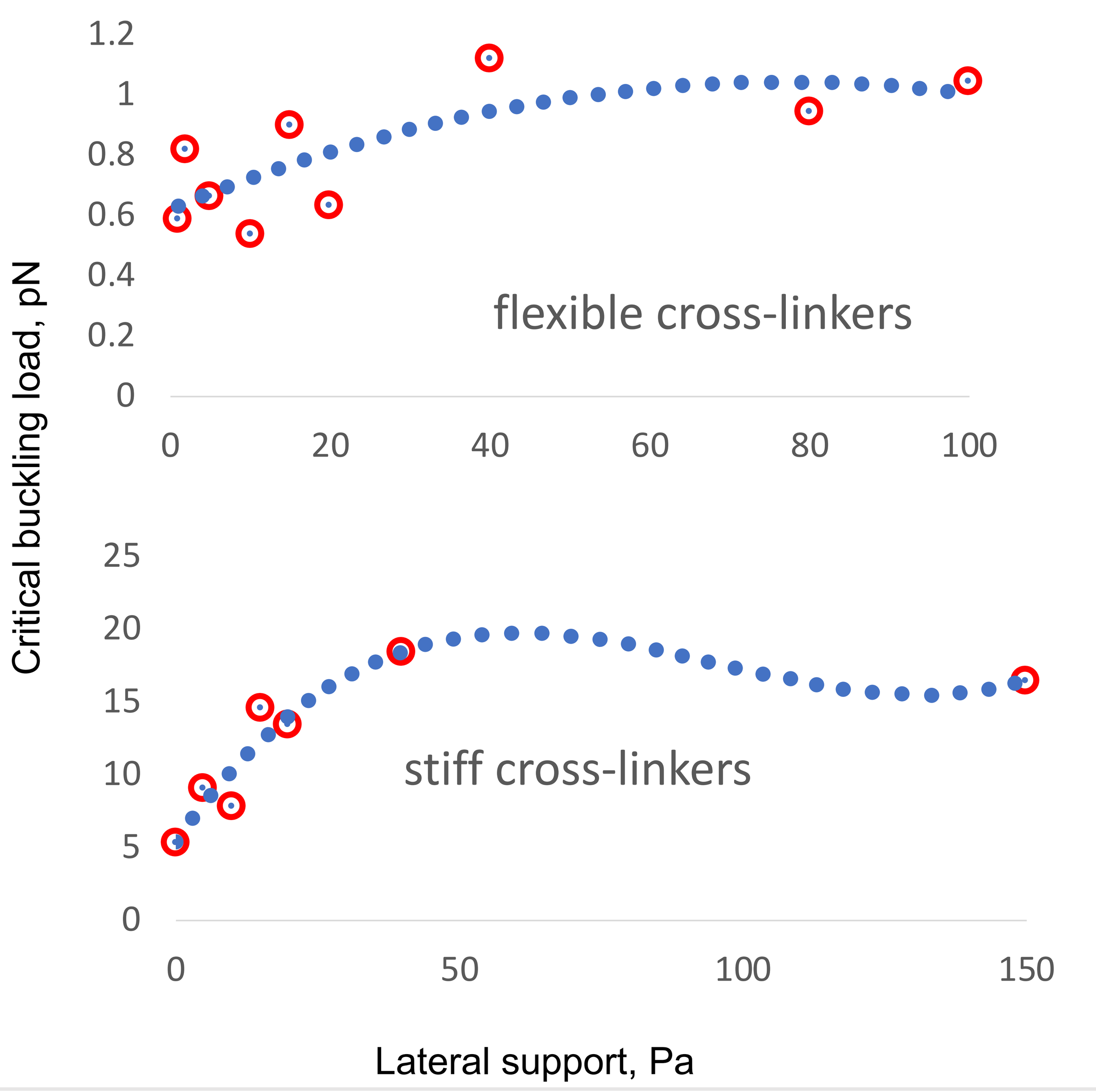
Advantages of Spindle FEA

Any physical or structural properties of the spindle can be easily adjusted in the job.py file of the application.

