Glass Performance Days 2025

10 – 12 JUNE 2025 | NOKIA ARENA - TAMPERE, FINLAND

GLASS PERFORMANCE DAYS 2025

Nonlinear Analysis of Curved Laminated Glass Structures

Addressing Challenges in Plates and Curved Shells

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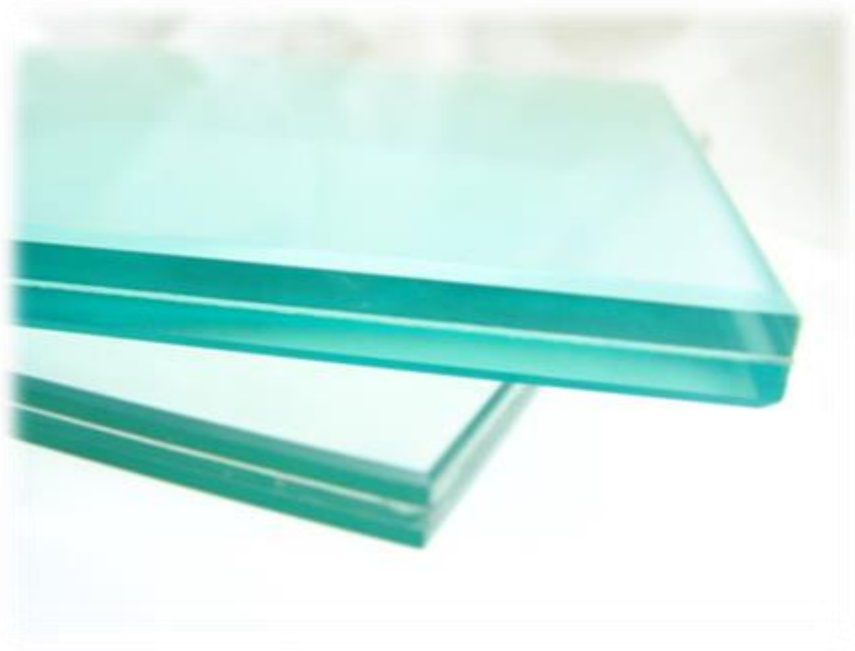
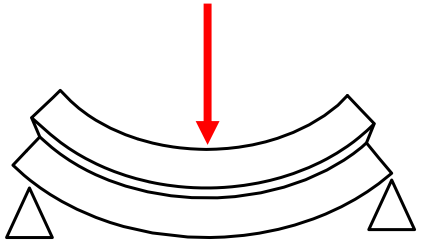
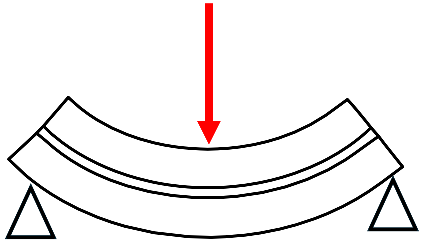
Laminated Glass & Layered Structures

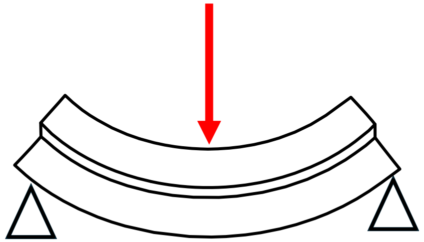




Layered limit:
free sliding glass plies



Monolithic limit:
slide-constrained glass plies



Intermediate response:
partially slide-constrained glass plies

Young modulus
- Glass: 70000 MPa
- Interlayer: 0.1 - 100 Mpa

(time and temperature dependent)

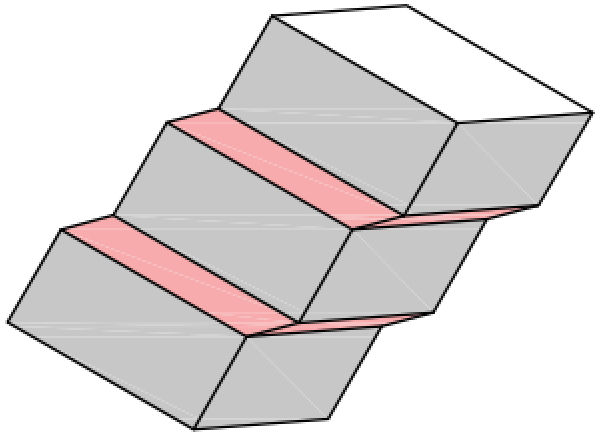
The Challenge: Modelling Stiff/Soft Layered Composites

Problem Statement:

- Traditional plate theories are unreliable for stiff/soft laminates due to significant transverse shear strains in soft interlayers, causing irregular cross-sectional warping.
- 3D finite element discretization is computationally expensive.

Limitations of Some Existing Dedicated Software:

- Often limited to flat geometries.
- Not exact for large deformations.
- May not be suitable for general instability problems.



Solid-Shell Approach

Reference curved configuration:

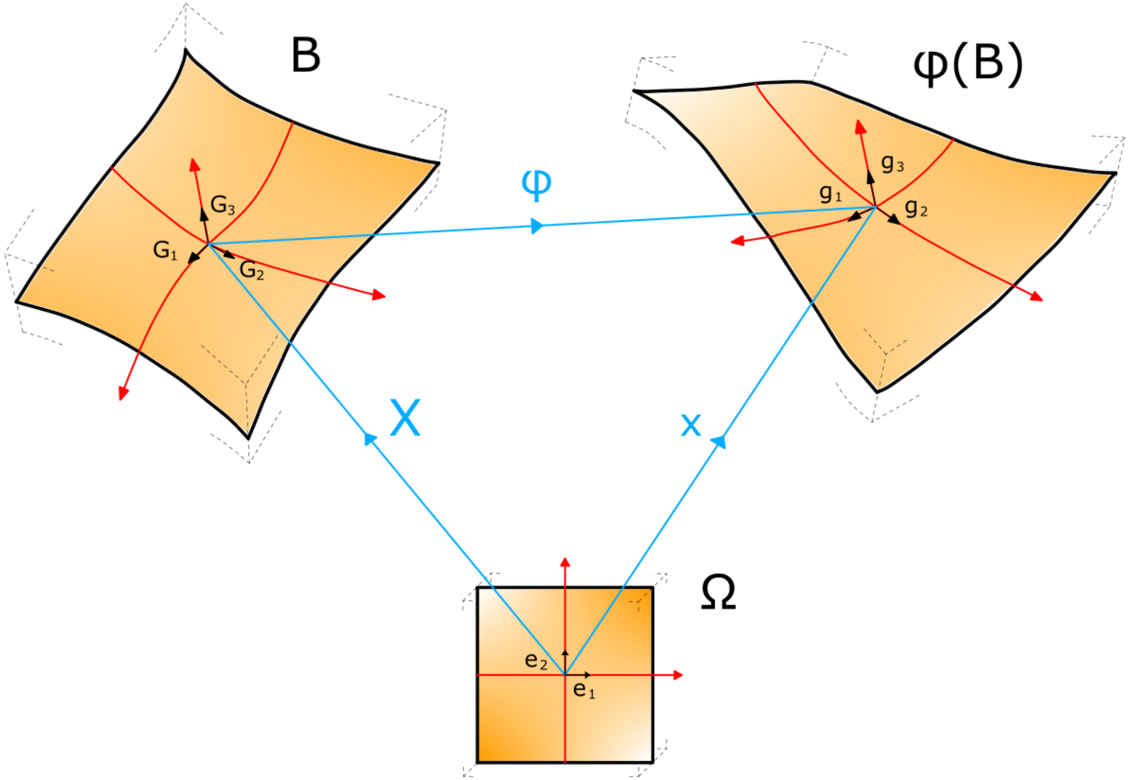
$$\boldsymbol{X}[\xi,\eta,\zeta] = (1-\zeta)\,\boldsymbol{X}_{bottom}[\xi,\eta] + (1+\zeta)\,\boldsymbol{X}_{top}[\xi,\eta]$$

Fully nonlinear strain tensor:

$$\varepsilon_{ij} = \frac{1}{2}\left(\boldsymbol{g}_i \cdot \boldsymbol{g}_{,j} - \boldsymbol{G}_i \cdot \mathbf{G}_{,j}\right)$$

To avoid numerical lockings:

Plane Stress + Assumed Natural Strain



Developed in collaboration with the University of Parma

Magisano, D., Leonetti, L., Garcea, G., & Royer-Carfagni, G. (2023). A constrained solid-shell model for the geometric nonlinear finite-element analysis of laminates with alternating stiff/soft layers. Int. Journal of solids and structures, **274**, *112287*

Core Assumptions

In plane $\varepsilon_{ij} = \varepsilon^0_{ij} + \zeta\, \varepsilon^0_{ij,3} \cancel{+ \zeta^2/2\, \varepsilon^0_{ij,3}}$

Transverse $\varepsilon_{3j} = \varepsilon^0_{3j} \cancel{+ \zeta\, \varepsilon^0_{3j,3}}$

Thickness $\varepsilon_{33} = \varepsilon^0_{33}$

Enforced plane stress

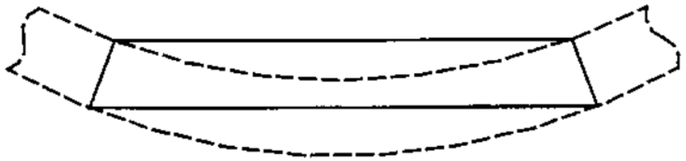
$$\sigma_{33} = \cancel{\lambda\, \varepsilon_{11} + \lambda\, \varepsilon_{22}} + (\lambda + 2\mu)\, \varepsilon_{33}$$

Pre-integration in thickness

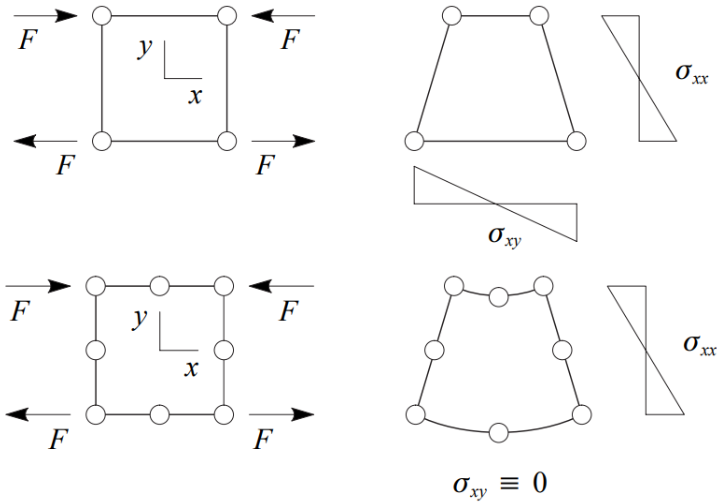
$$\frac{1}{2}\int_{-h/2}^{h/2} \mathbb{E}|_{\xi,\eta,\zeta}\ \mathbb{C}\ \mathbb{E}|_{\xi,\eta,\zeta}\ d\zeta = \frac{1}{2}\, \breve{\varepsilon}|_{\xi,\eta}\ \boldsymbol{\mathcal{C}}|_{\xi,\eta}\ \breve{\varepsilon}|_{\xi,\eta}$$

Assumed Natural Strains

Trapezoidal locking



Shear locking



Advantages

Computational efficiency

- Reduced number of parameters
- Simple strain expressions and locking free

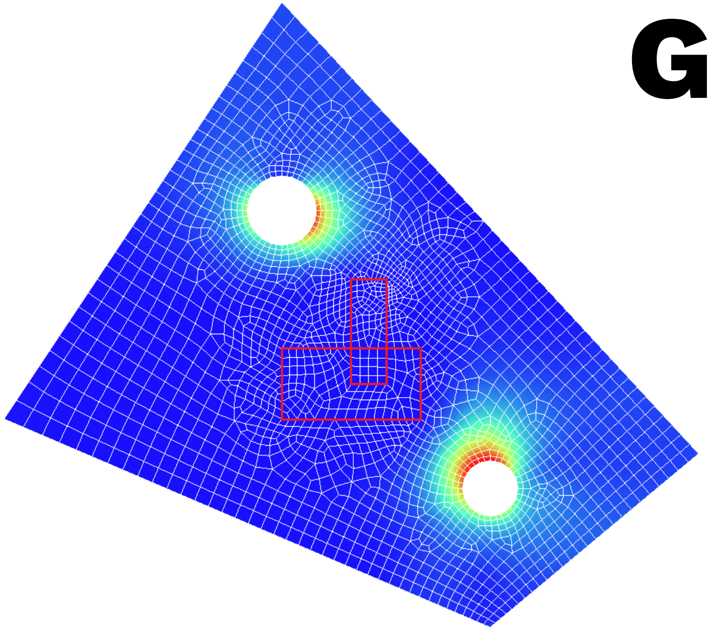
Accuracy

- Geometrically exact strain measure
- Demonstrated accuracy in large deformation (also curved geometries) and buckling case-studies

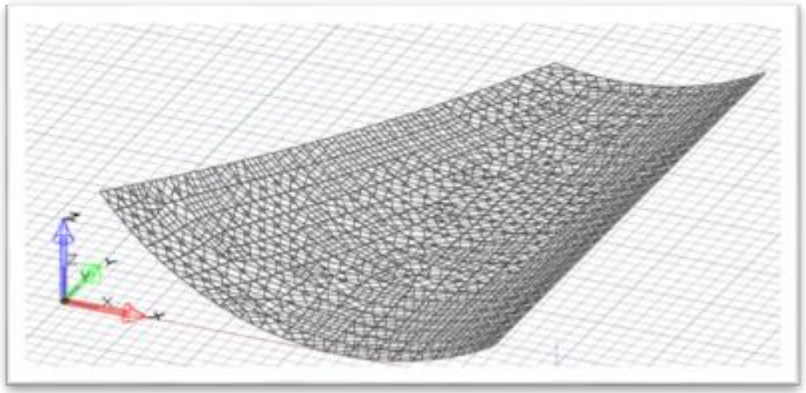
Versatility

- Applicable to various multi-layered composite structures with alternating stiff/soft layers
- Allows modelling of connections and 3D stress concentrations by coupling with full solid discretization

