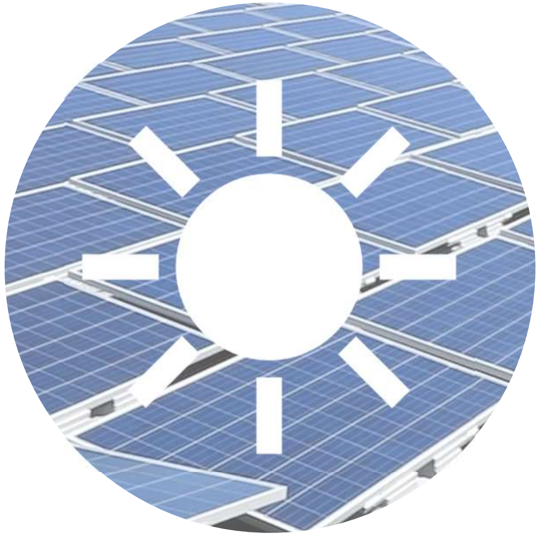
Ocean Energy

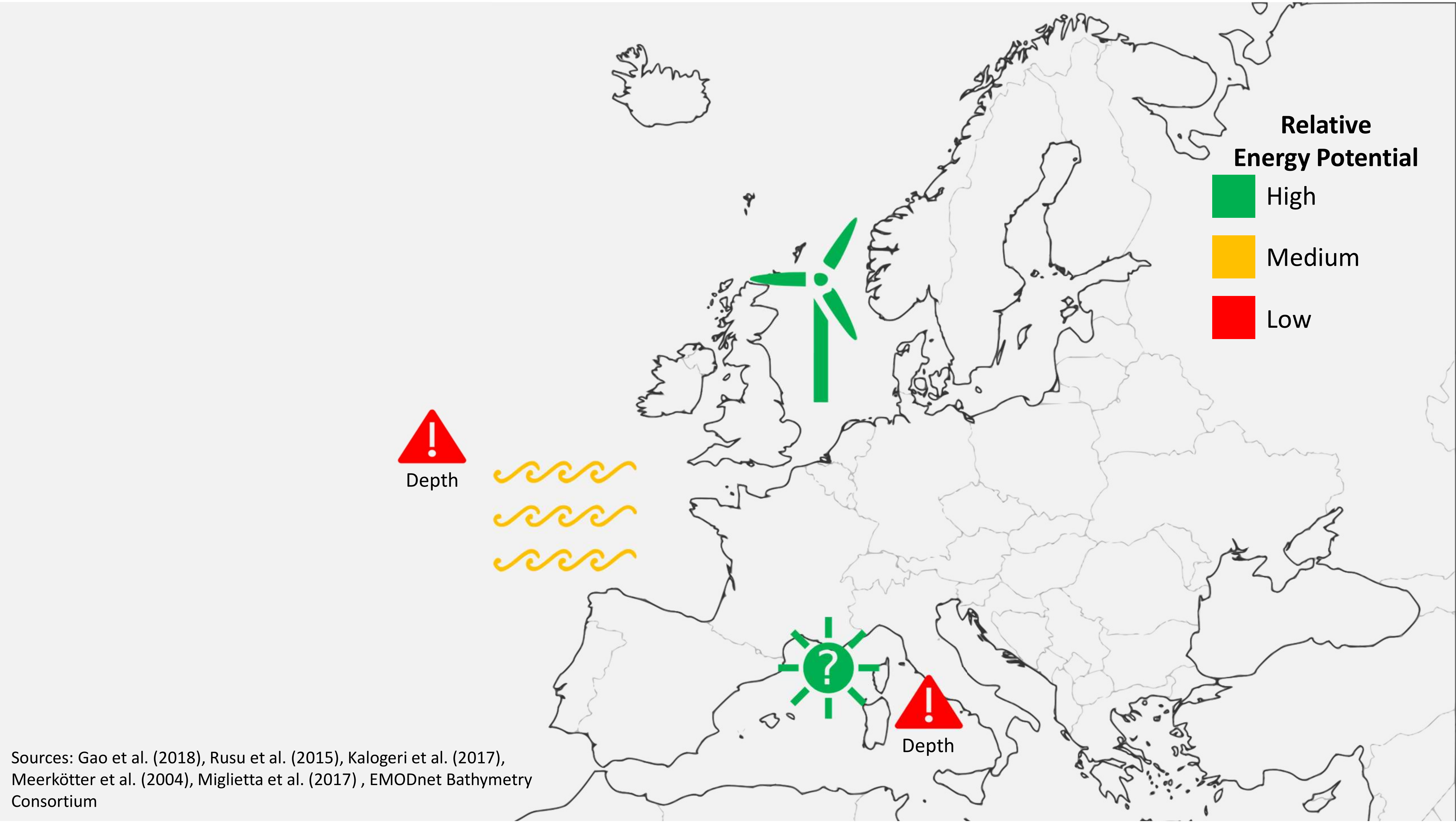
Wave



Solar

Tidal

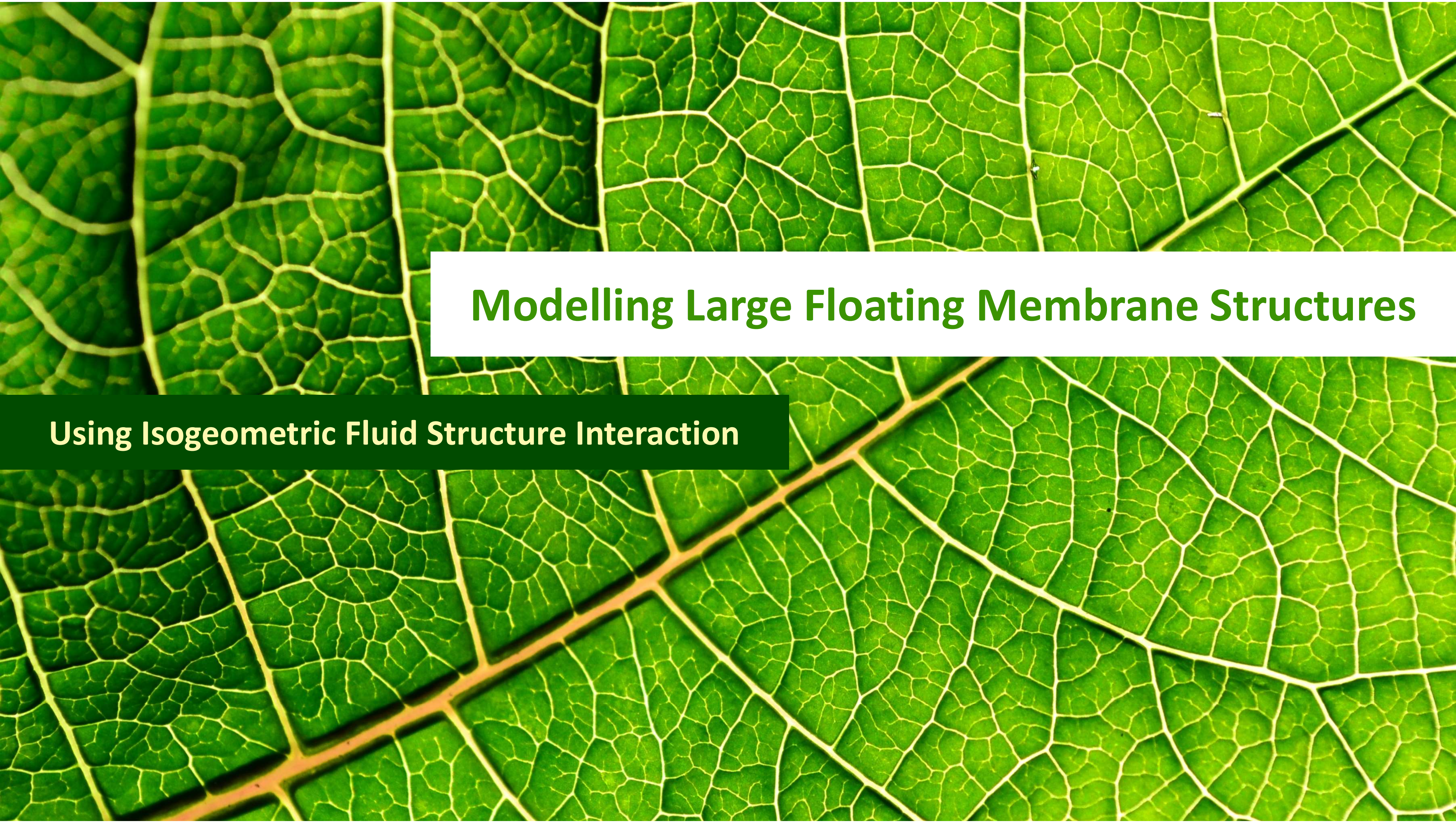
Wind



Sources: Gao et al. (2018), Rusu et al. (2015), Kalogeri et al. (2017), Meerkötter et al. (2004), Miglietta et al. (2017) , EMODnet Bathymetry Consortium

Modelling Large Floating Membrane Structures

Using Isogeometric Fluid Structure Interaction



Outline

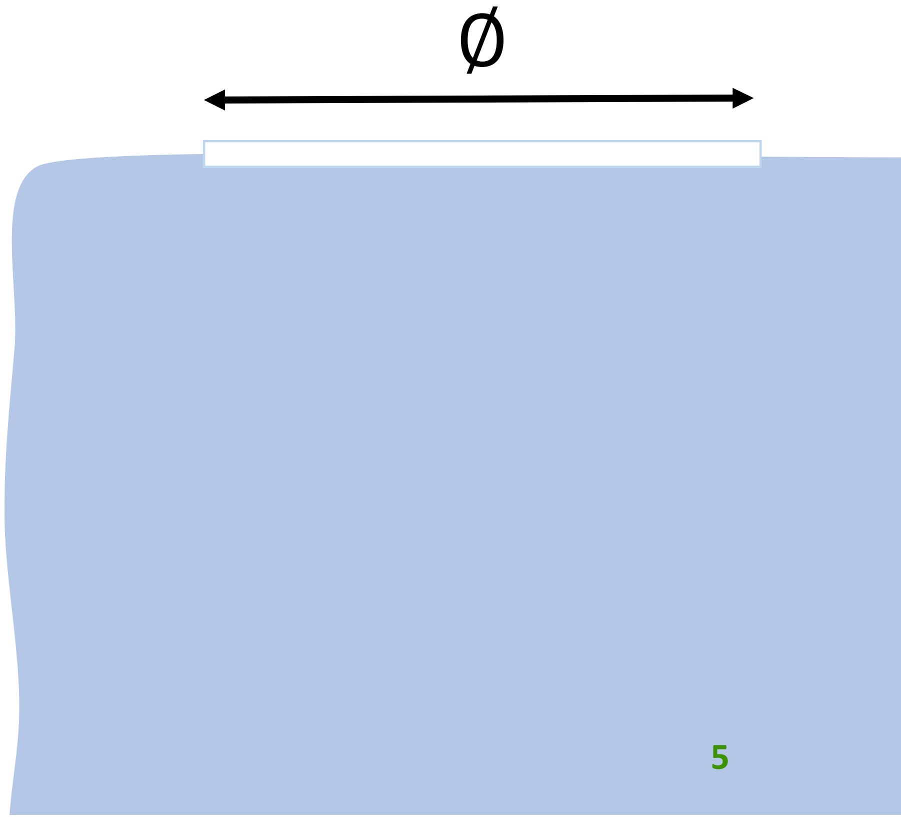
1. Introduction
2. Literature Review
3. Numerical Models
   a. Beam Model
   b. Shell Model
   c. Fluid Models
   d. Fluid-Structure Interaction
4. Results and Discussion
5. Application: Wrinkling and Folding
6. Conclusions & Recommendations

Introduction - Characteristics

Ø ≈1-10 km

Flexible and continuous

Light-weight



Introduction - Goal

"Develop and implement a **Fluid-Structure Interaction** framework using **Isogeometric Analysis** for application for offshore membrane structures, with emphasis on **structural failure modes**."

