

# Computationally Efficient Buckling Analysis of Damaged Composite Sandwich Panels in Wind Turbine Blades

Felix Prigge<sup>a</sup>, Malo Rosemeier<sup>b</sup>, Claudio Balzani<sup>a</sup>

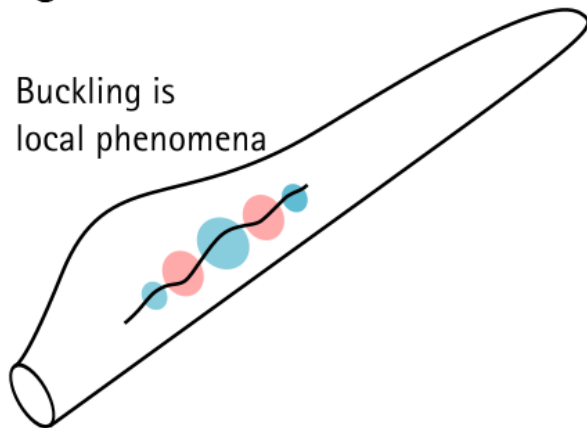
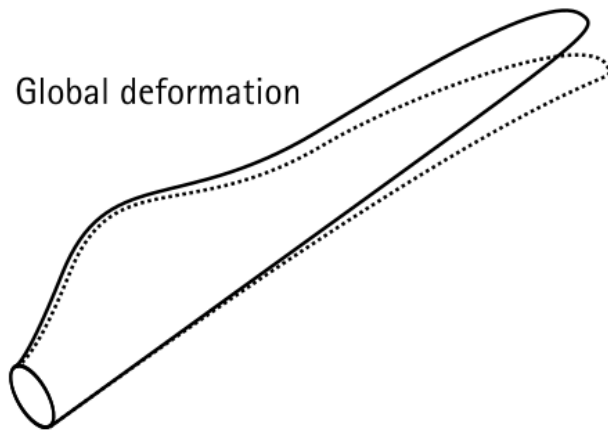
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# Introduction

## Global and local effects at blade and panel scales

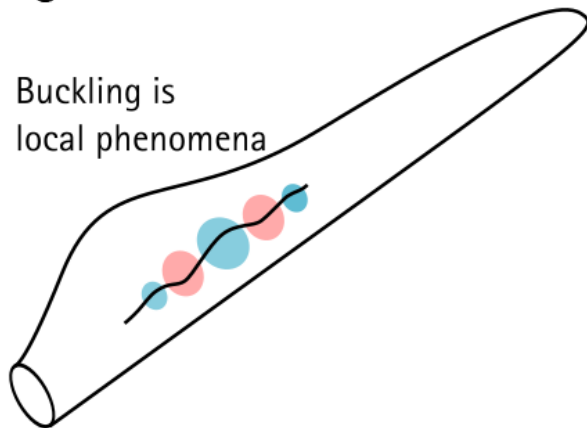
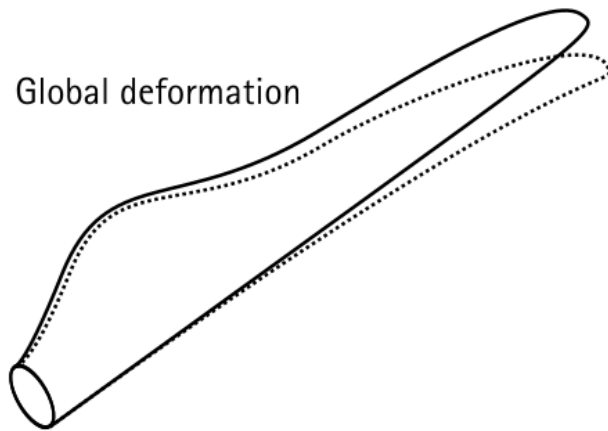
### Blade scale



# Introduction

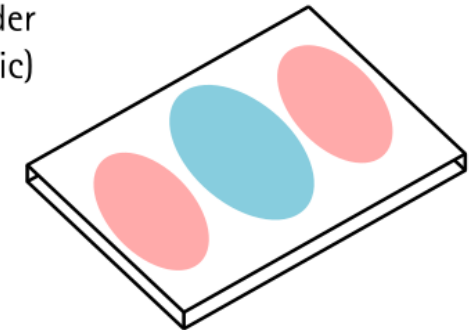
## Global and local effects at blade and panel scales

### Blade scale



### Panel scale

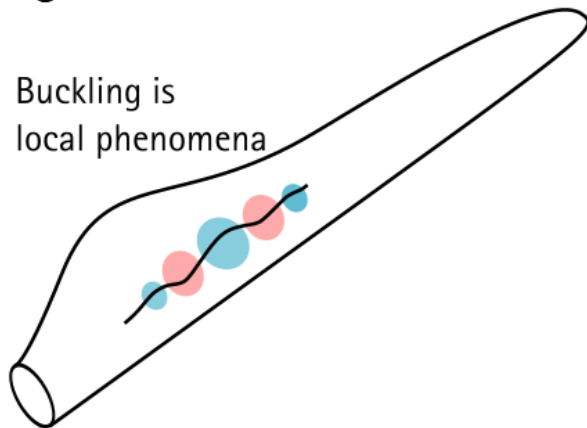
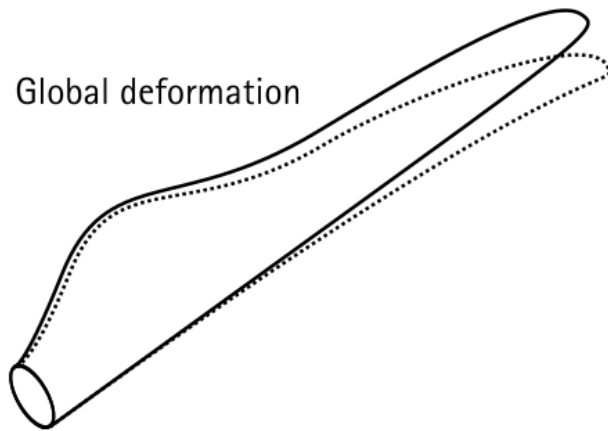
Global buckling  
(low order  
harmonic)



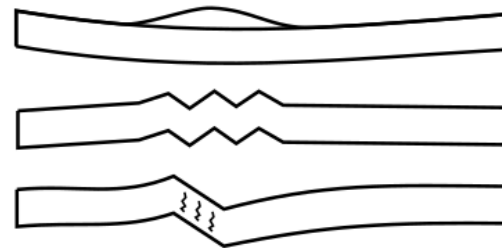
# Introduction

## Global and local effects at blade and panel scales

### Blade scale

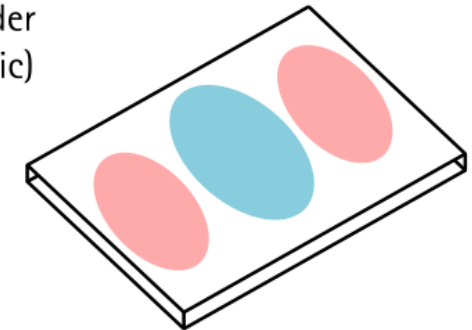


Local effects:  
Delamination  
Face wrinkling  
Shear crimping



### Panel scale

Global buckling  
(low order harmonic)