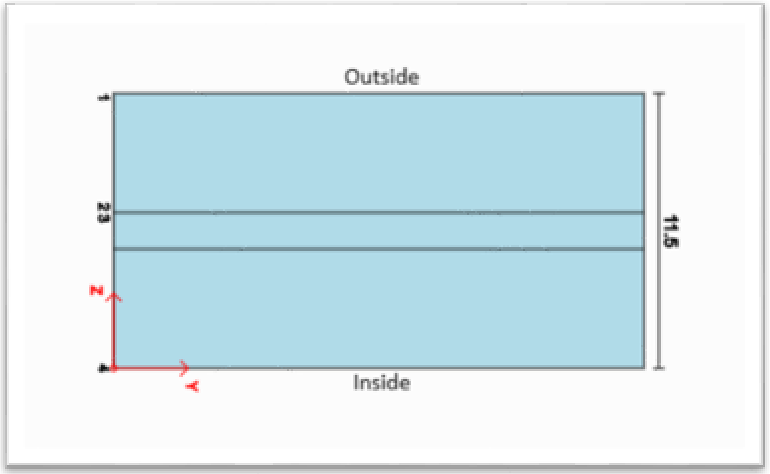
Geometry



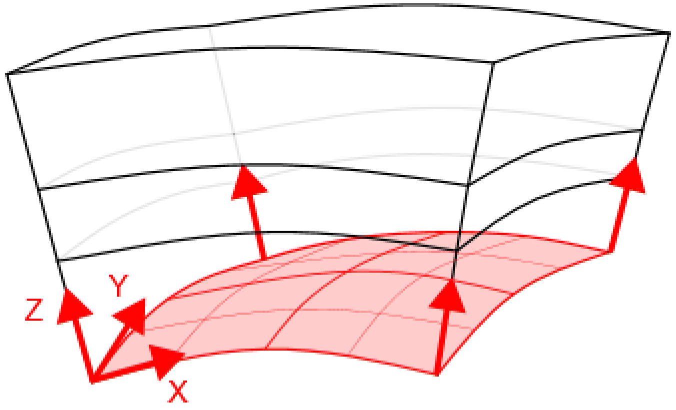
Quadrilateral 2D mesh generation



Surface embedding in 3D



Laminated Shell

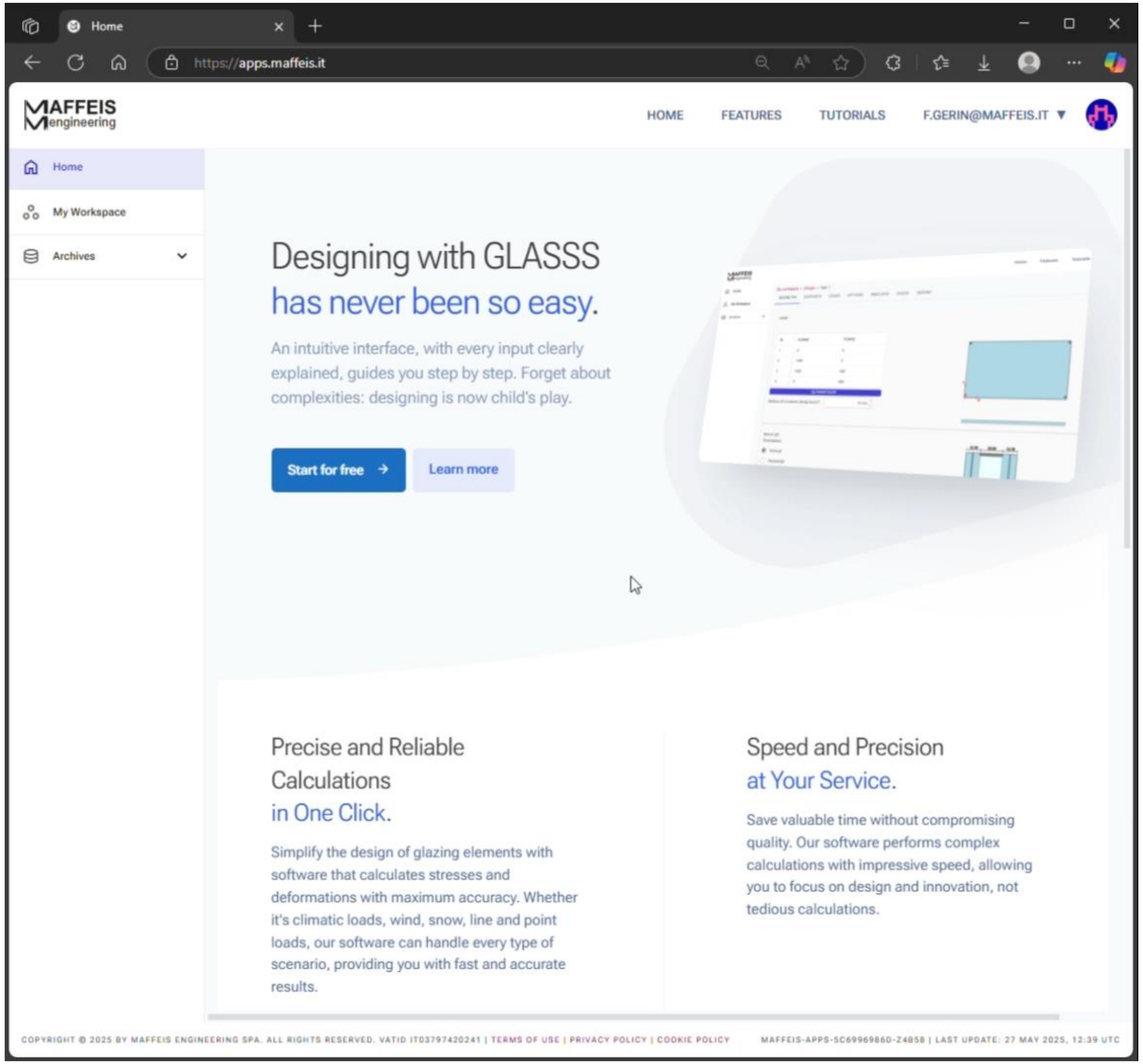


Extrusion along normals

The GLASSS **Software**

- Web application
- Cloud based
- Free of charge

Visit our site at
www.maffes.it/glasss



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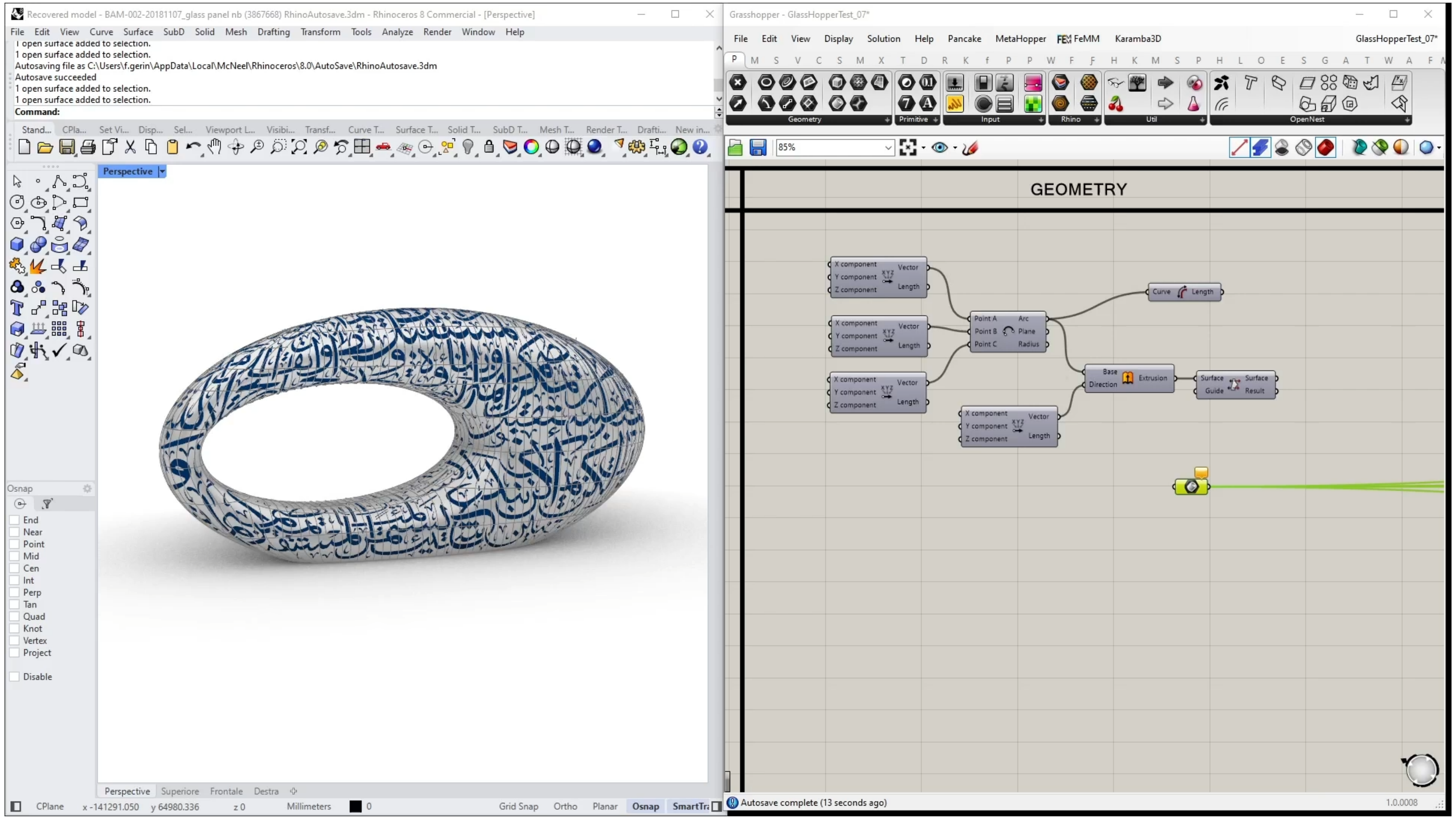
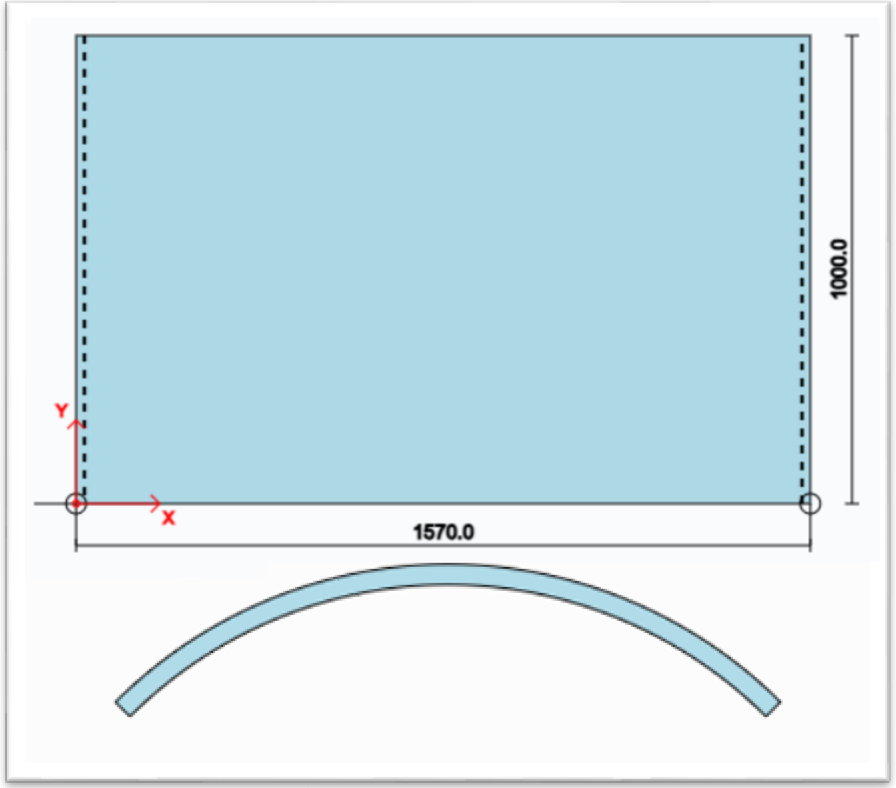
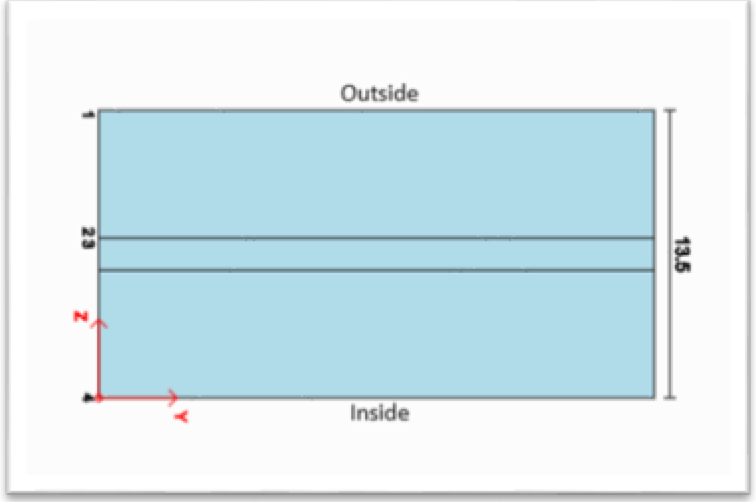
- Grasshopper plugins
- Simplified workflow
- Free of charge