Literature Review - VLFSs

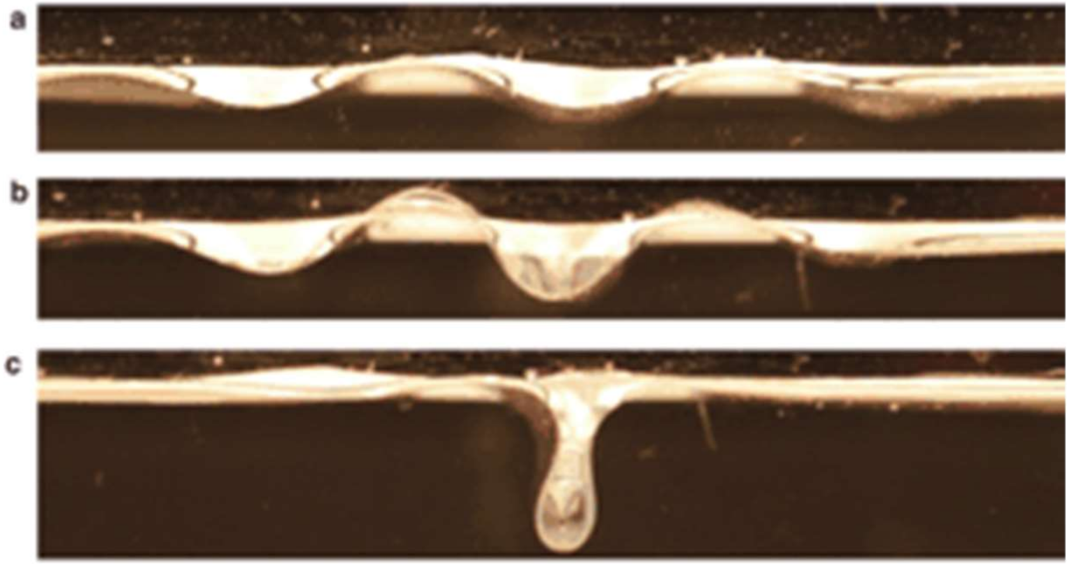
Very Large Floating Structures (VLFSs)

- Work by Kashiwagi et al. in the early 2000s using **modal expansions** and **potential flow**. The structure is governed by **linear Euler-Bernoulli beam theory**.
- Further works include **time-domain** methods and **FEM-BEM** coupling in the **frequency domain**.
- However, in all cases; **limited wave heights** and **linear structural behaviour** are used.

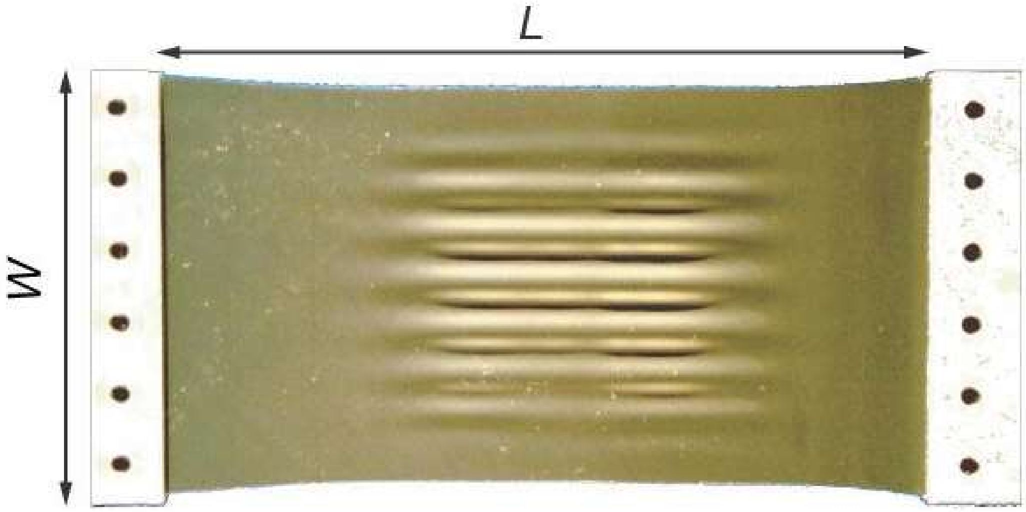
Literature Review – Wrinkling/Folding

- Occurs when a **thin membrane** supported by a **substrate** is under in-plane compressive loading.
- **State-of-the-art:**
  - Mathematical model based on **uniform, inextensible membrane** on **linear substrate**
  - Experimental results
  - Limited numerical studies
  - All unidirectional load cases

Literature Review – Wrinkling/Folding



Compressive Force
Elastic/Liquid foundation



Tensional force
No Foundation

Sources: Pocivavsek et al. (2008), Cerda et al. (2002)

Literature Review - FSI

Weakly Coupled FSI

Characteristics:

- Large structural stiffness
- $\rho_{\text{structure}} \gg \rho_{\text{fluid}}$

Applications:

- Aero/Hydro-elasticity

Coupling:

- One-way Partitioned, Analytical

Strongly Coupled FSI

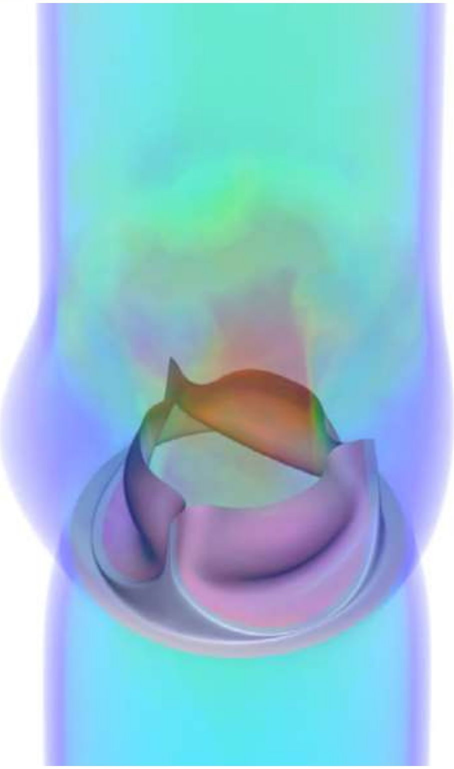
Characteristics:

- Flexible structures
- $\rho_{\text{structure}} \approx \rho_{\text{fluid}}$

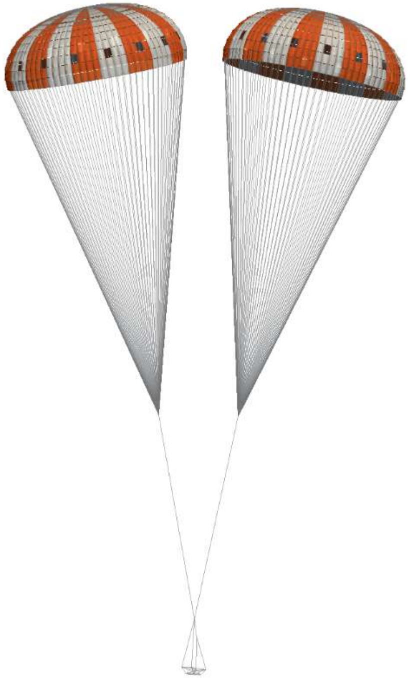
Coupling:

- Iterative Partitioned or Monolithic

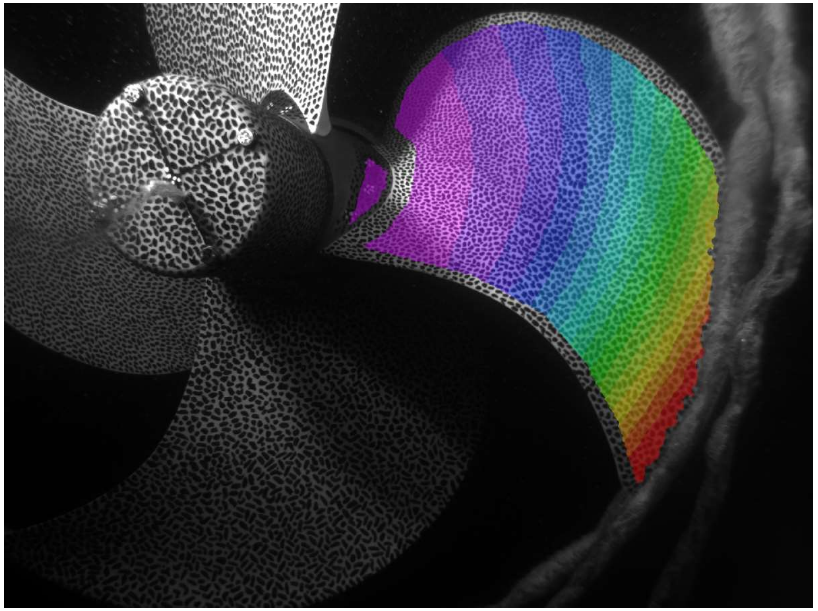
Literature Review - FSI



Cardiovascular Biology



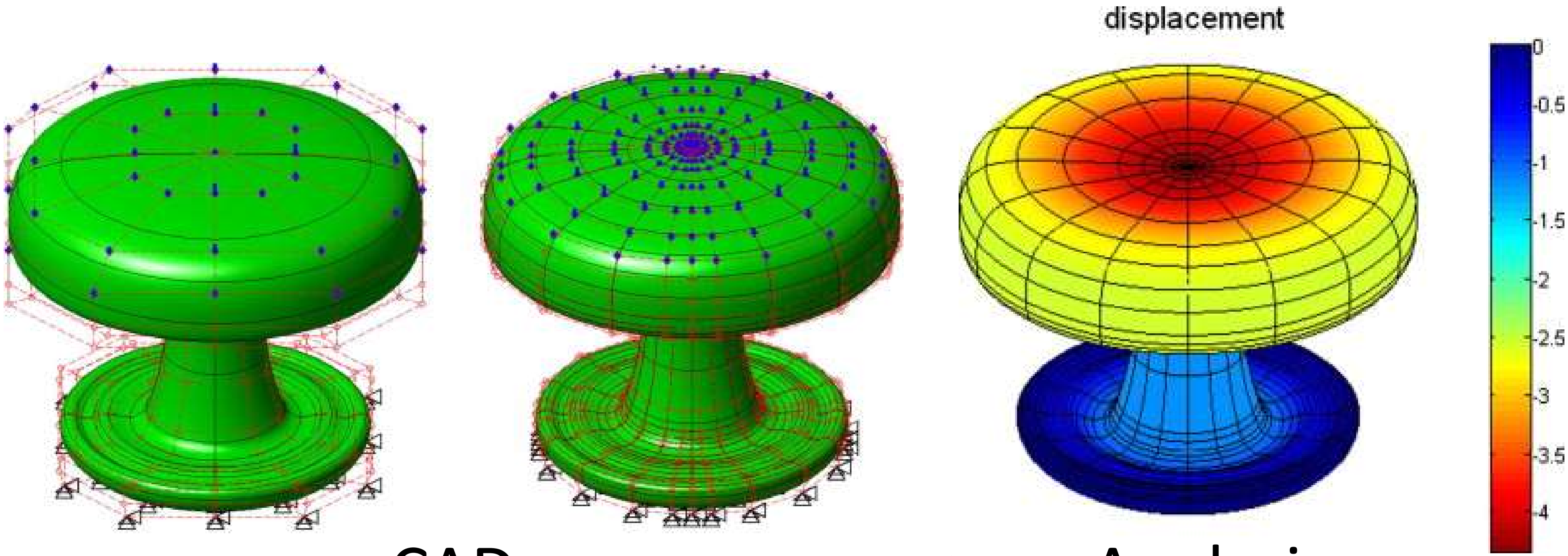
Parachute/Sail design



Maritime/Aeronautical Engineering

Sources: Hsu et al. (2015), Takizawa et al. (2013), Maljaars et al. (2018)

Literature Review - IGA



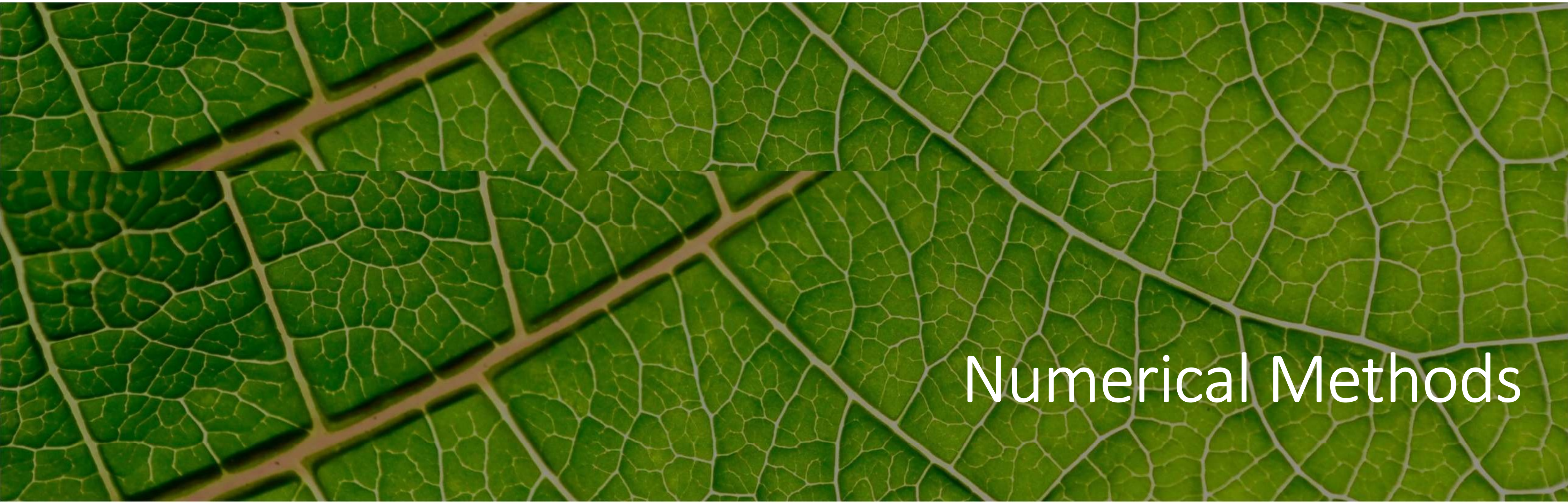
CAD → Analysis

Source: Kiendl et al. (2009)

Literature Review - IGA

State-of-the-art:

- **Reissner-Mindlin** and **Kirchhoff-Love** shells implemented. Including plasticity, instability, vibrations, assemblies etc. including different **material models**
- Several fluid descriptions included
- Strongly and Weakly coupled **FSI applications**, mostly with real flow.
- eXtended IGA (XIGA), Spectral Stochastic IGA (SSIGA) developed



Numerical Methods

Beam Model

Key Features:

- ✓ Pinned, Clamped, Rolled supports
- ✓ (Following) Force, Moment, (Following) Pressure loads
- ✓ Isogeometric basis
- ✓ Forward/Backward Euler, Trapezium, Newmark, Bathe, RK/ERK/ESDIRK time integration methods
- ✓ Curvilinear geometry based on (NUR)B-splines
- ✓ **Verified all of the above** using manufactured solutions in space and time, analytical solutions, benchmarks for curvilinear system (Cazzani et al.) and theoretical results on vibrations.
- ✓ Initial vertical deflection can be added

Work in progress:

- ○ Nonlinear beam on foundation to observe **wrinkling**

Python

TU Delft

Shell Model

Shell model available in **G+smo** library (C++)

Additional features developed:

✓ Mass matrix debugged

✓ Time integration for linear and nonlinear shell

✓ Application of (non-following) pressures

To be developed:

○ (Following pressure)

○ Validation time integration

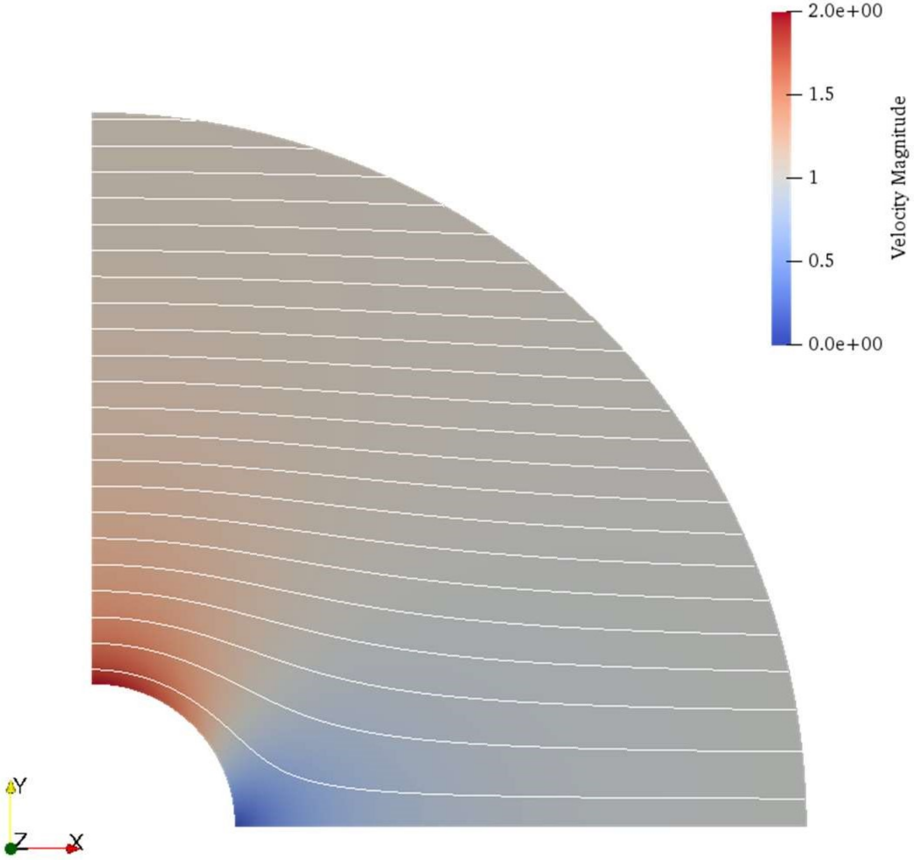
G+smo
(C++)

Flow Model

Available fluid models:

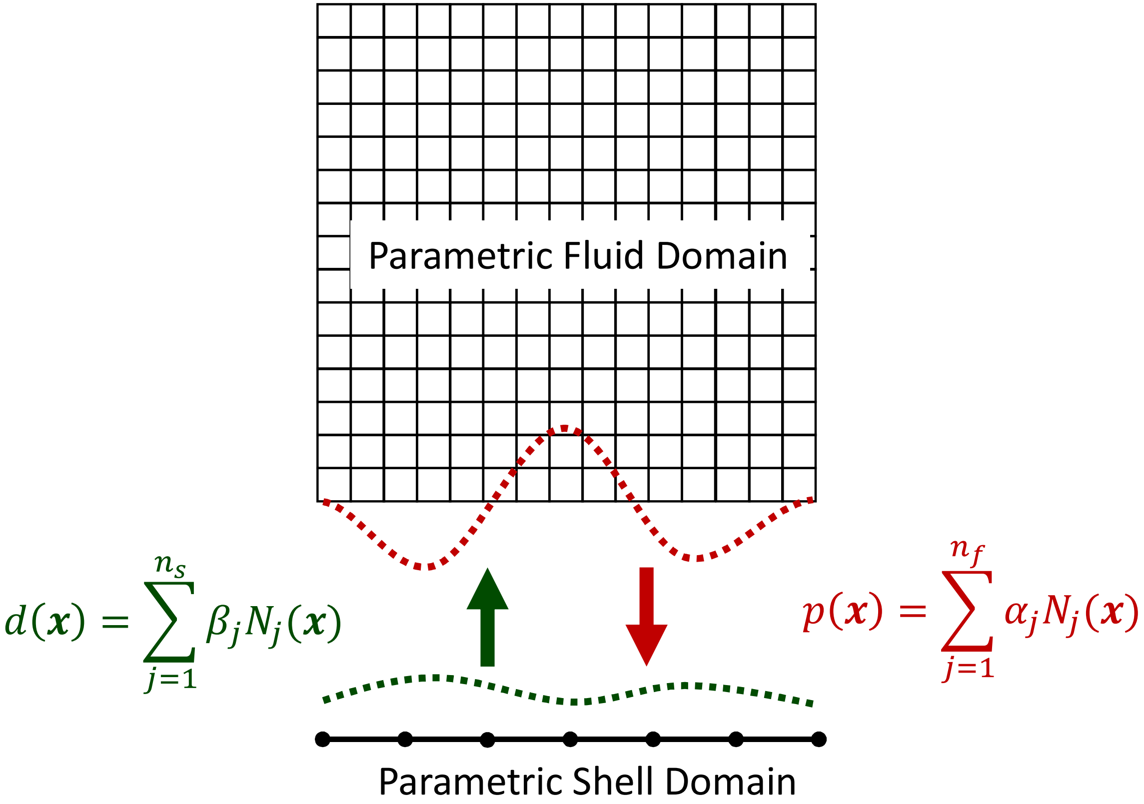
- Navier-Stokes
  - **SUPG/PSPG** or **k-ω-solver**
  - Steady/Unsteady
  - Developed by University of West Bohemia (Pilsen, CZ)
- Ideal Flow solver:
  - Steady by nature
  - However, pressures computed based on **unsteady Bernoulli equation**