## Motivation

Creating a mesh generator for arbitrary curved and pre-damaged sandwich panels for large parameter studies  
Ansys Mechanical APDL 19.2



### Fastness:

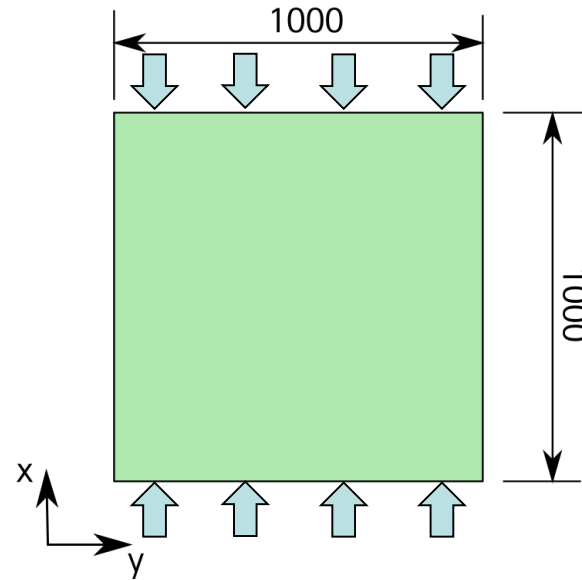
Least required DOF / mesh resolution to model damages?

### Robustness:

Meshing procedure robust enough for a large variation of parameters,  
e.g. different layer thicknesses?  
Critical element aspect ratios?

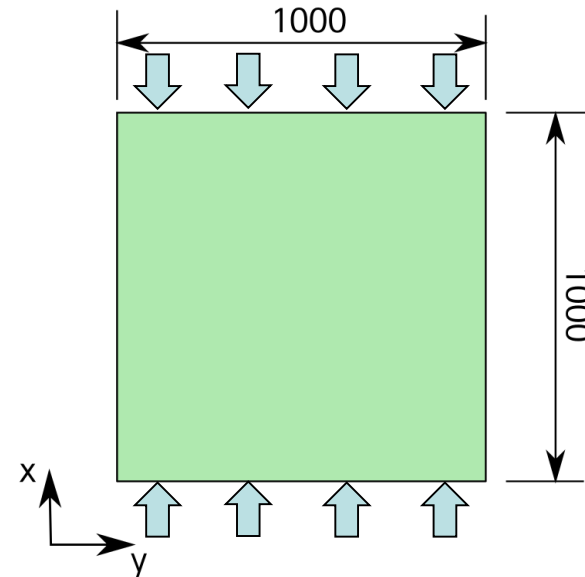
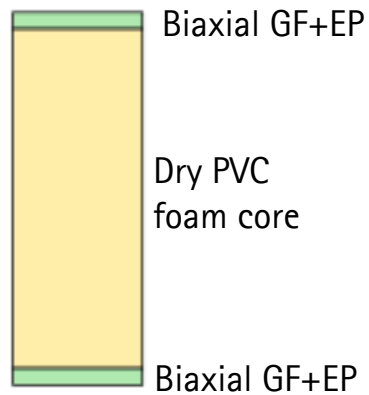
Equal refinement in all three dimensions not really suitable for sandwich structures:  
Complication with classical mesh convergence study

# Properties of investigated sandwich panel



# Properties of investigated sandwich panel

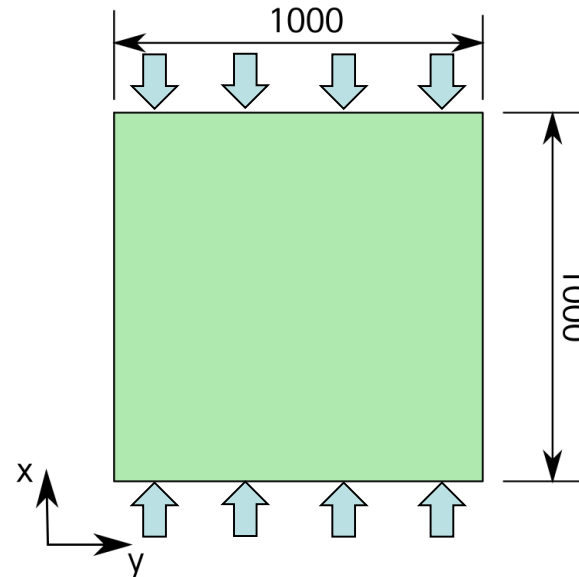
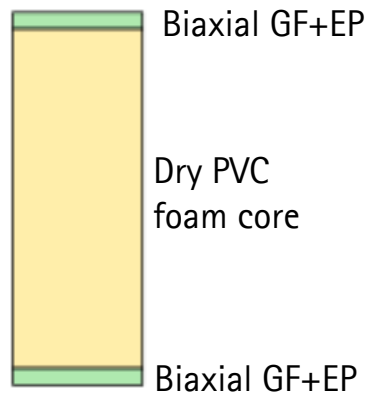
Material layup:



Properties	t	$E_{11}$ [MPa]	$E_{22}$	$E_{33}$	$G_{12}$	$G_{23}$	$G_{13}$	$\nu_{12}$	$\nu_{23}$	$\nu_{13}$
Unit	[mm]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]			
2AX-0800-0440	2.2	13445	13445	11932	3864.6	3864.6	3864.6	0.67	0.2	0.2
2AX-0800-0440 damaged	2.2	12101	12101	10739	3478.1	3478.1	3478.1	0.67	0.2	0.2
C7055_dry	45	45	45	45	22	22	22	0.3	0.3	0.3

# Properties of investigated sandwich panel

Material layup:



Boundary conditions:  
Simple support on all edges

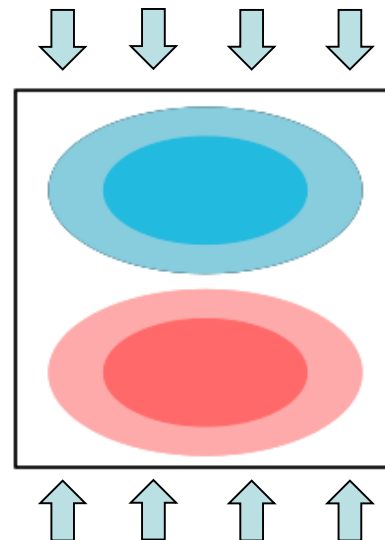
Properties	t	$E_{11}$ [MPa]	$E_{22}$	$E_{33}$	$G_{12}$	$G_{23}$	$G_{13}$	$\nu_{12}$	$\nu_{23}$	$\nu_{13}$
Unit	[mm]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]			
2AX-0800-0440	2.2	13445	13445	11932	3864.6	3864.6	3864.6	0.67	0.2	0.2
2AX-0800-0440 damaged	2.2	12101	12101	10739	3478.1	3478.1	3478.1	0.67	0.2	0.2
C7055_dry	45	45	45	45	22	22	22	0.3	0.3	0.3