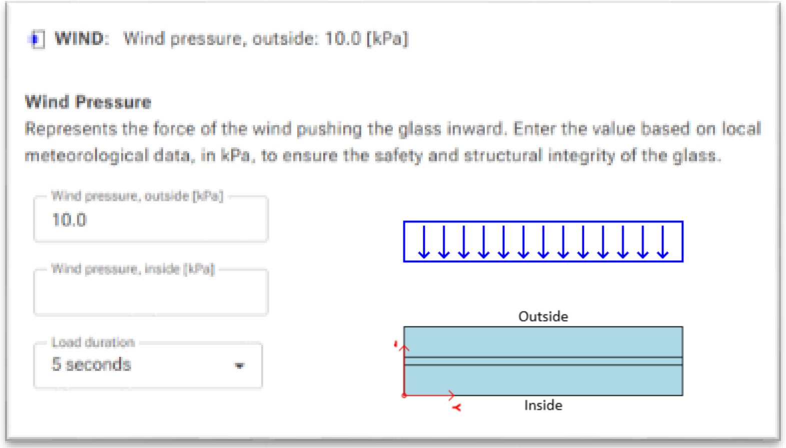


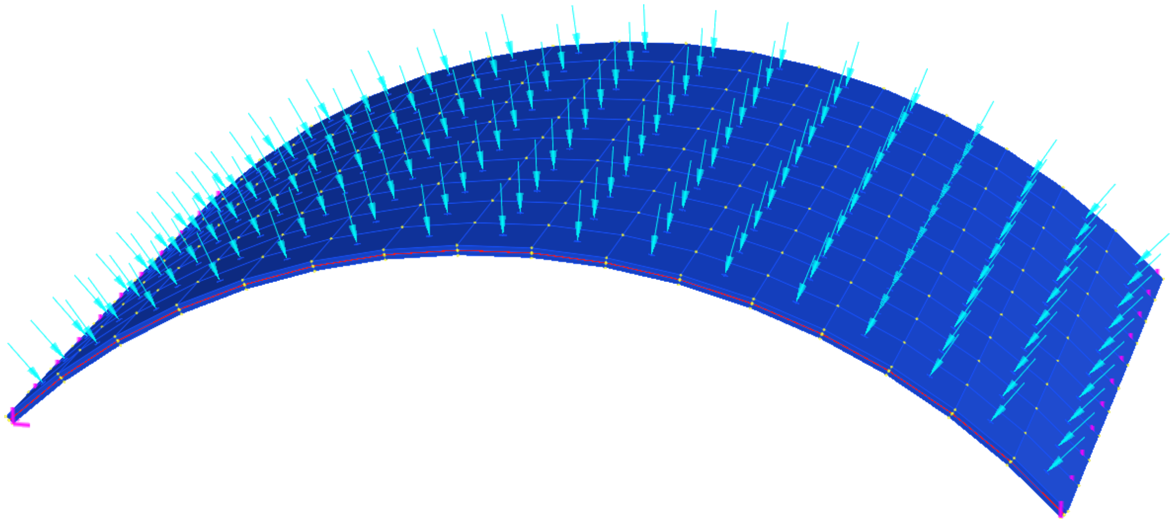
Example 1





- Curved Shell
- 2 Sides Supported
- Normal Uniform Load
- Interlayer: E = 2.0 MPa, $\nu \cong 0.5$