Flow Model – Ideal Flow



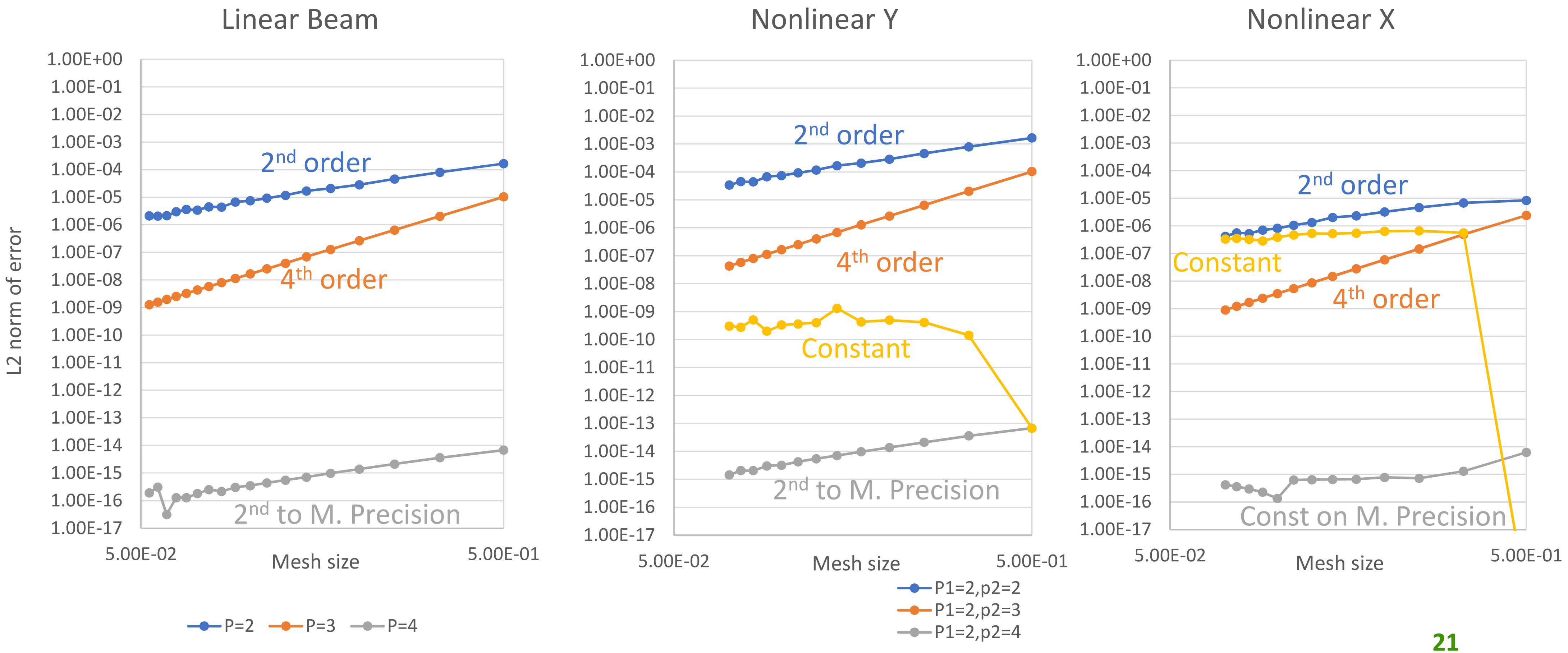
Fluid-Structure Interaction

- ✓ Mesh deformation based on **Linear Elasticity** (solids)
- ✓ **Pressure** and **Displacement** transfer function developed for **ideal flow**
- ✓ Coupling method independent of **mesh matching**
- ○ **ALE Formulation** for Ideal Flow and NS Flow to be developed