# Analytic results of buckling modes

Eigenmode	1.
Mode shape	Second half wave
Buckling resistance	$k=1.675$

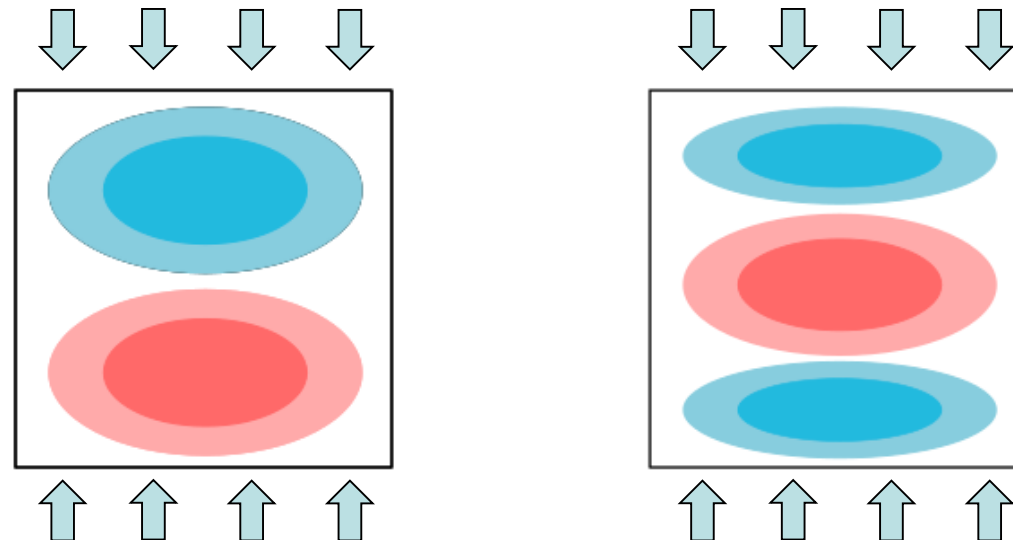
WIEDEMANN, J. (2007)



# Analytic results of buckling modes

Eigenmode	1.	2.
Mode shape	Second half wave	Third half wave
Buckling resistance	$k=1.675$	$k=1.720$

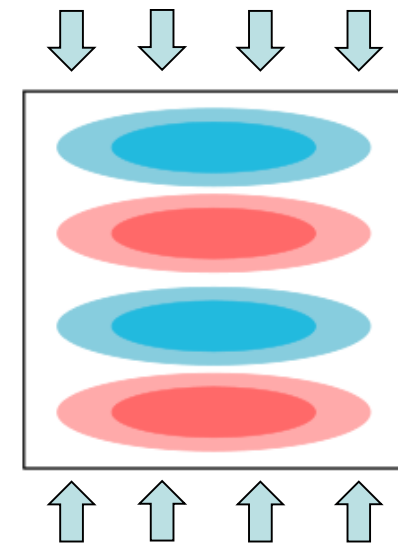
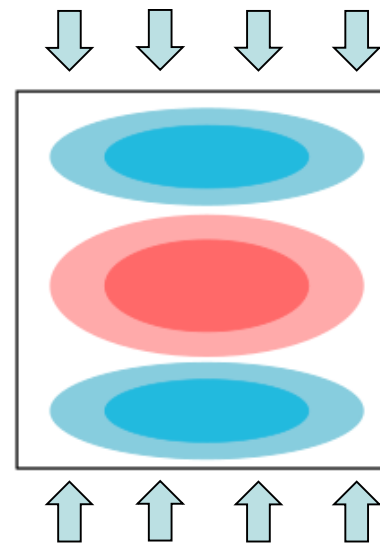
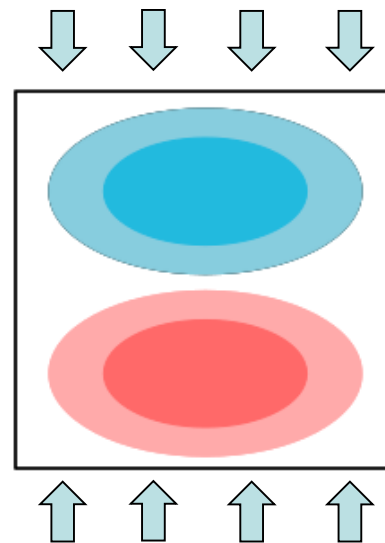
WIEDEMANN, J. (2007)



# Analytic results of buckling modes

Eigenmode	1.	2.	3.
Mode shape	Second half wave	Third half wave	Fourth half wave
Buckling resistance	$k=1.675$	$k=1.720$	$k=1.758$

WIEDEMANN, J. (2007)

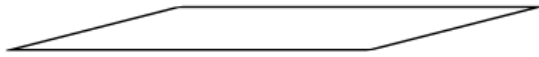


## Investigated element types

- Shell elements:
  - Linear trial functions:
    - 4-node shell
  - Quadratic trial functions:
    - 8-node shell
- Continuum elements:
  - Linear trial functions:
    - 8-node layered solids
    - 8-node solid shell
  - Quadratic trial functions:
    - 20-node layered solid

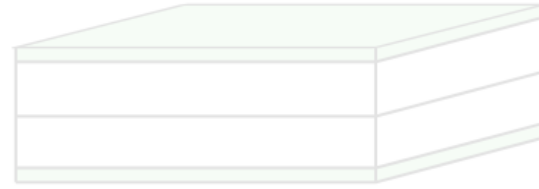
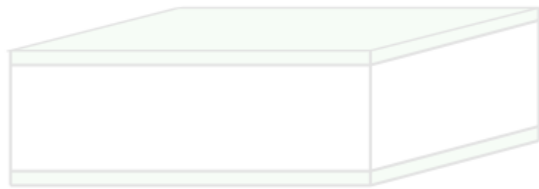
# Investigated mesh topologies

Shell elements:



Shell elements with layered material definition

Continuum elements:



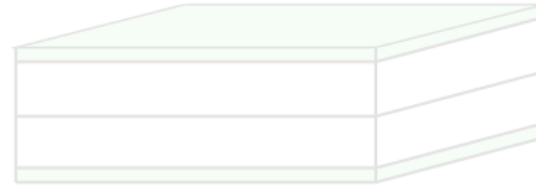
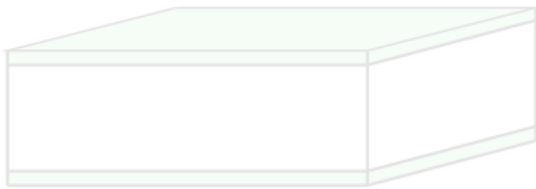
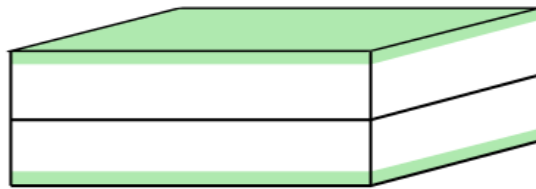
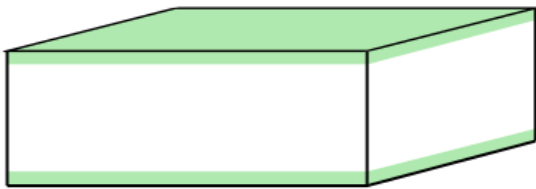
# Investigated finite element mesh topologies

Shell elements:



Layered element definition.  
Mesh topology does not represent material layup

Continuum elements:



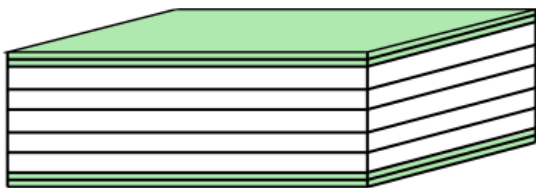
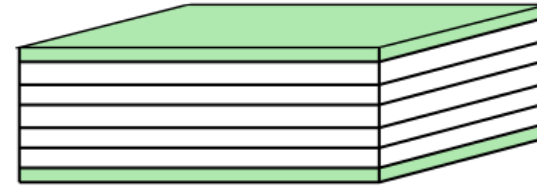
# Investigated finite element mesh topologies

Shell elements:



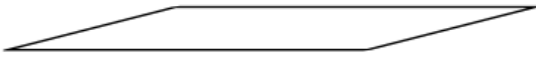
Mesh topology represents material layup

Continuum elements:

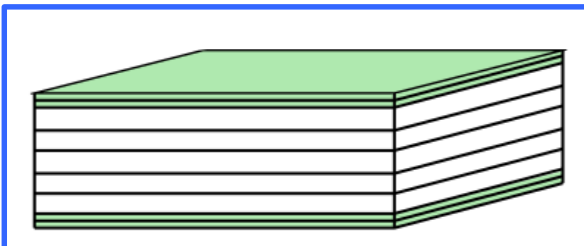
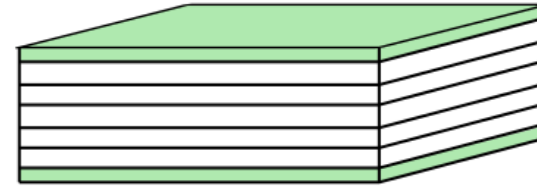
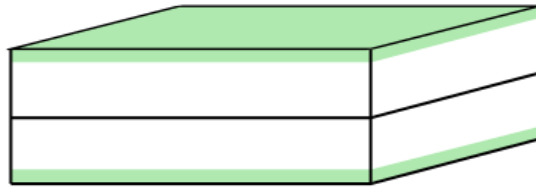
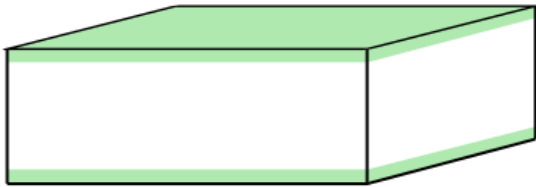


# Investigated finite element mesh topologies

Shell elements:



Continuum elements:

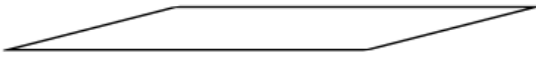


Mesh topology for high resolution reference simulation

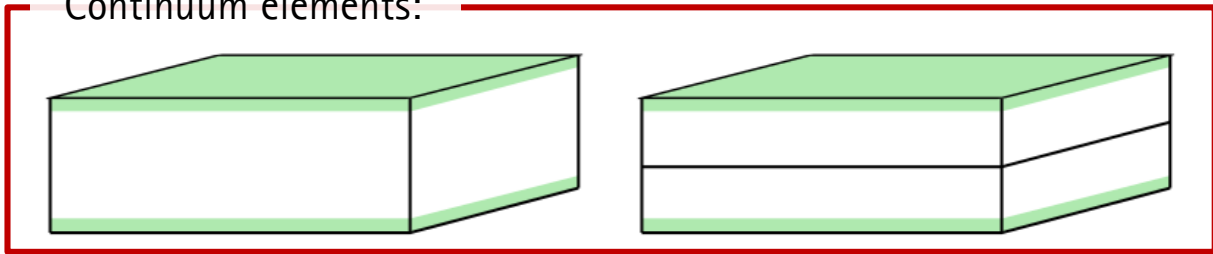


# Investigated finite element mesh topologies

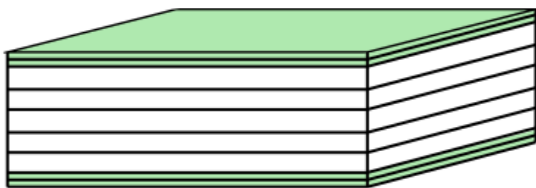
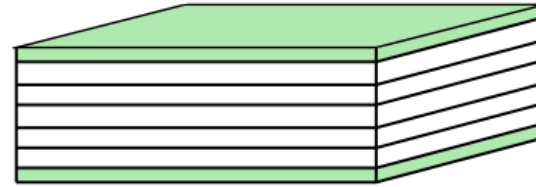
Shell elements:



Continuum elements:

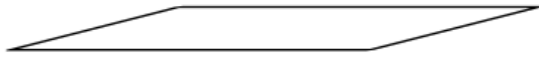


Mesh topology not suitable  
for buckling analysis.  
Results are skipped

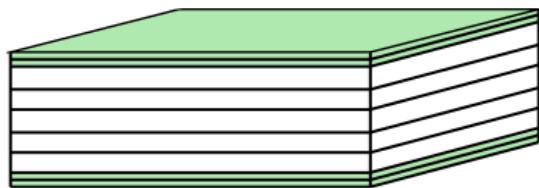
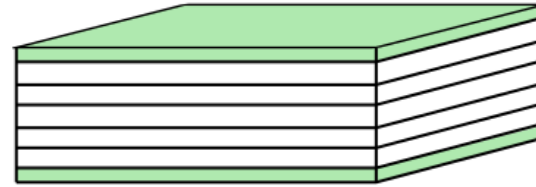


# Investigated finite element mesh topologies

Shell elements:

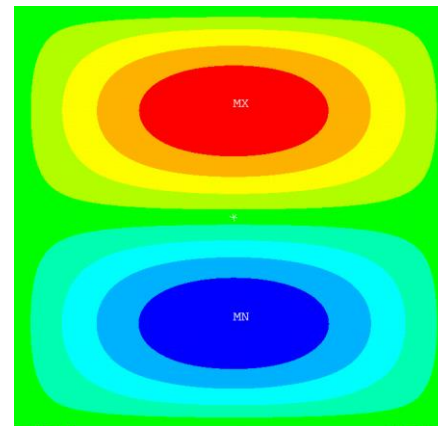
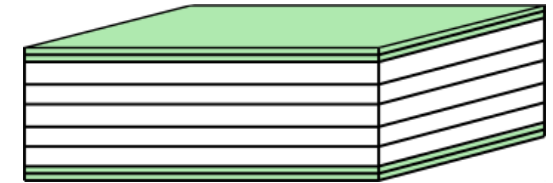


Continuum elements:

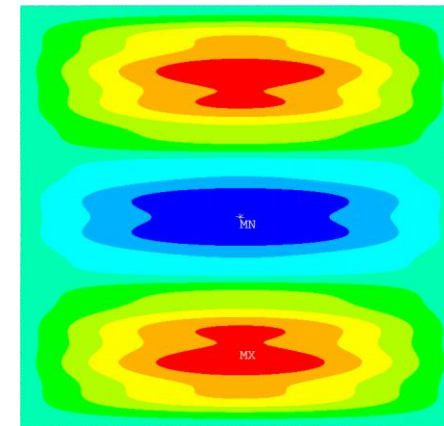


Homogeneous mesh refinement in x and y direction

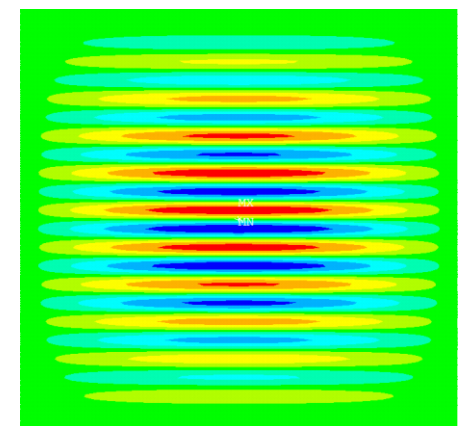
# High resolution reference mesh. Linear eigenvalue buckling 2 layers in face sheets, 5 layers in core, 20-node layered solids



Eigenmode 1:  
 $k=1.6810$   
low order harmonic  
2nd half-wave



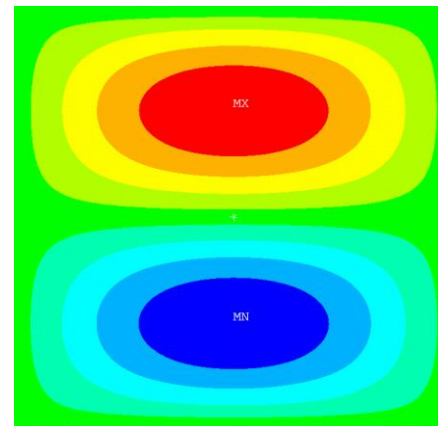
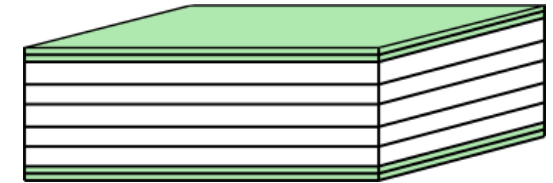
Eigenmode 2:  
 $k=1.7395$   
Mode superposition,  
dominated by  
3rd half-wave



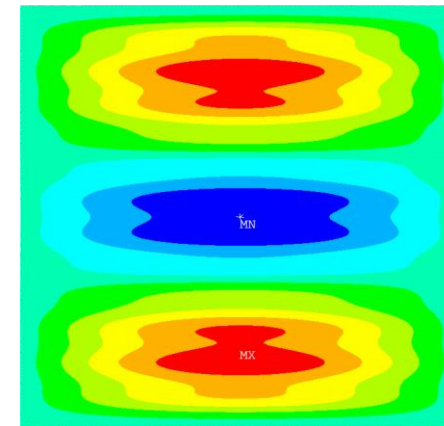
Eigenmode 3:  
 $k=1.7400$   
Mode superposition of high  
order harmonics

# High resolution reference mesh

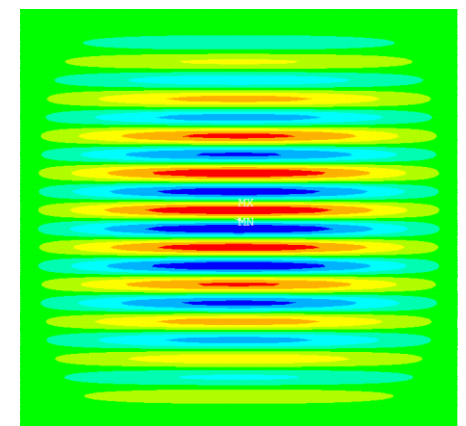
2 layers in face sheets, 5 layers in core, 20-node layered solids



Eigenmode 1:  
 $k=1.6810$   
low order harmonic  
2nd half-wave



Eigenmode 2:  
 $k=1.7395$   
Mode superposition,  
dominated by  
3rd half-wave



Eigenmode 3:  
 $k=1.7400$   
Mode superposition of high  
order harmonics

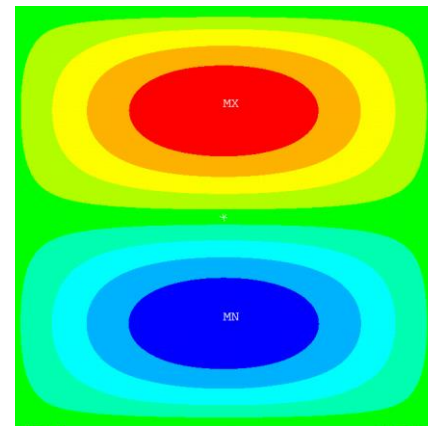
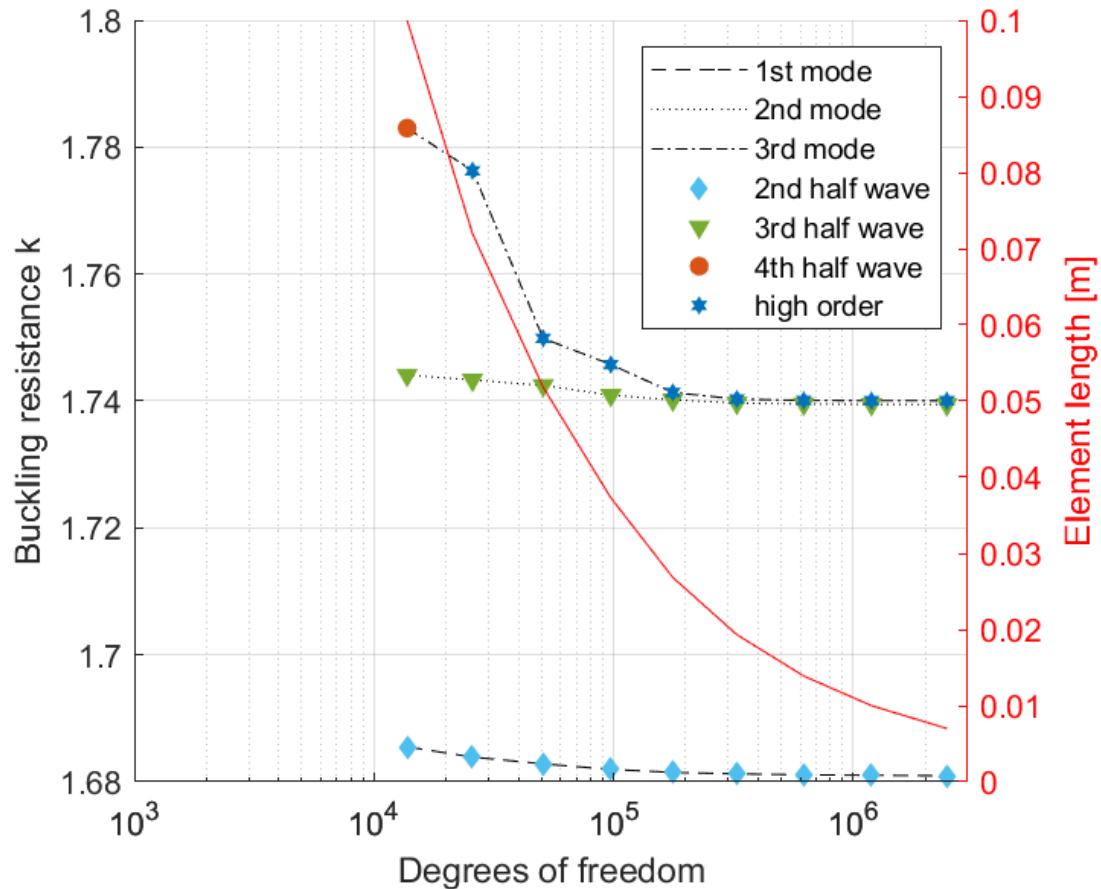
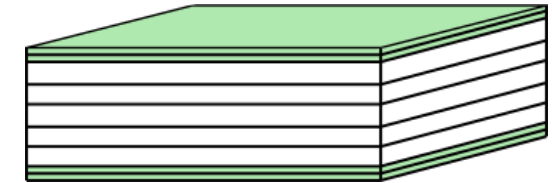
Analytical result:

$k=1.675$

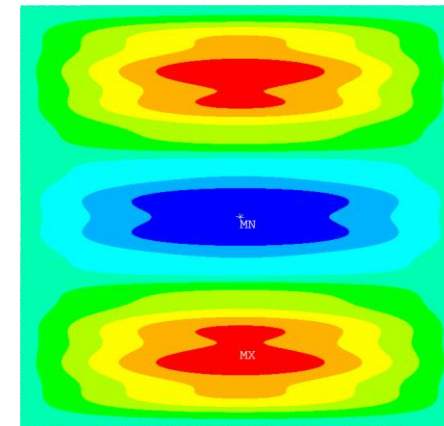
$k=1.720$

# High resolution reference mesh

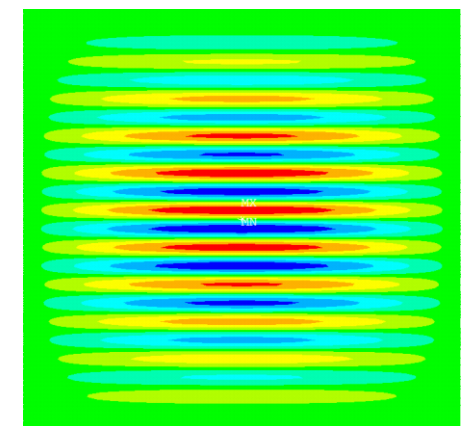
2 layers in face sheets, 5 layers in core, 20-node layered solids



Eigenmode 1:  
 $k=1.6810$   
 low order harmonic  
 2nd half-wave



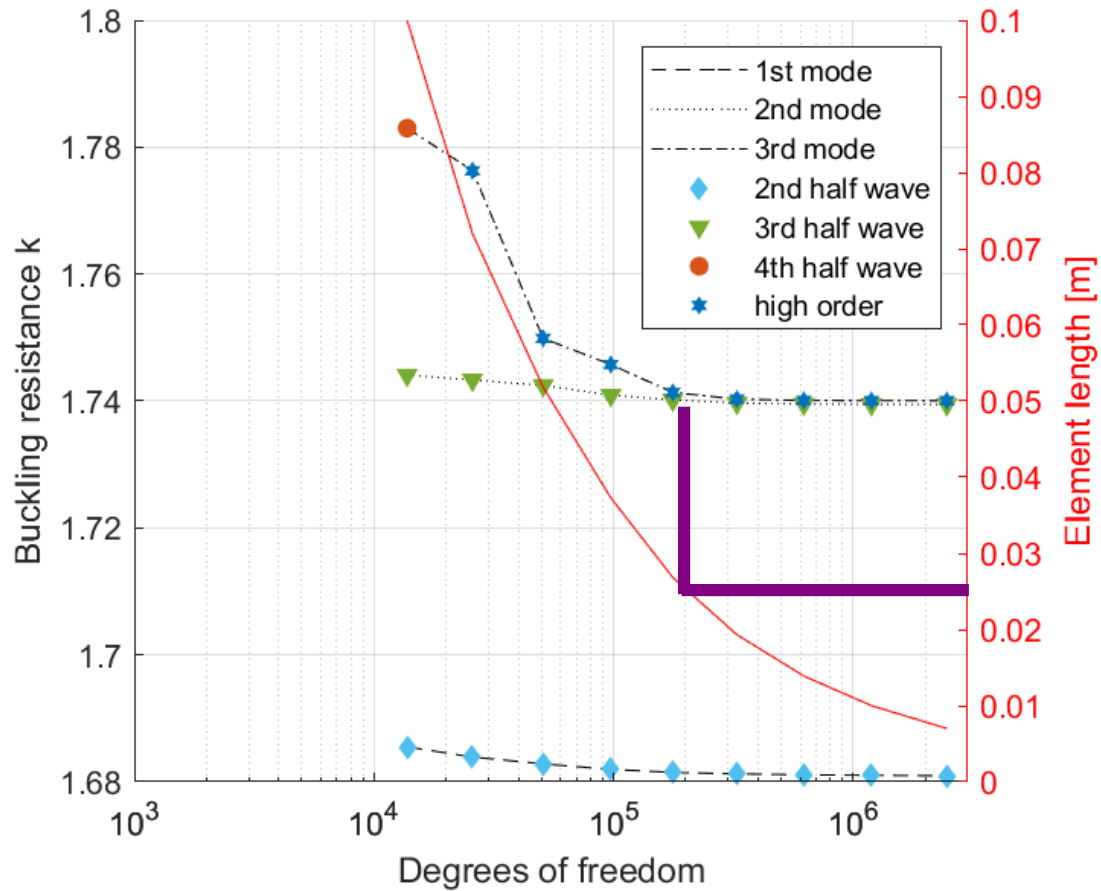
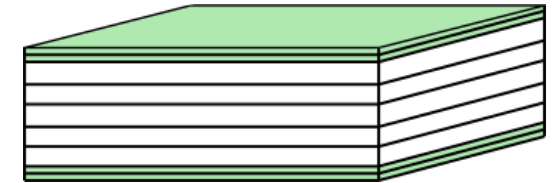
Eigenmode 2:  
 $k=1.7395$   
 Mode superposition,  
 dominated by  
 3rd half-wave