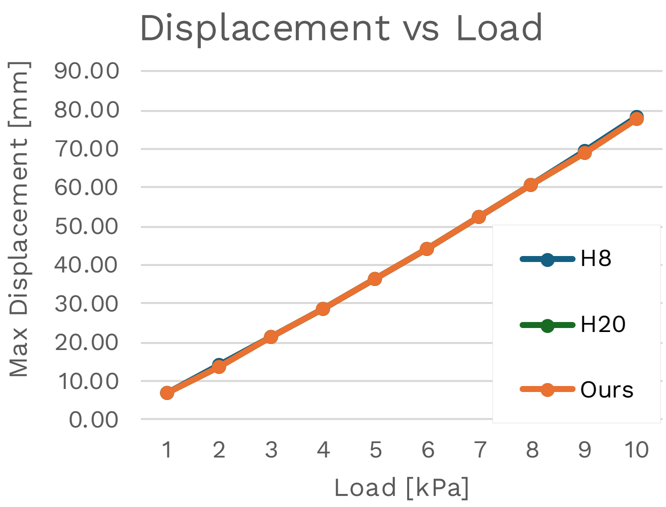


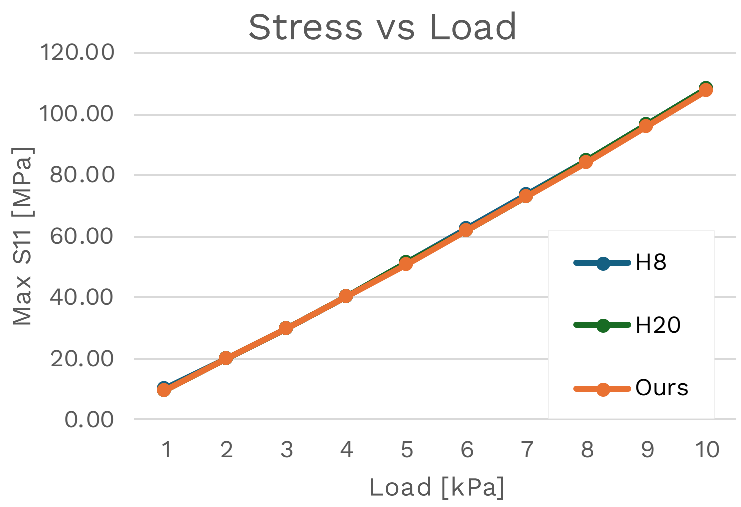
Example 1

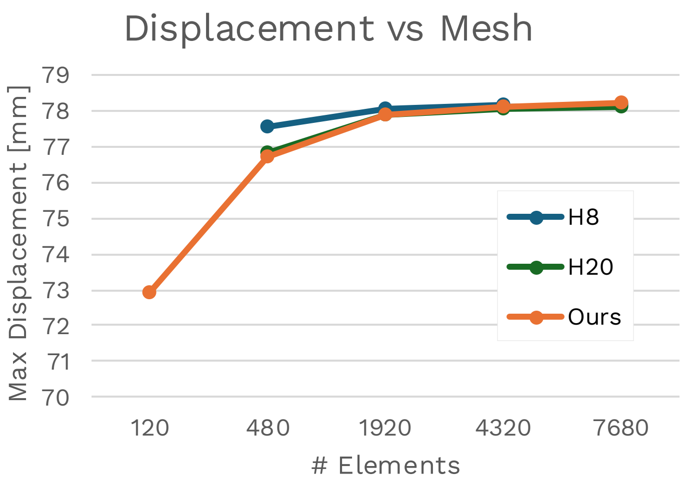
Comparison with

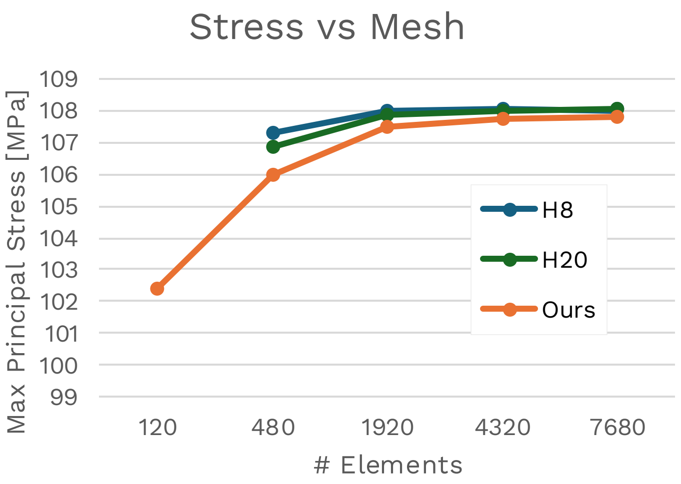
Strand7®
FINITE ELEMENT ANALYSIS

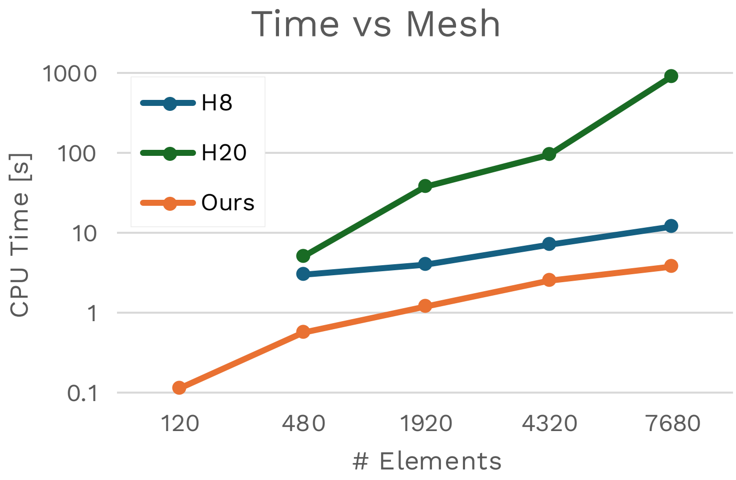
H8 and **H20** brick elements



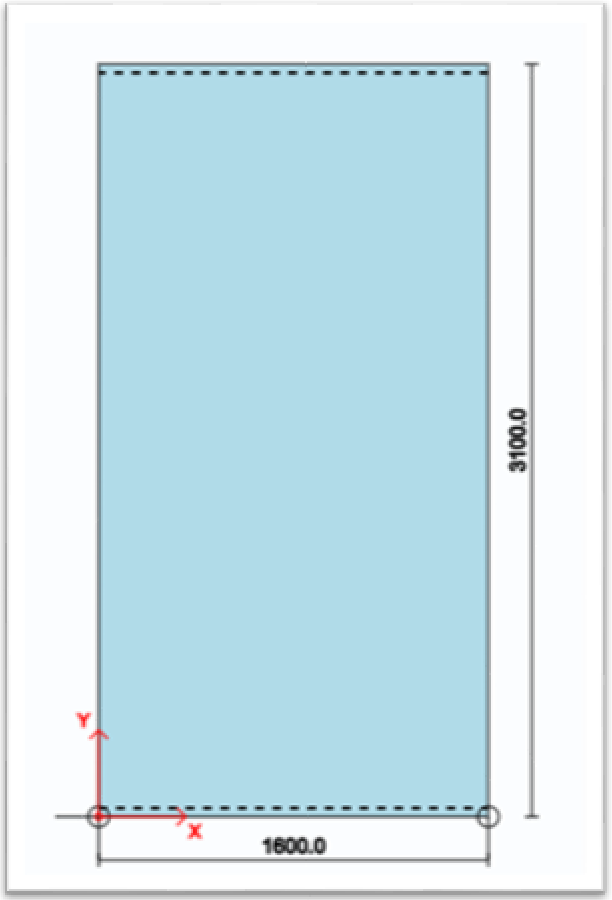


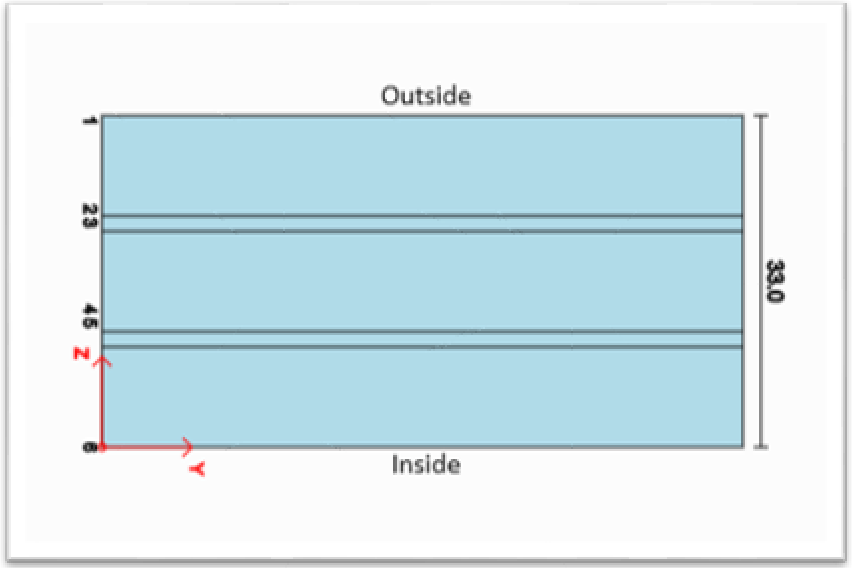




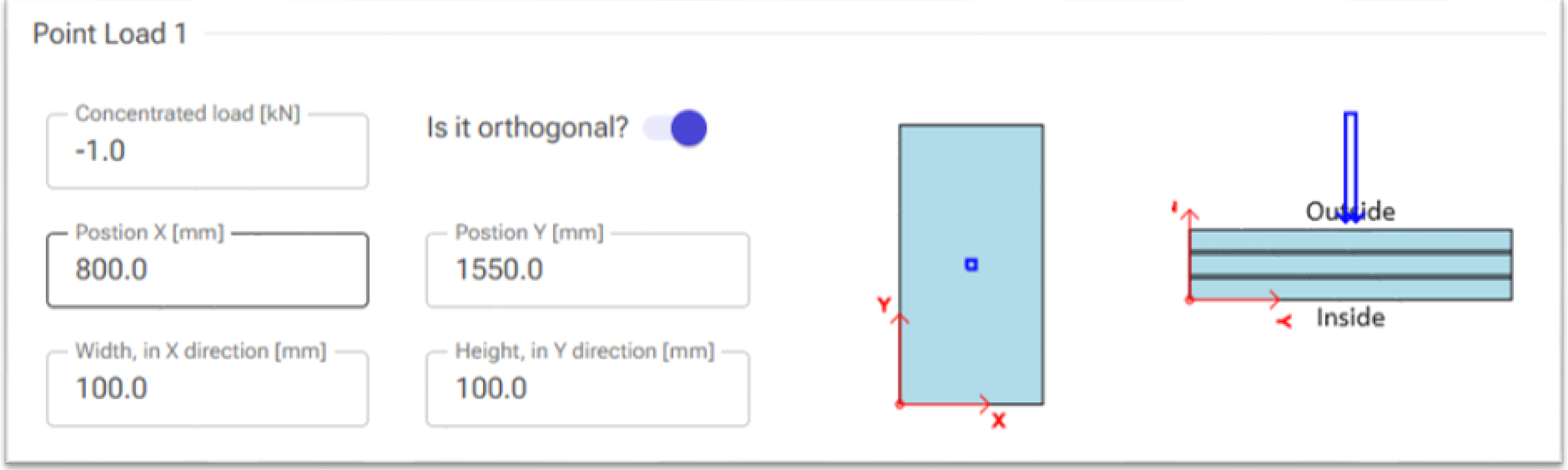


Example 2





- Triple Laminate
- 2 Sides Support
- Pseudo-concentrated Load
- Interlayer: E = 2.0 MPa, $\nu \cong 0.5$