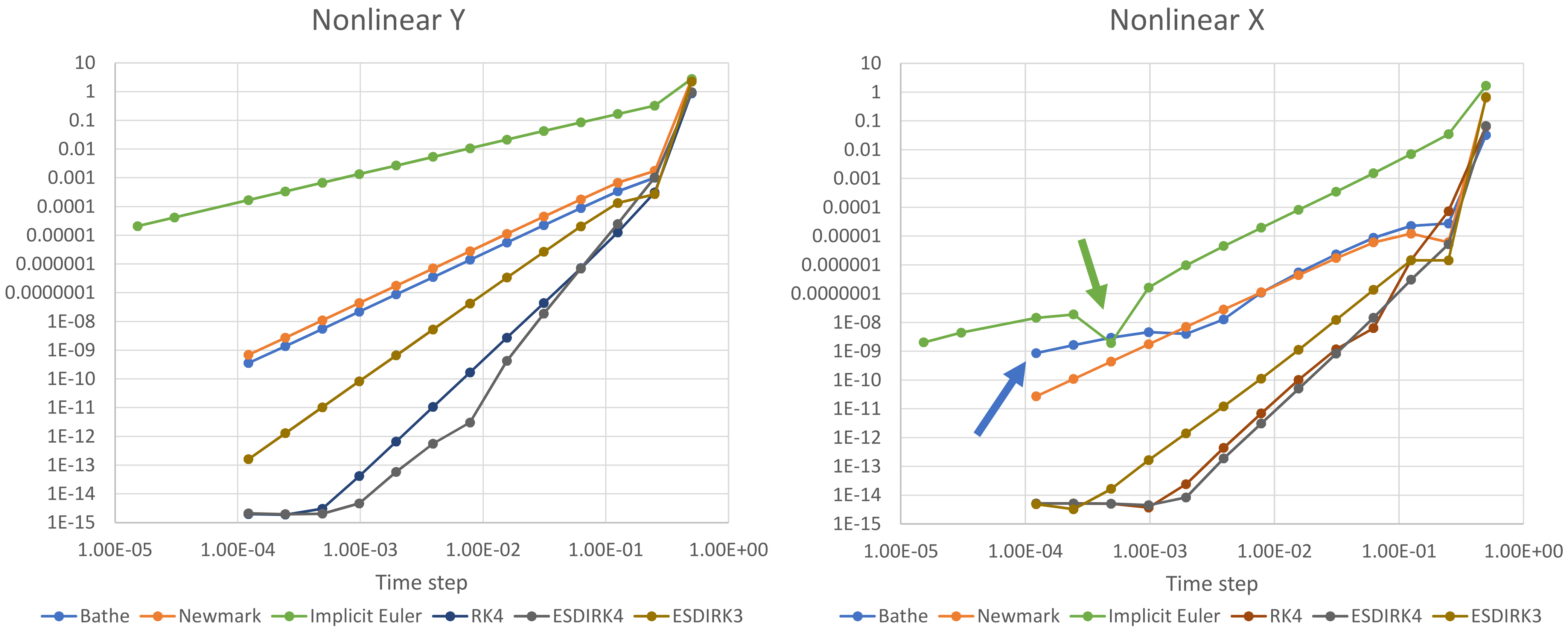


Results and Discussions

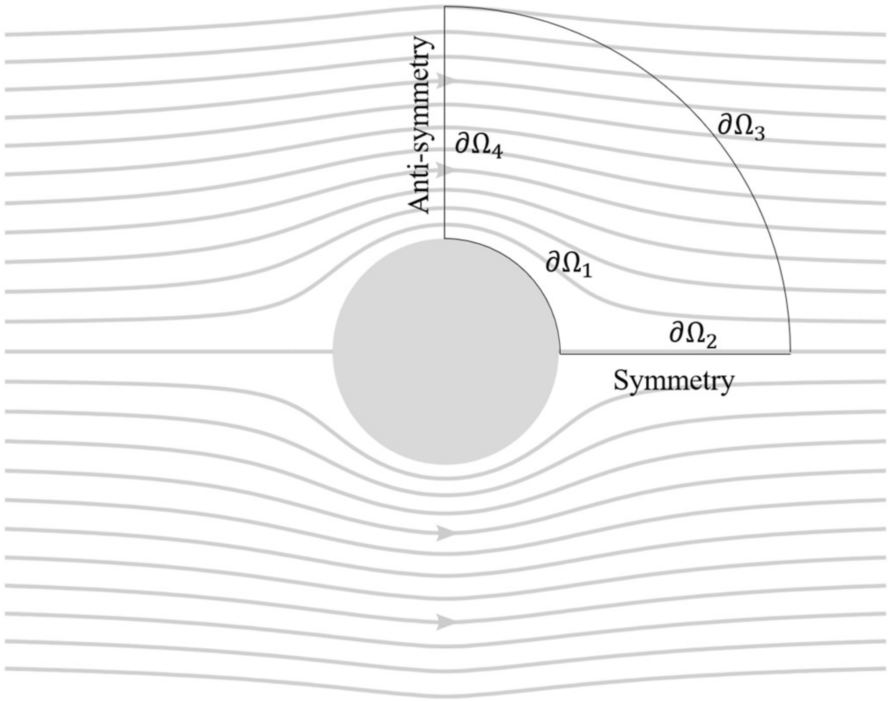
Beam Model – Spatial Convergence

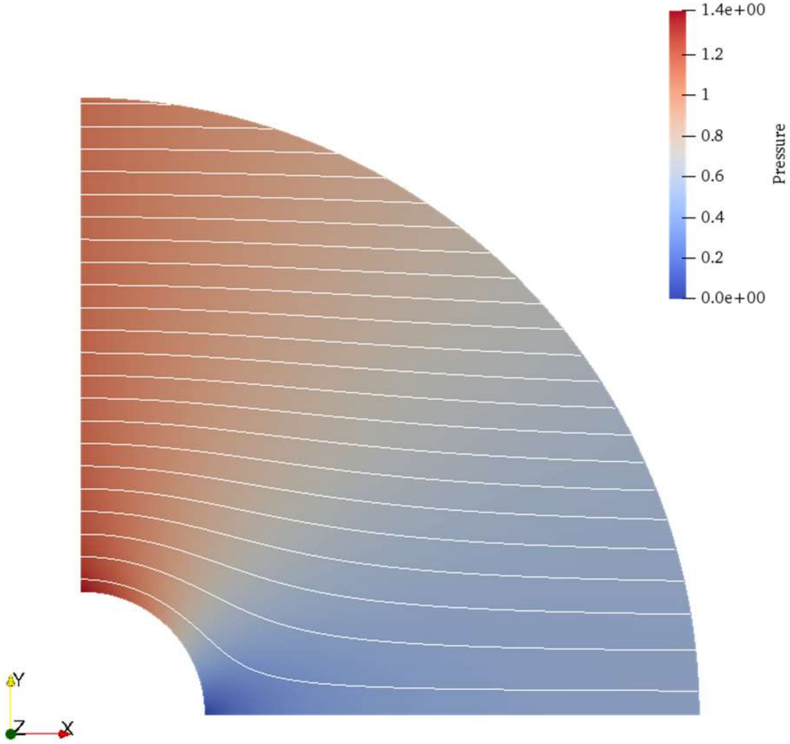


Beam Model - Temporal Convergence

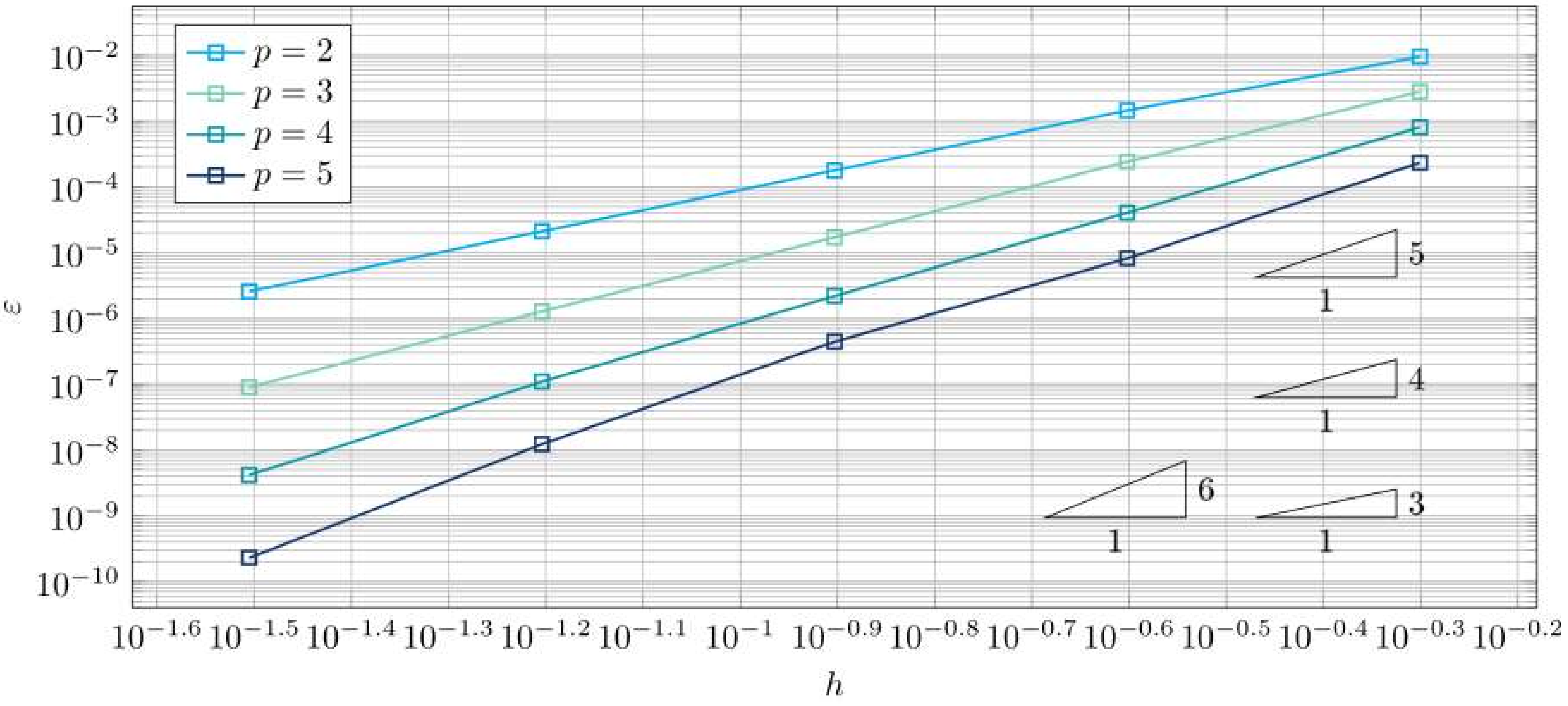


Fluid Model – Ideal Flow

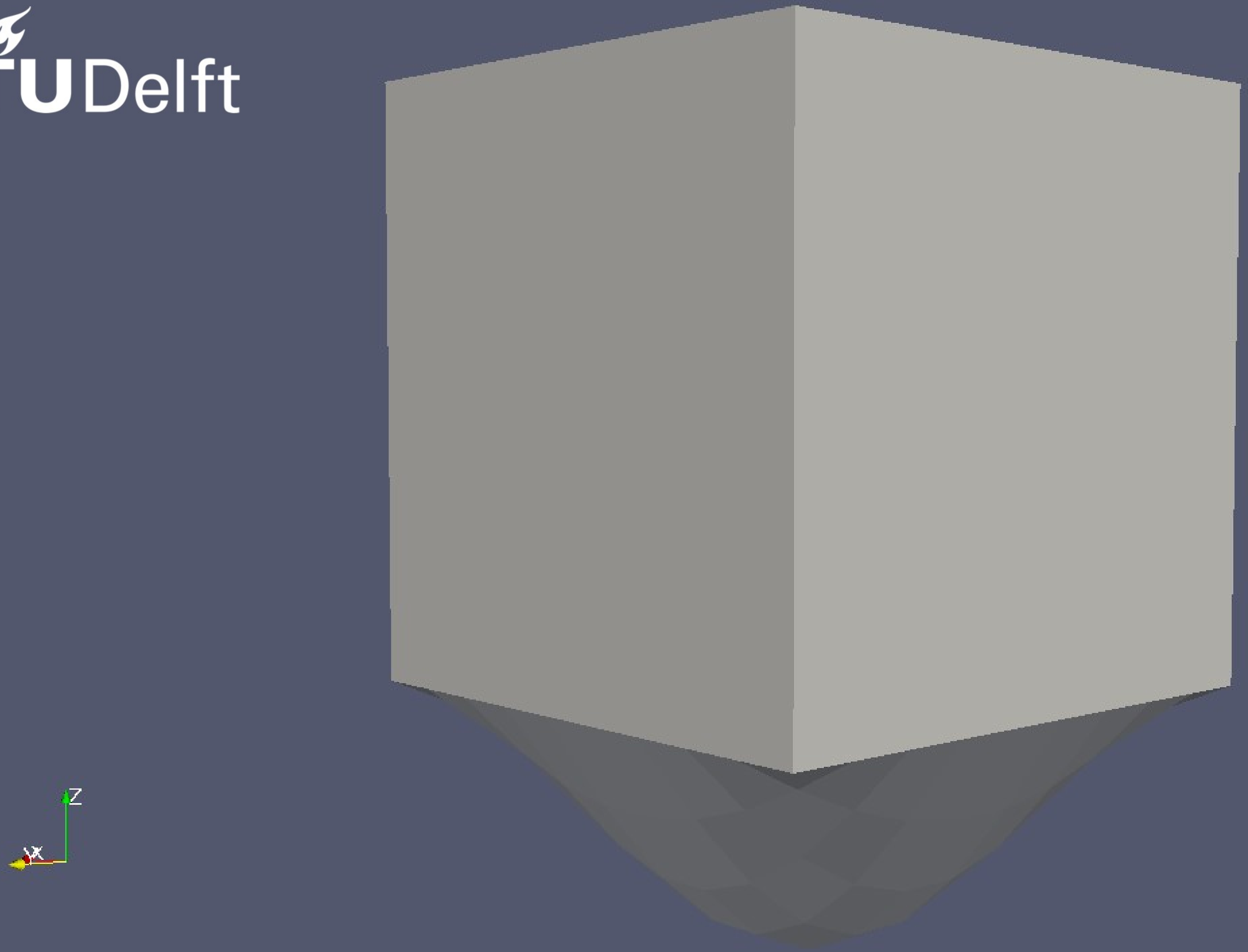




Fluid Model – Ideal Flow



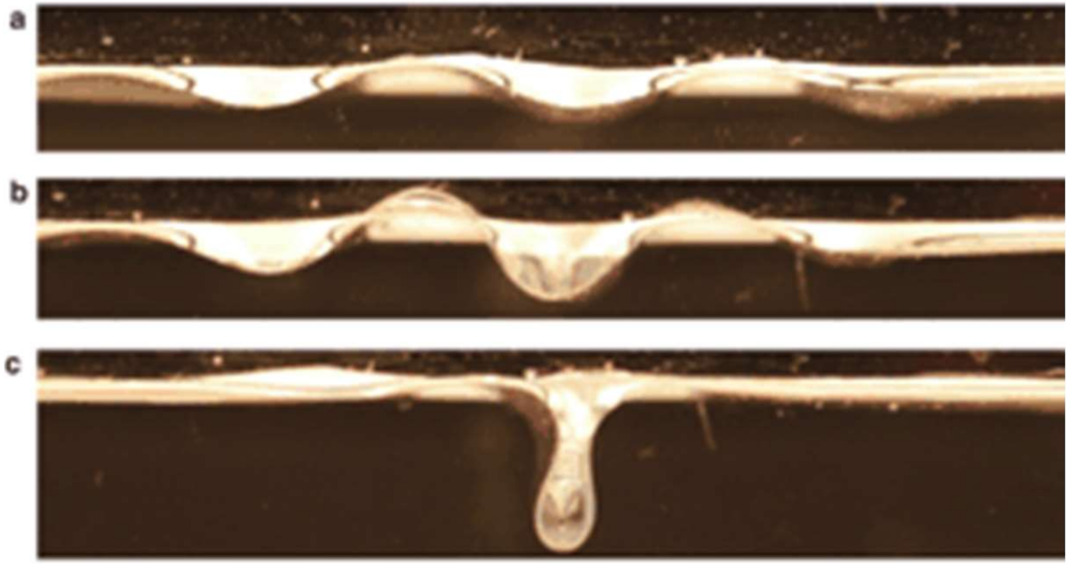
FSI



Application: Wrinkling and Folding

Beam Model

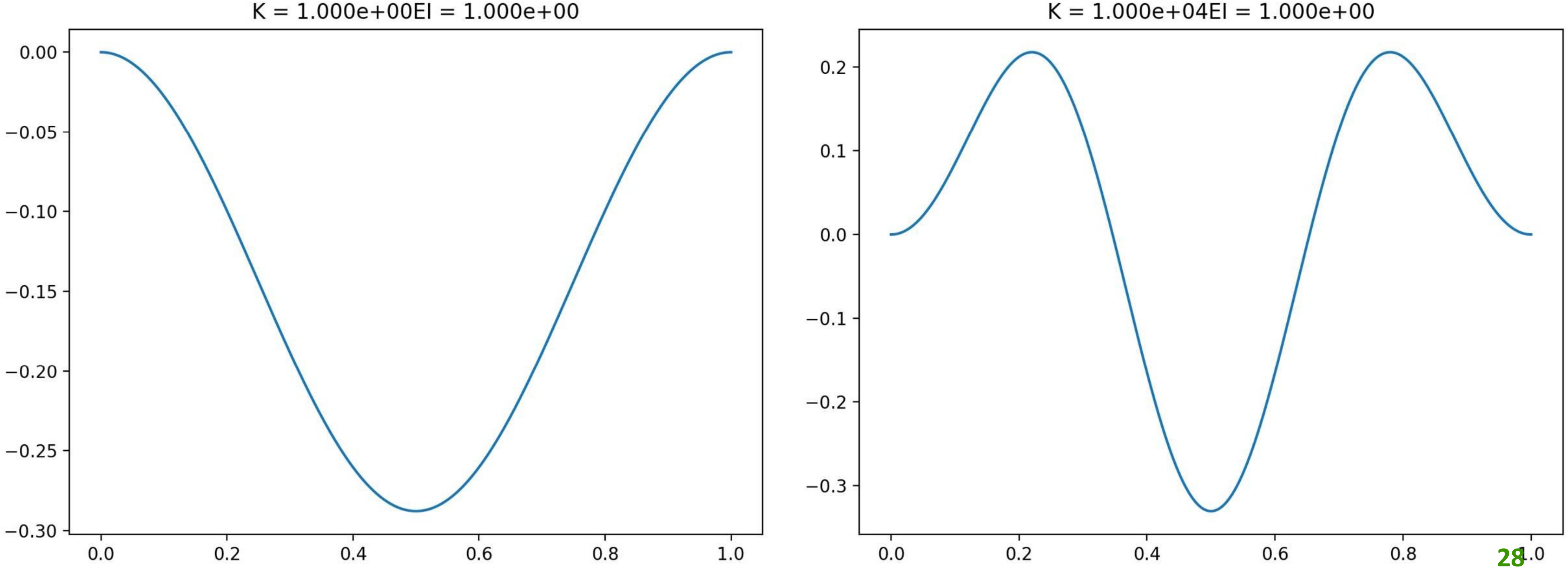
Remember…



Compressive Force
Elastic/Liquid foundation

Beam Model