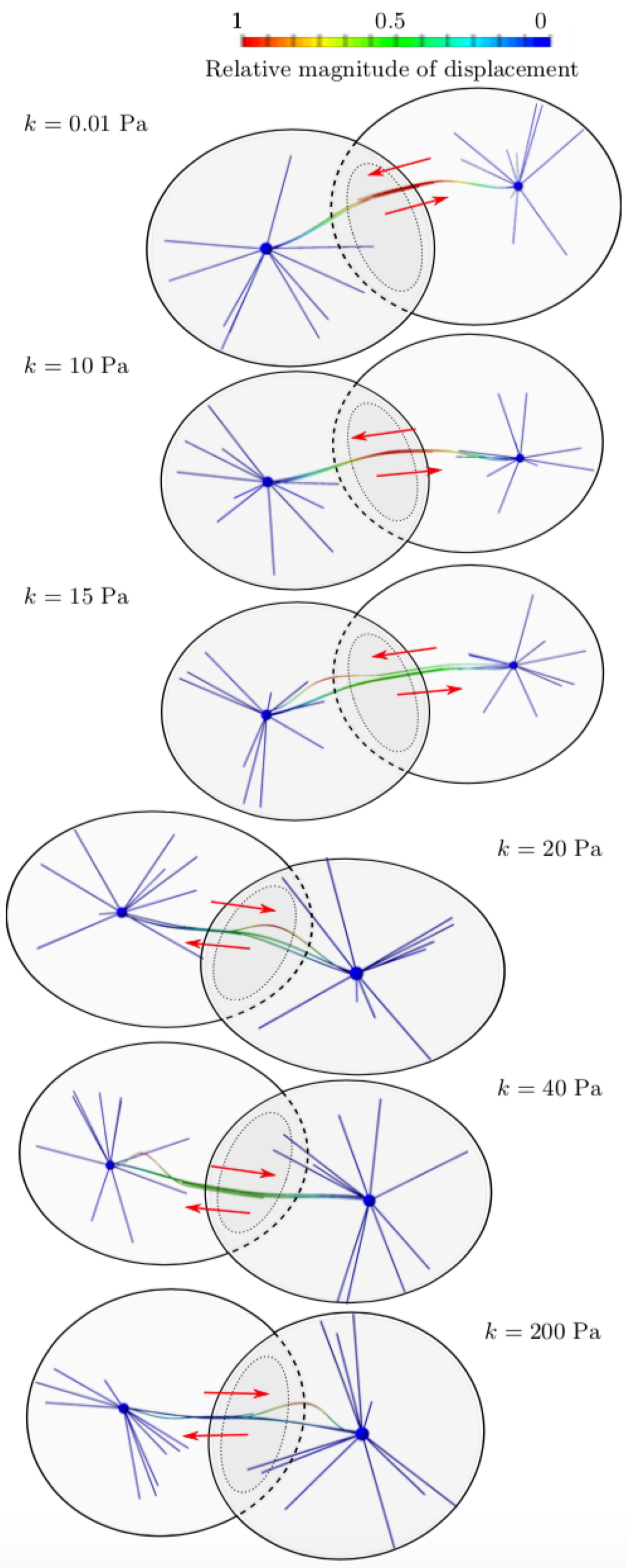
Parametric studies of spindle buckling can be easily performed by varying one or many parameters specified within job_parametric.py file.

Non-linear material models, post-buckling analysis, orthotropic models of the MTs and other may be incorporated through provided Python modules.

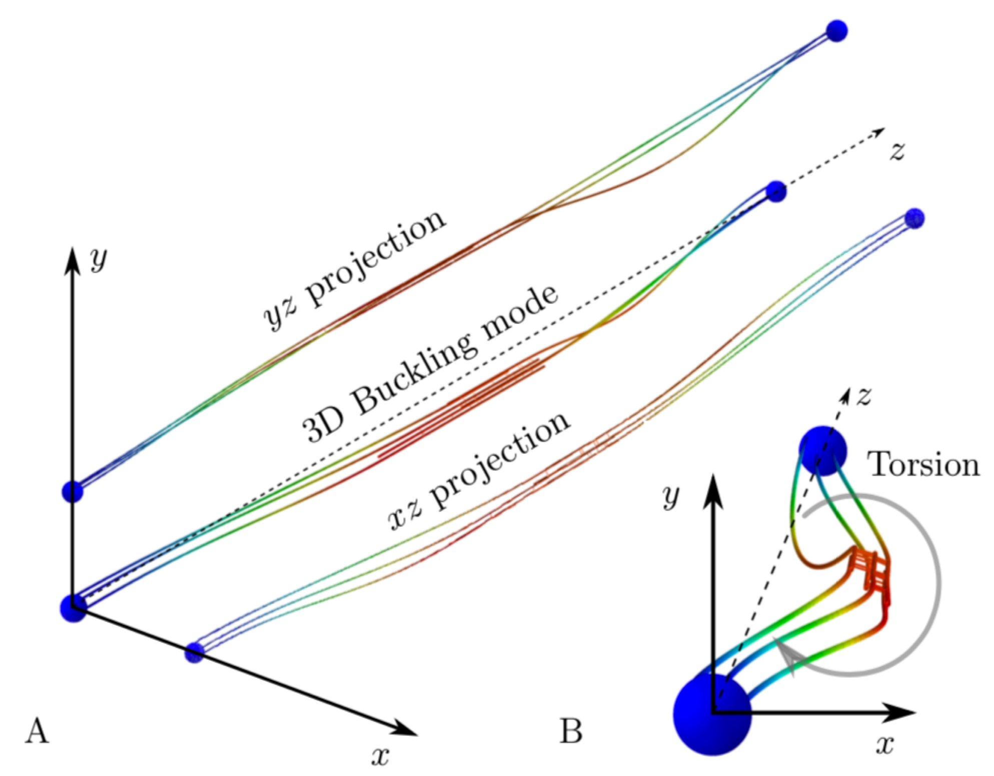
Spindle forces vs. lateral support stiffness



Localisation of spindle deformation



Bending-torsion coupling in 3D modes



A 3D buckling mode of the inter-polar MT bundle. Projections of 3D buckling mode on XZ and YZ plains as well as the isometric view of the inter-polar bundle show a twisted cross-section for large lateral support stiffness.

References

[1] Müller-Reichert, T., Kiewisz, R., Redemann, S., 2018. Mitotic spindles revisited – new insights from 3D electron microscopy. Journal of Cell Science 131, jcs211383.

[2] Ward, J.J., Roque, H., Antony, C., Nédélec, F., 2014. Mechanical design principles of a mitotic spindle. eLife 3, e03398. https://doi.org/10.7554/eLife.03398

Spindle FEA links

https://git.soton.ac.uk/ai1v14/SpindleFEA

http://doi.org/10.5258/SOTON/D0603 (will be live soon)

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