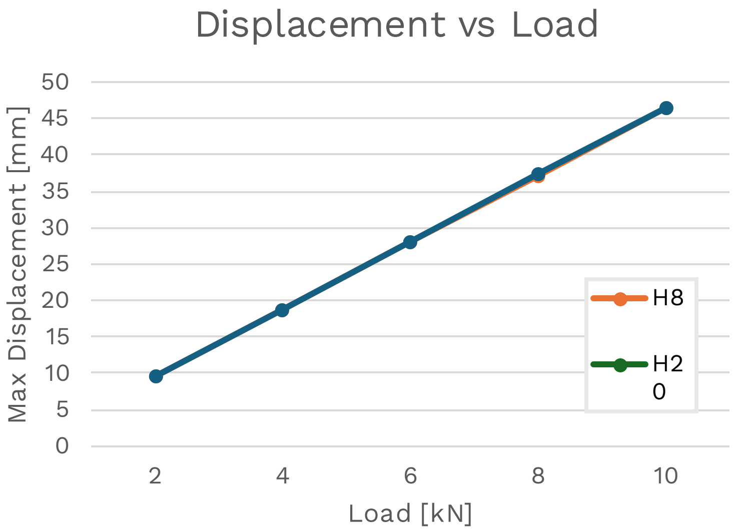


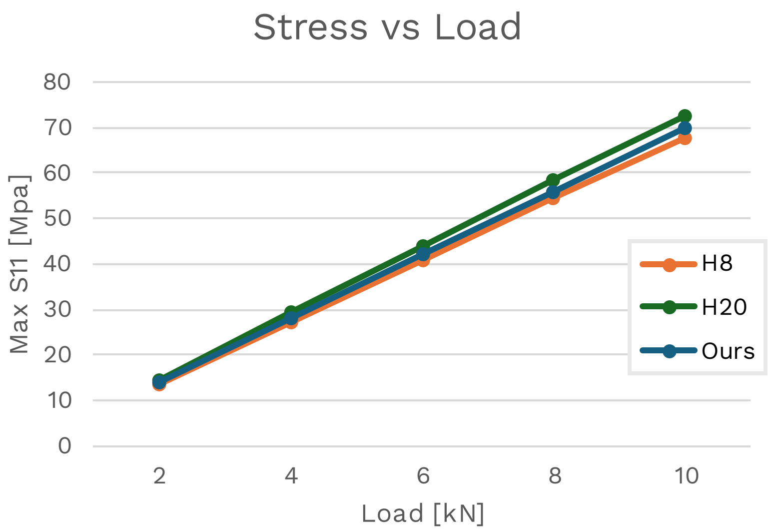
Example 2

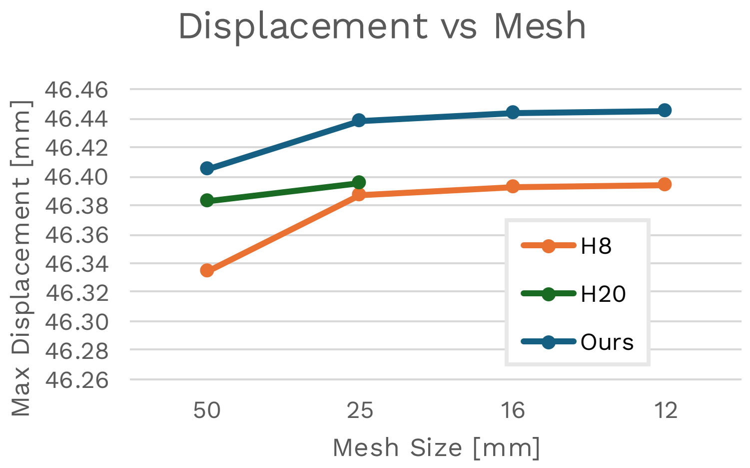
Comparison with

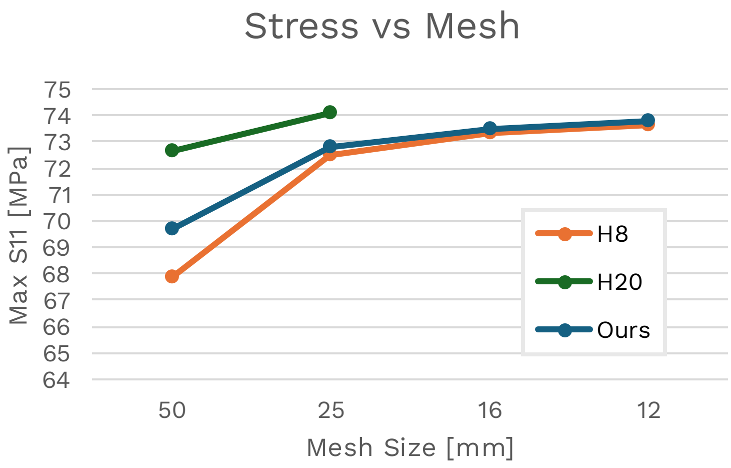
Strand7® FINITE ELEMENT ANALYSIS

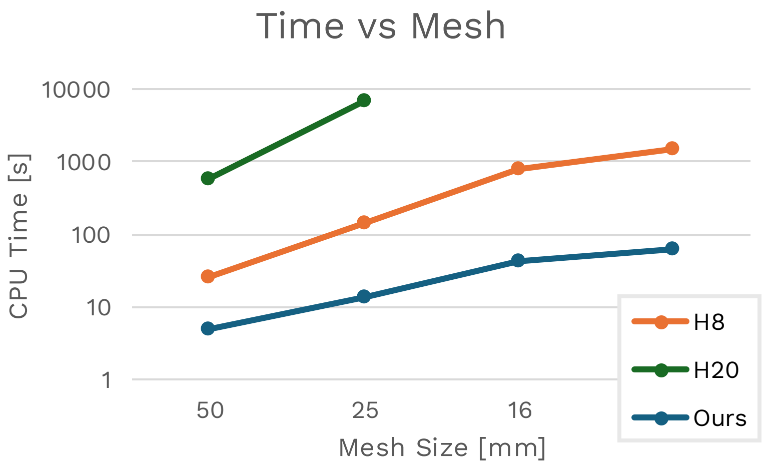
H8 and **H20** brick elements



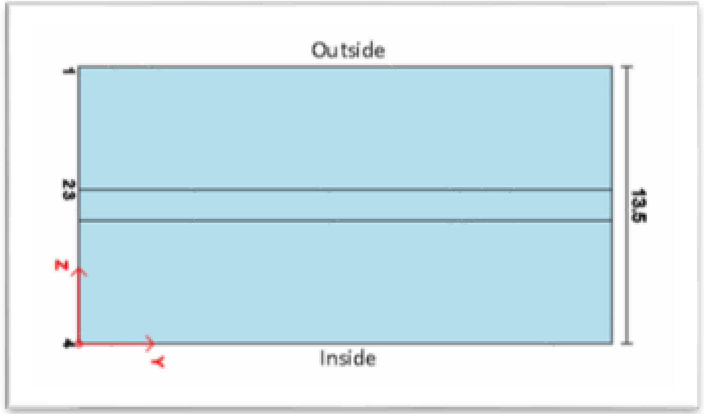




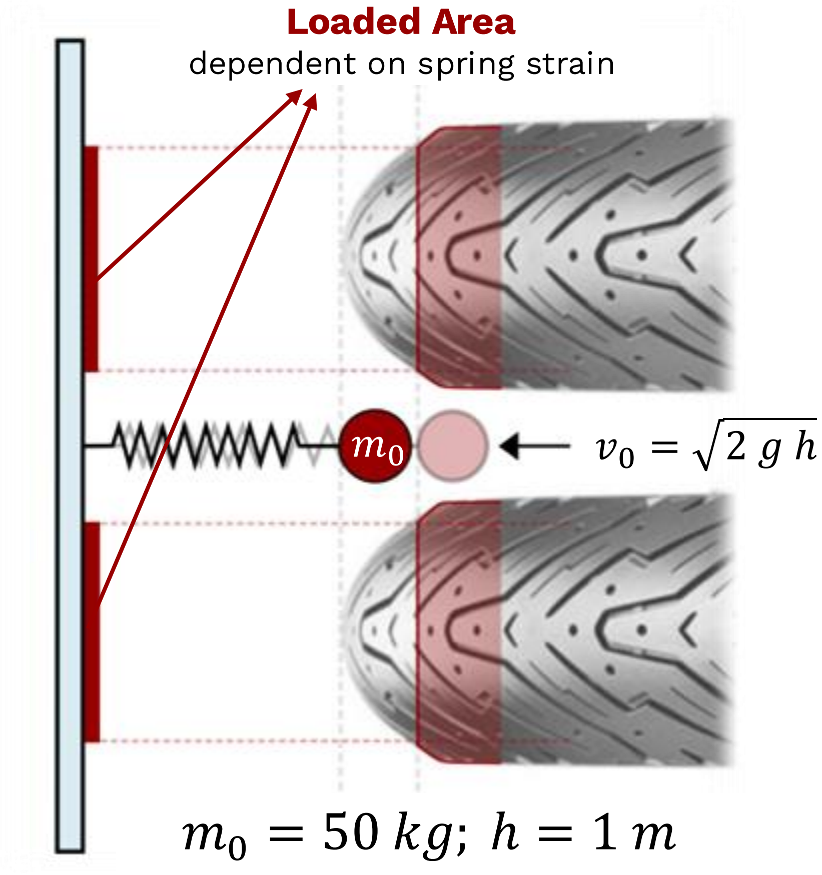


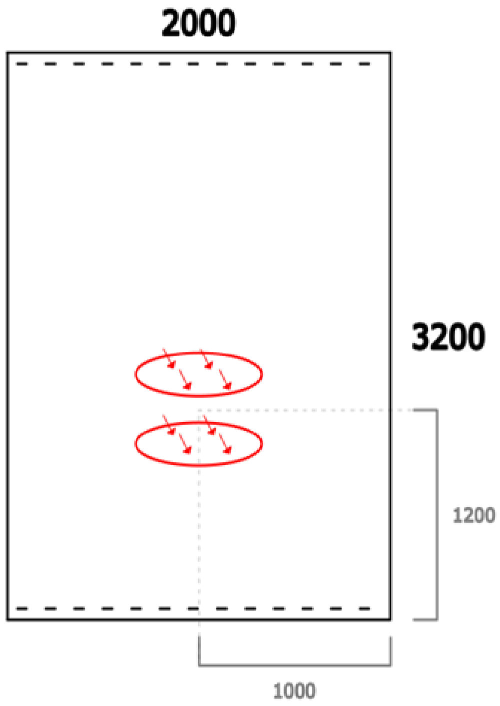


Example 3

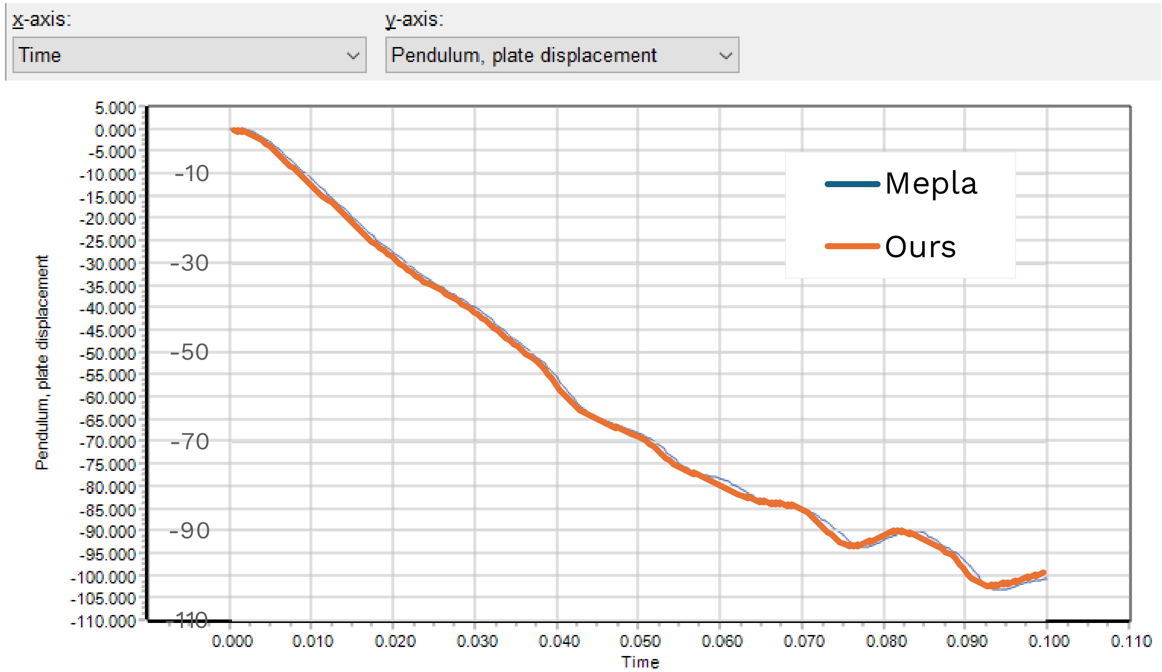


- 2 Sides Supported
- Pendulum Impact
- DIN EN 12600

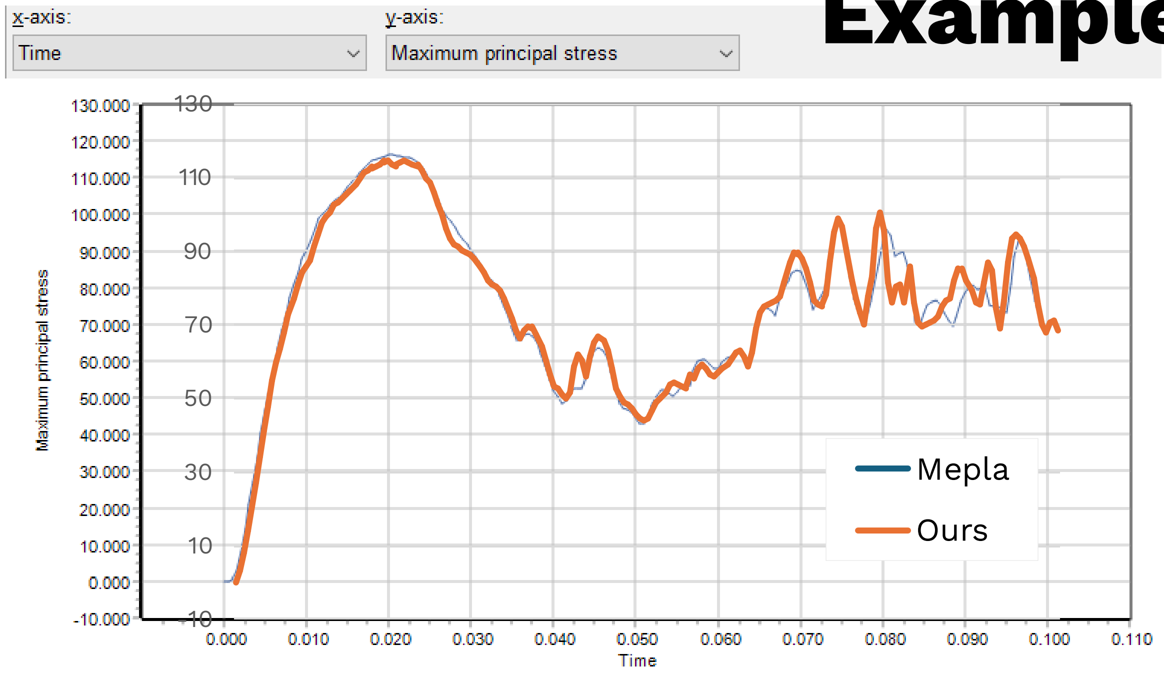




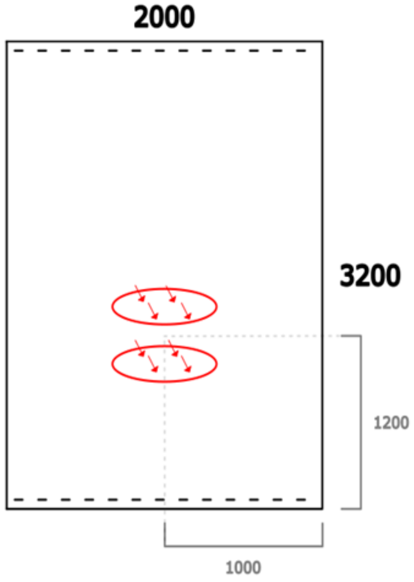
Example 3



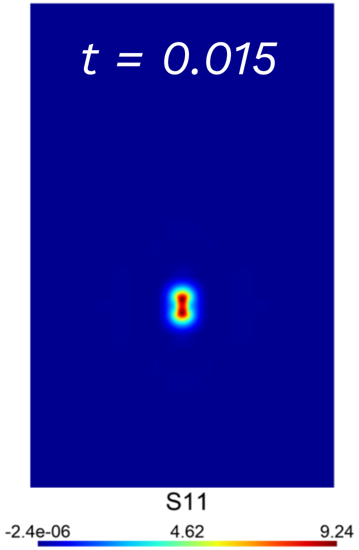