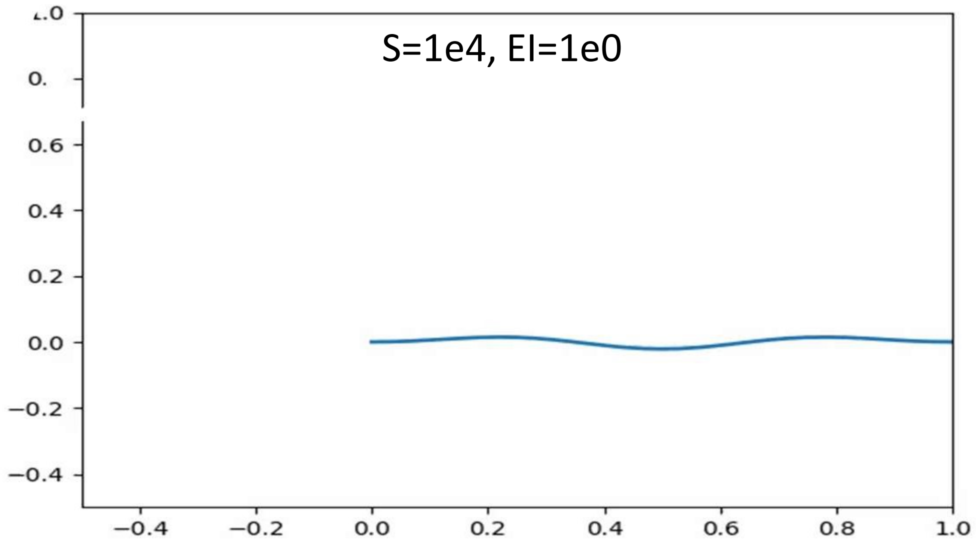
Initial shapes

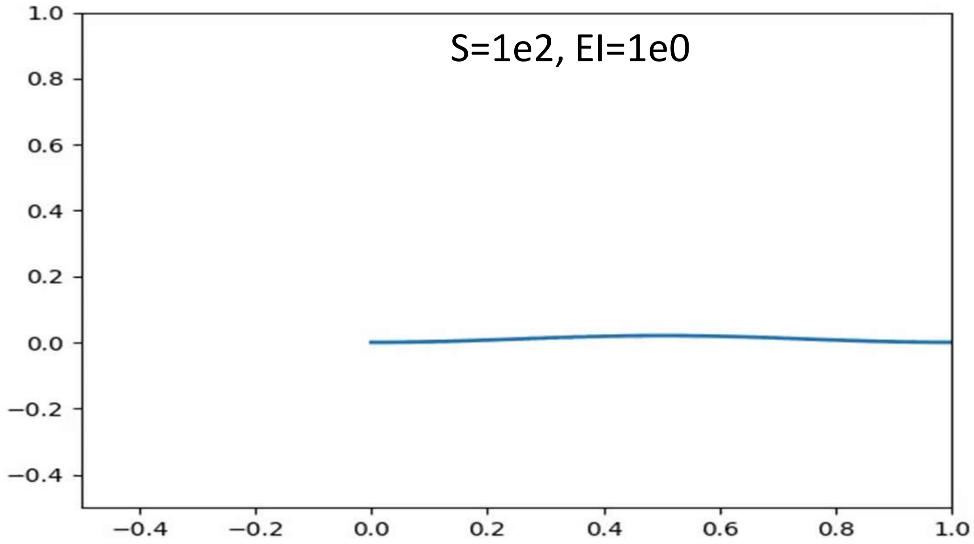


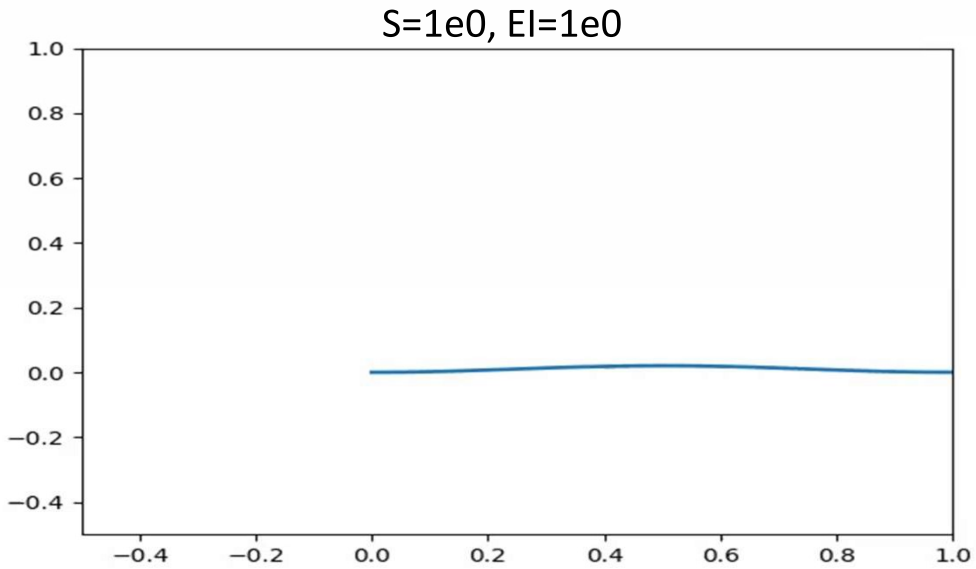
Beam Model

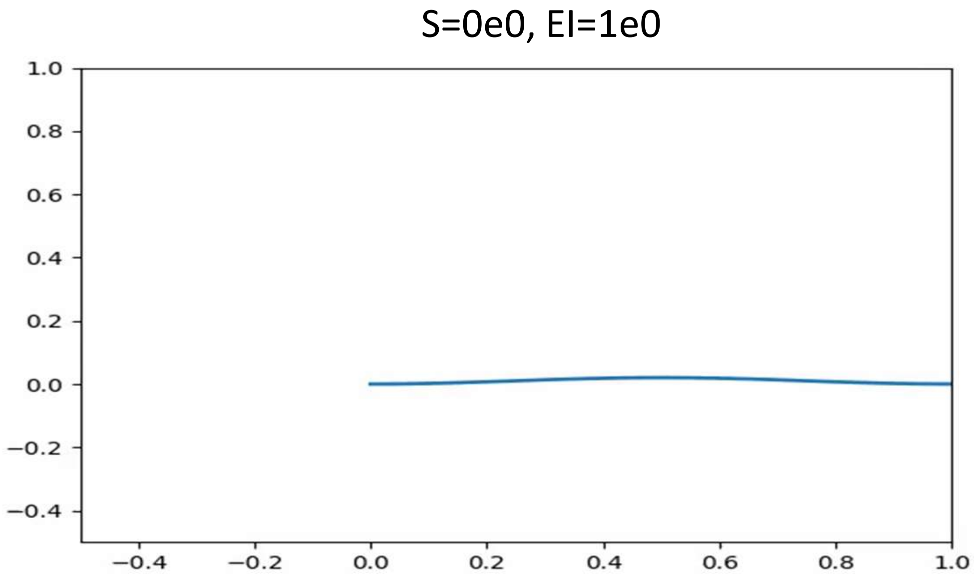
Try-out 1:

- Knot vector [0,0.5,1.0]
- Beam under increasing compressive load


S=1e4, EI=1e0
.0
0.
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0


S=1e2, EI=1e0
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0


S=1e0, EI=1e0
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0


S=0e0, EI=1e0
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0

Beam Model

Try-out 1:

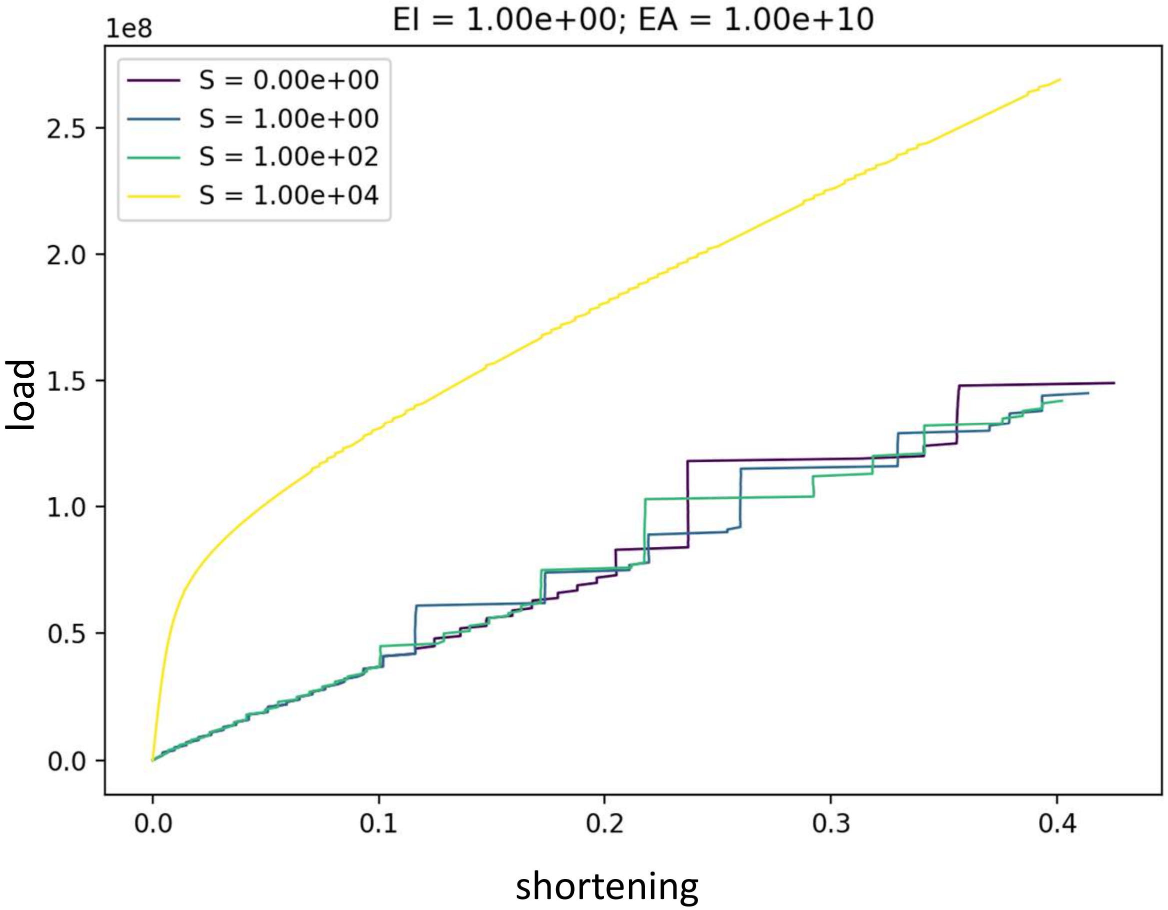
- Knot vector [0,0.5,1.0]
- Beam under increasing compressive load

Observations:

- ‘Shocky’ shortening
- Always one extremum

Lessons learned:

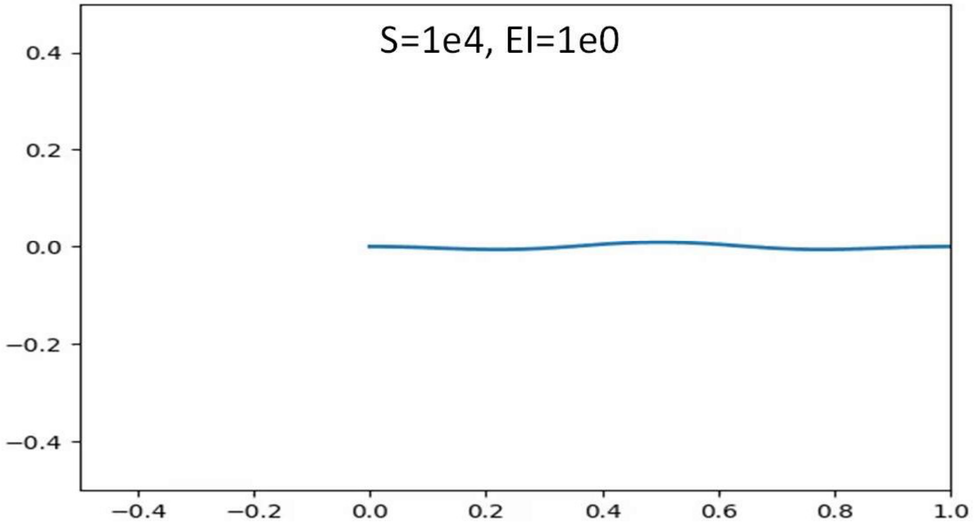
- Knot vector too course
- Hence, energy state not possible?!

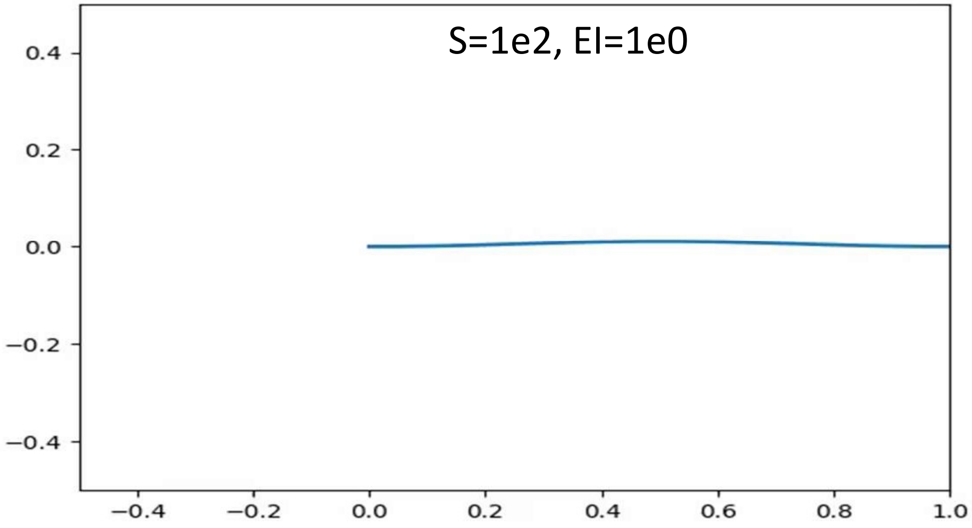


Beam Model

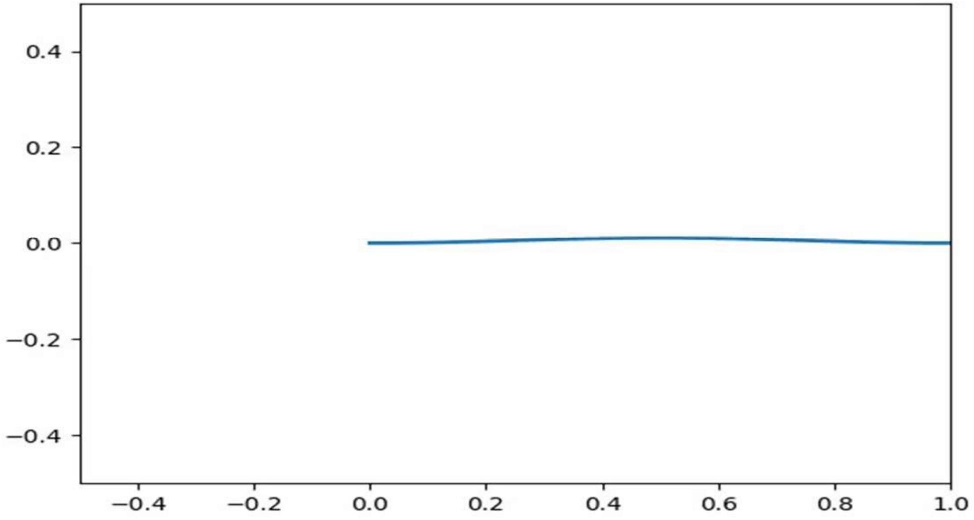
Try-out 2:

- Knot vector [0,1/8,…,7/8,1.0]
- Beam under increasing compressive load

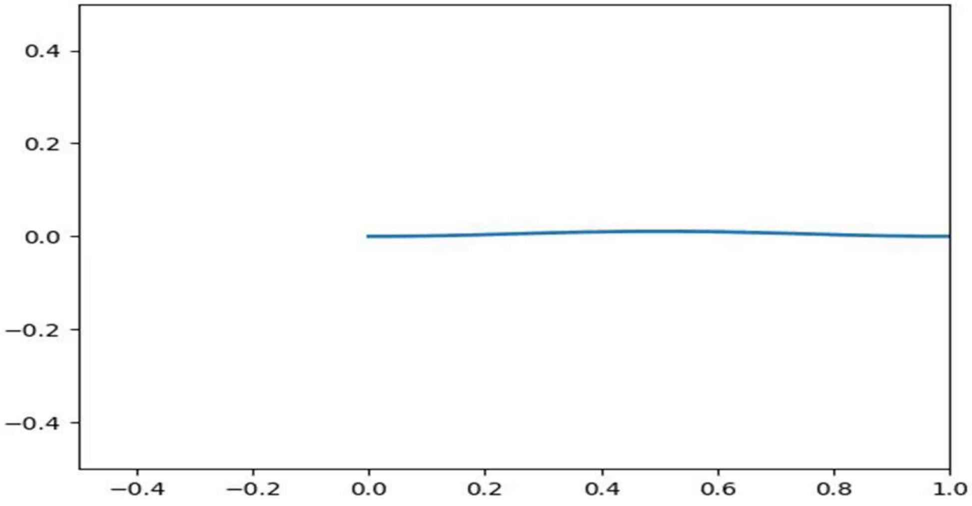

S=1e4, EI=1e0


S=1e2, EI=1e0

S=1e0, EI=1e0



S=0e0, EI=1e0



Beam Model

Try-out 2:

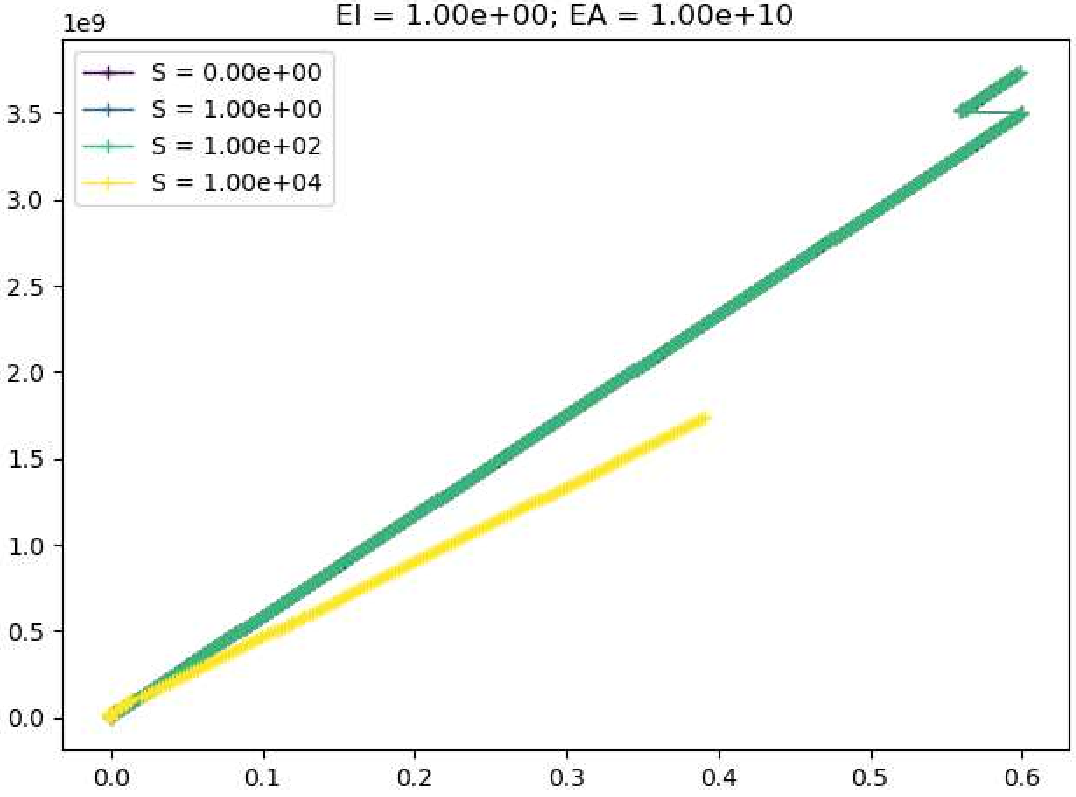
- Knot vector [0,1/8,…,7/8,1.0]
- Beam under increasing compressive load

Observations:

- ‘Shocky’ shortening disappeared
- No ‘trivial mode’ for S=0?