Eigenmode 3:  
 $k=1.7400$   
 Mode superposition of high  
 order harmonics

# High resolution reference mesh

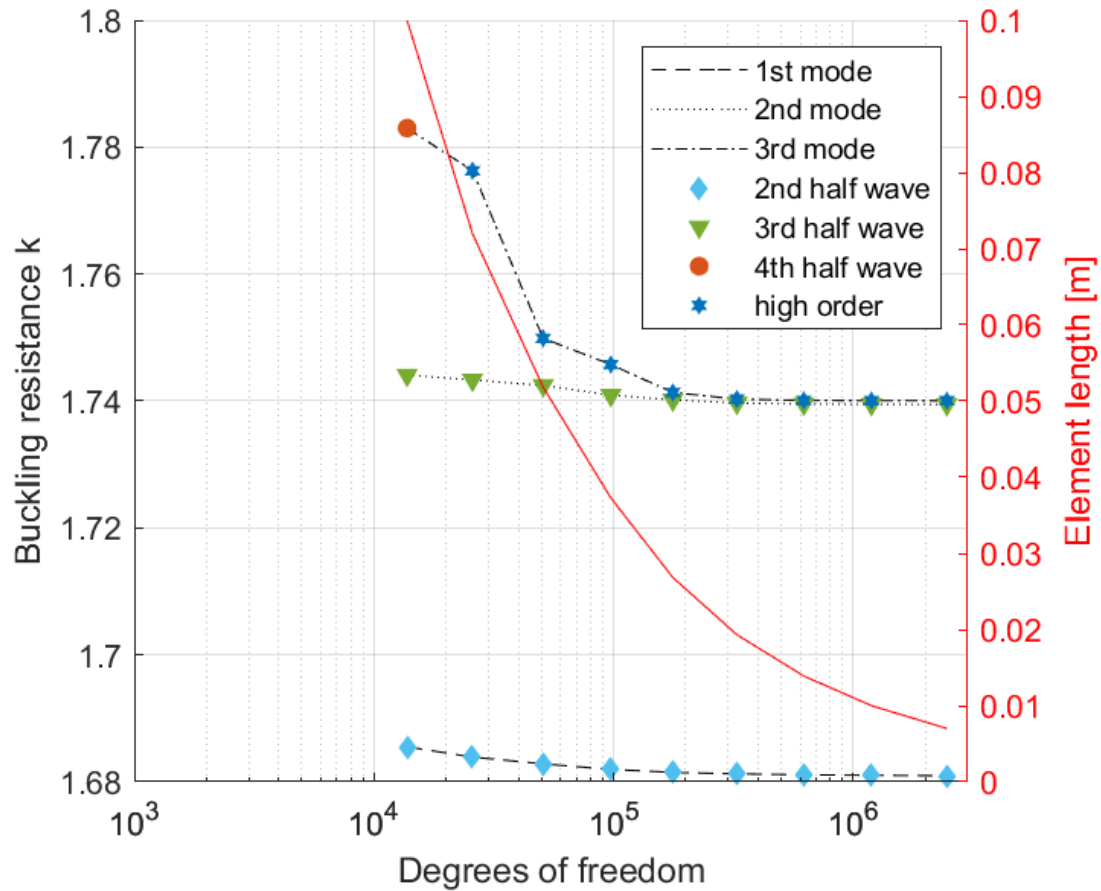
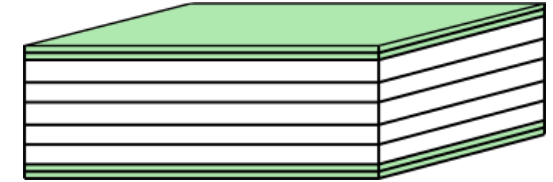
2 layers in face sheets, 5 layers in core, 20-node layered solids



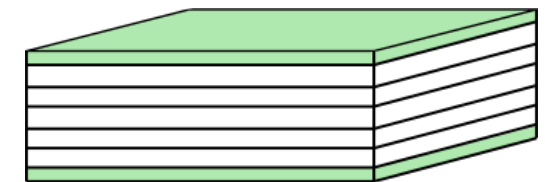
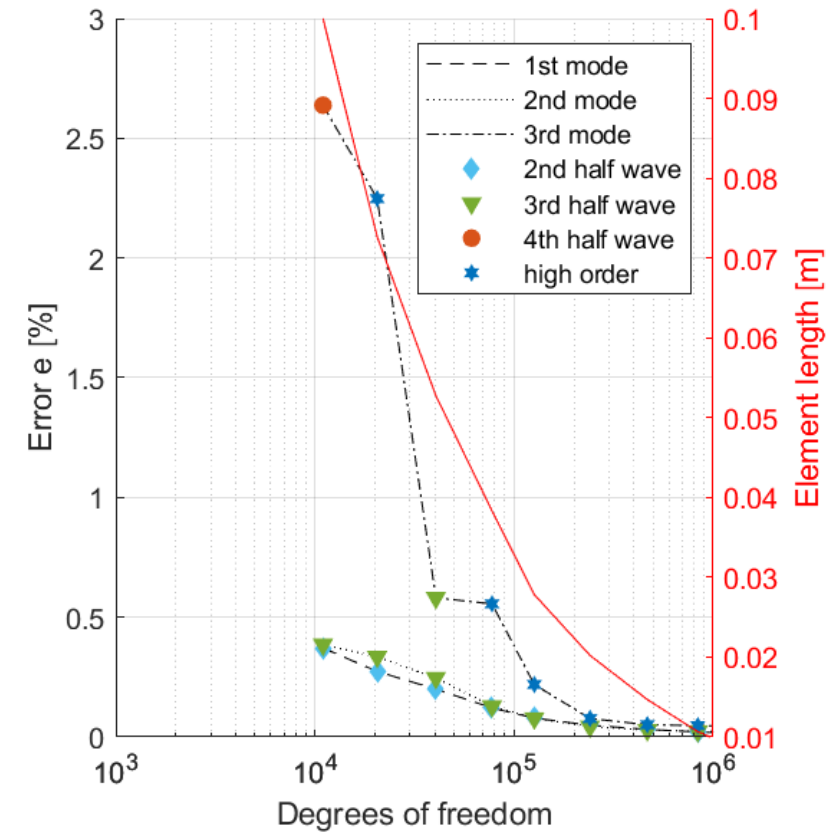
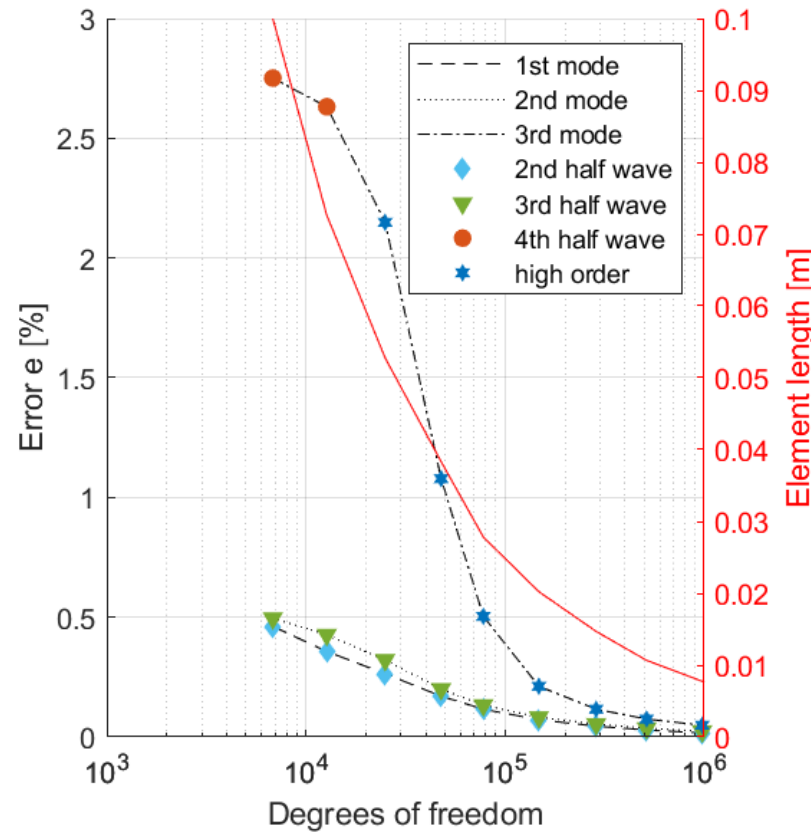
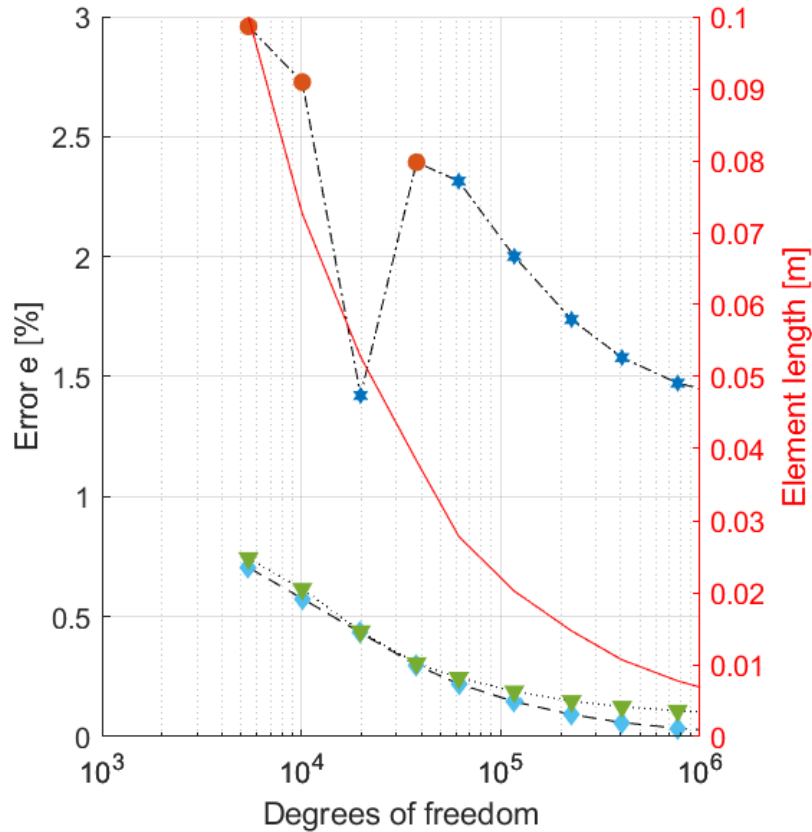
Face sheet element aspect ratio:  
> 20:1