x-axis:
Time
y-axis:
Pendulum, plate displacement
Pendulum, plate displacement
5.000
0.000
-5.000
-10.000
-15.000
-20.000
-25.000
-30.000
-35.000
-40.000
-45.000
-50.000
-55.000
-60.000
-65.000
-70.000
-75.000
-80.000
-85.000
-90.000
-95.000
-100.000
-105.000
-110.000
-10
-30
-50
-70
-90
-110
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
0.110
Time
Mepla
Ours



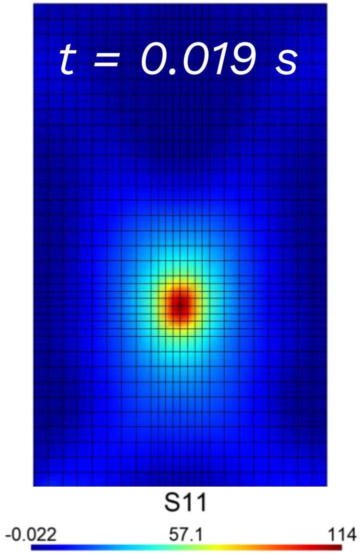
x-axis:
Time
y-axis:
Maximum principal stress
Maximum principal stress
130.000
120.000
110.000
100.000
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
130
110
90
70
50
30
10
-10
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
0.110
Time