Open question:

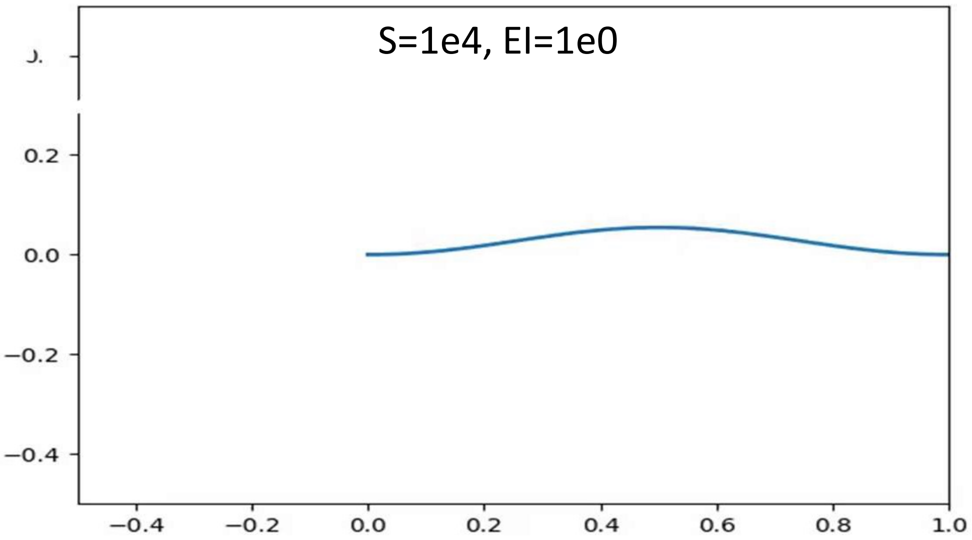
- What happens if first mode is sin(x)?
- Force steps too big?

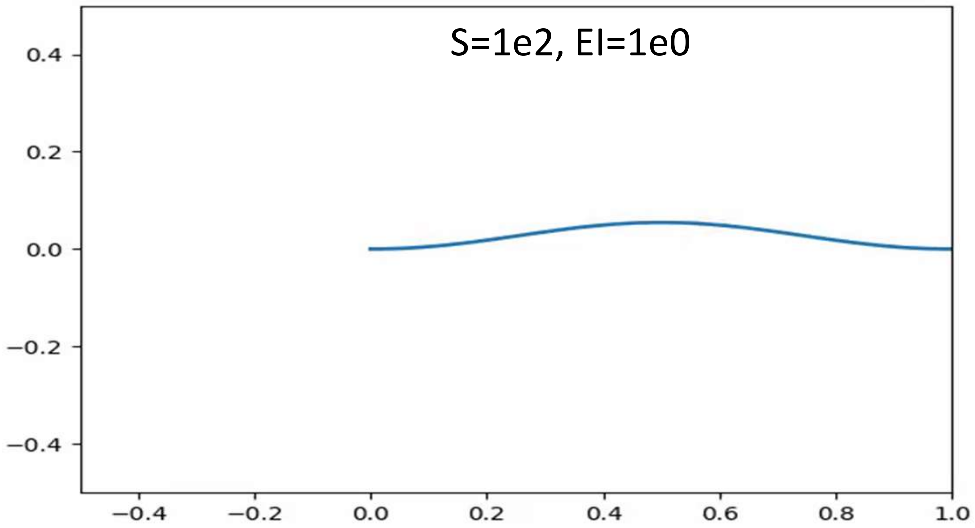


Beam Model

Try-out 3:

- Knot vector [0,1/8,…,7/8,1.0]
- Beam under increasing compressive load (smaller step)
- Sin(x) initially


S=1e4, EI=1e0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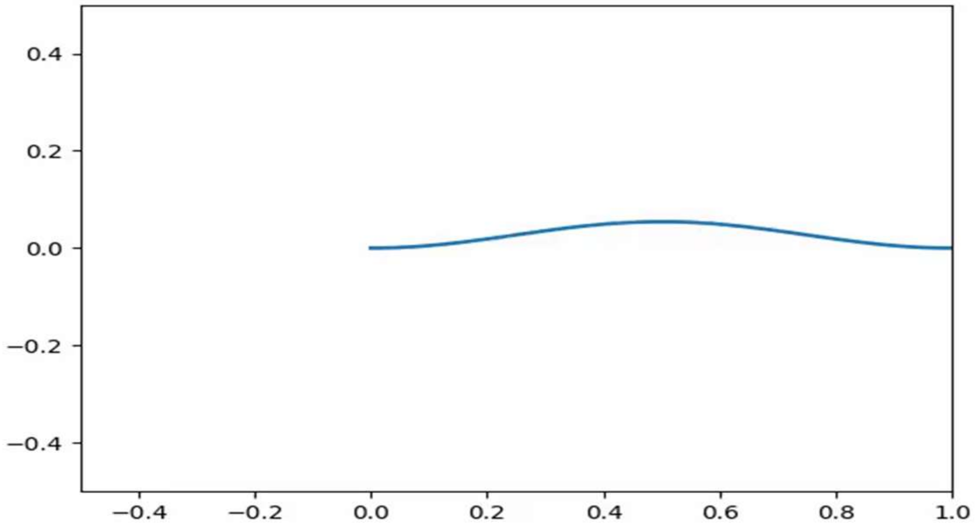
S=1e0, EI=1e0 not finished

S=0e0, EI=1e0



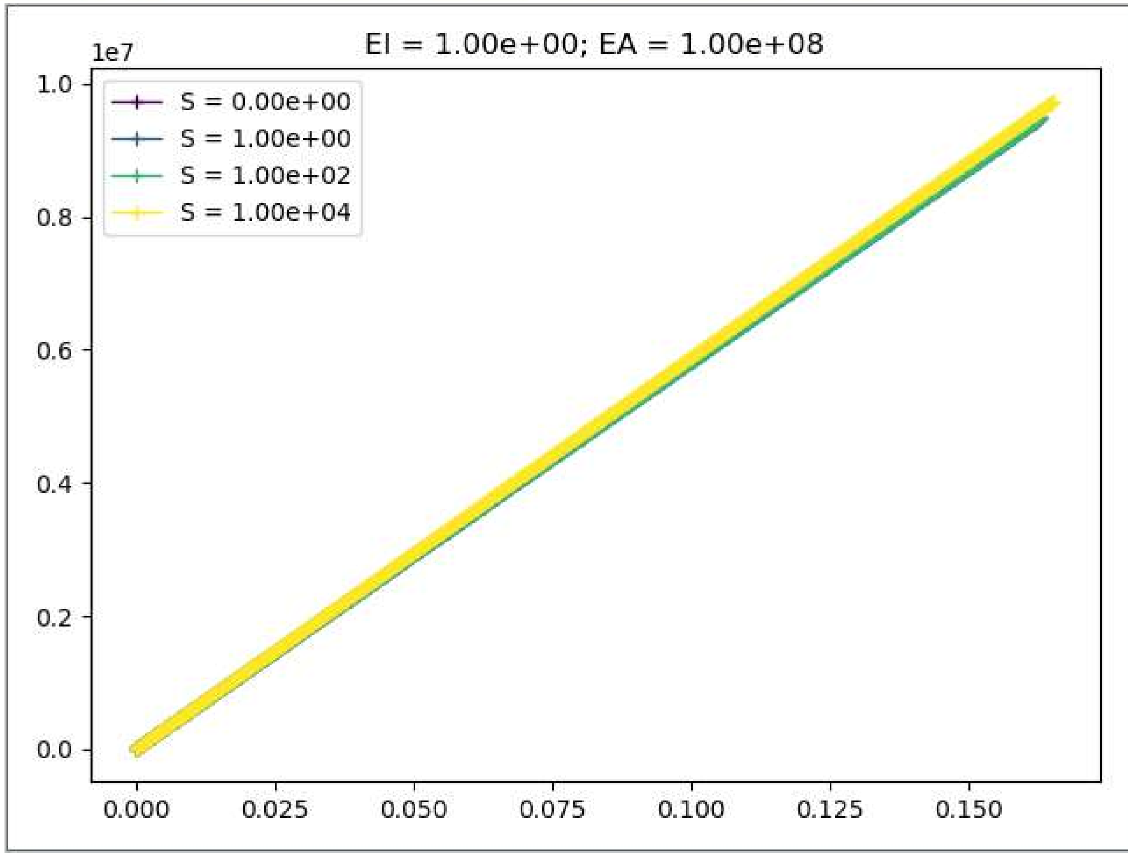
Beam Model

Try-out 3:

- Knot vector [0,1/8,…,7/8,1.0]
- Beam under increasing compressive load (smaller step)
- Sin(x) initially

Observations:

- ‘Shocky’ shortening disappeared
- No ‘trivial mode’ for S=0?
- Same modes visible, despite sin(x) initially



Conclusions and Recommendations

Conclusions – Beam Model

Beam model developed and verified

- Space and time discretisations verified using manufactured solutions
- Time integration schemes can be assessed further
- More features

Beam model application to wrinkling:

- ‘Fine’ knot vector
- Initial deformation can be chosen arbitrarily? (hypothesis)
- However, without spring term, no ‘trivial mode’…

Conclusions – Shell Model

Shell model developed

- Validated for simple, linear cases
- Working on validation for time integration (Euler methods)
- Working on non-linear, force incremental code

FSI with potential flow

- Weak partitioned scheme works
- Next step: strong coupling

Way Forward and Open Questions

- Suggestions for wrinkling problems in Python?
- Should the wrinkling in G+smo be quasi-static or dynamic?
- Couple fluid and structure in G+smo? Or make complicated foundation? Can also make foundation with other solid?
- Pressures following?
- Focus on instabilities? Requires assembly of geometric stiffness matrix.

$$[\mathbf{k}_\sigma] = \int_{-1}^{1}\int_{-1}^{1} [\mathbf{G}_I]^T[\mathbf{J}]^{-T} \begin{bmatrix} N_x & N_{xy} \\ N_{xy} & N_y \end{bmatrix} [\mathbf{J}]^{-1}[\mathbf{G}_I]\, J\, d\xi\, d\eta$$

When is the next meeting?