Mepla
Ours



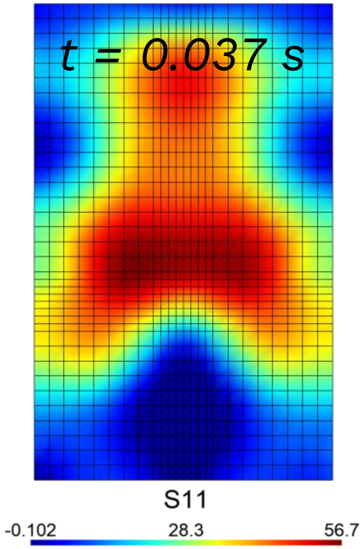
2000
3200
1200
1000



t = 0.015
S11
-2.4e-06
4.62
9.24



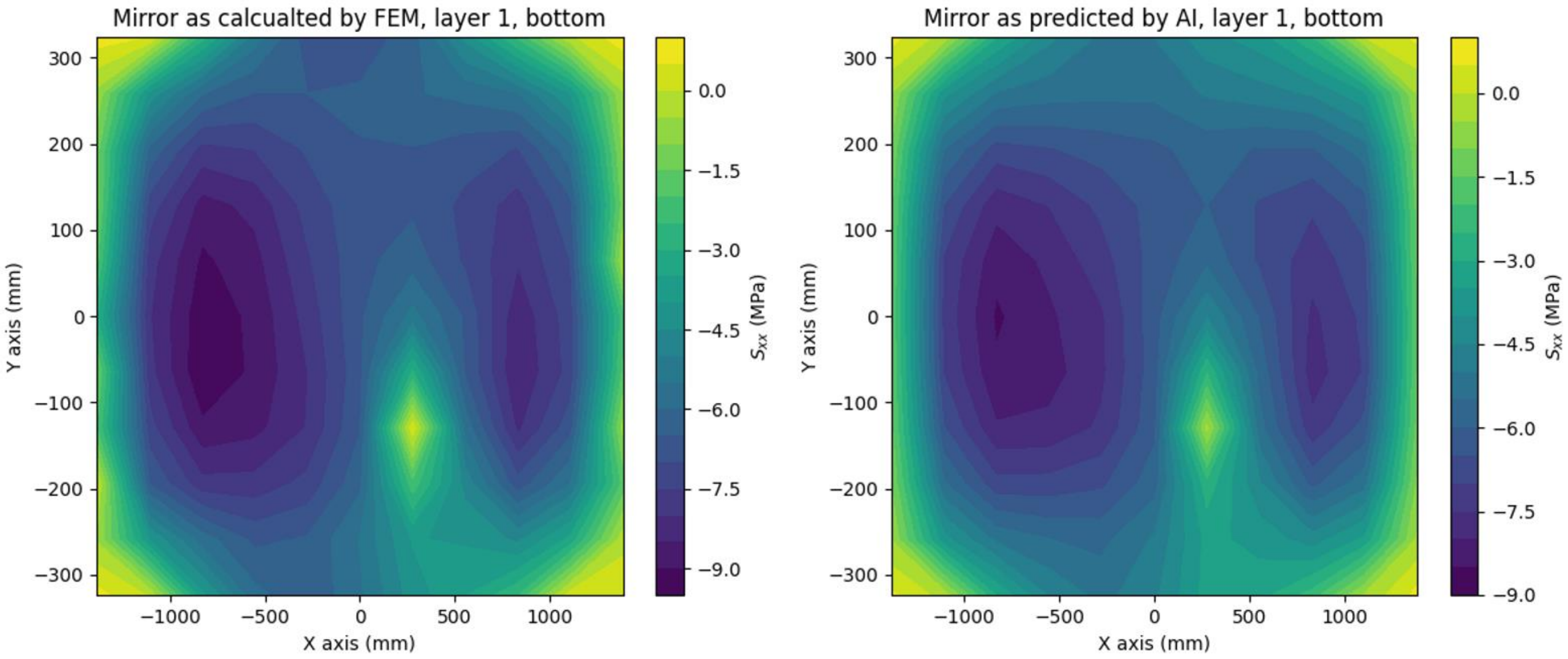
t = 0.019 s
S11
-0.022
57.1
114



t = 0.037 s
S11
-0.102
28.3
56.7

Neural netwok FEM preview

- A trained neural network can predict the outcomes of the FEM calculator in almost zero time and with excellent precision
- We display here S_{xx} when calculated by the FEM and when predicted by the AI for a mirror undergoing a pointy, non-uniform load, self-weight, wind and snow
- Analogous results for climate load and barrier loads!



The GLASSS **Software**

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