# High resolution reference mesh

2 layers in face sheets, 5 layers in core, 20-node layered solids

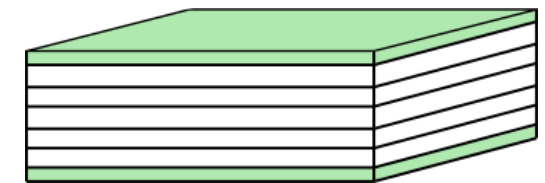
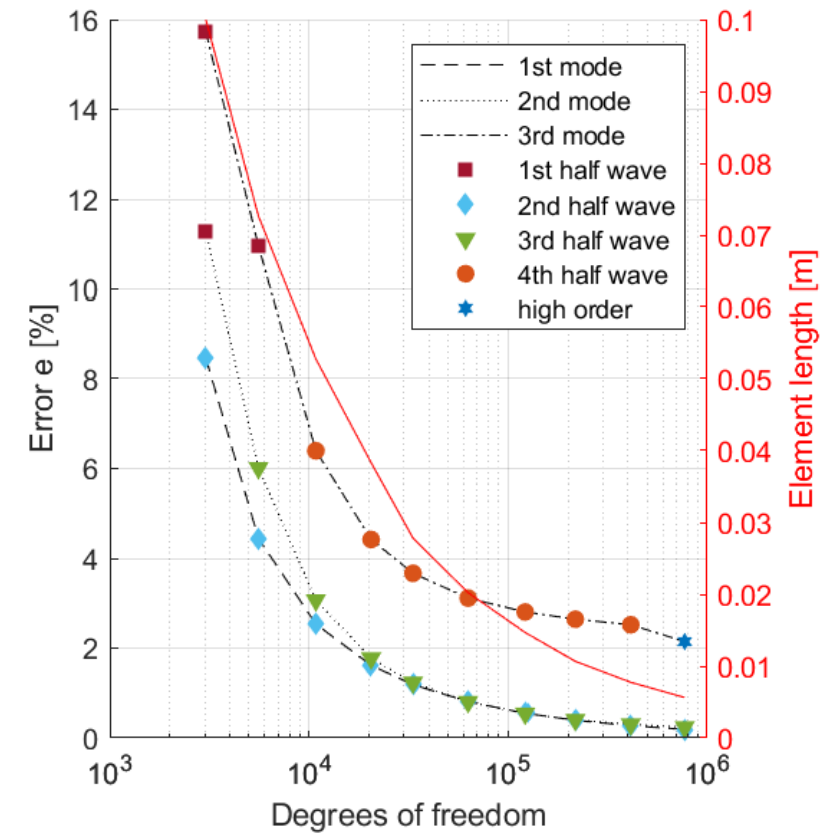
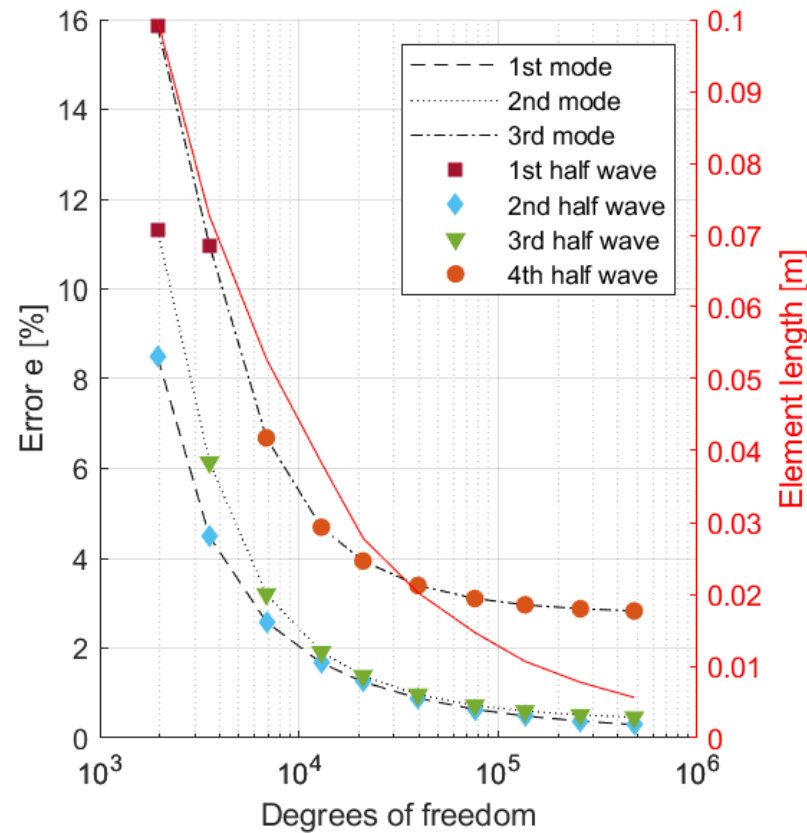
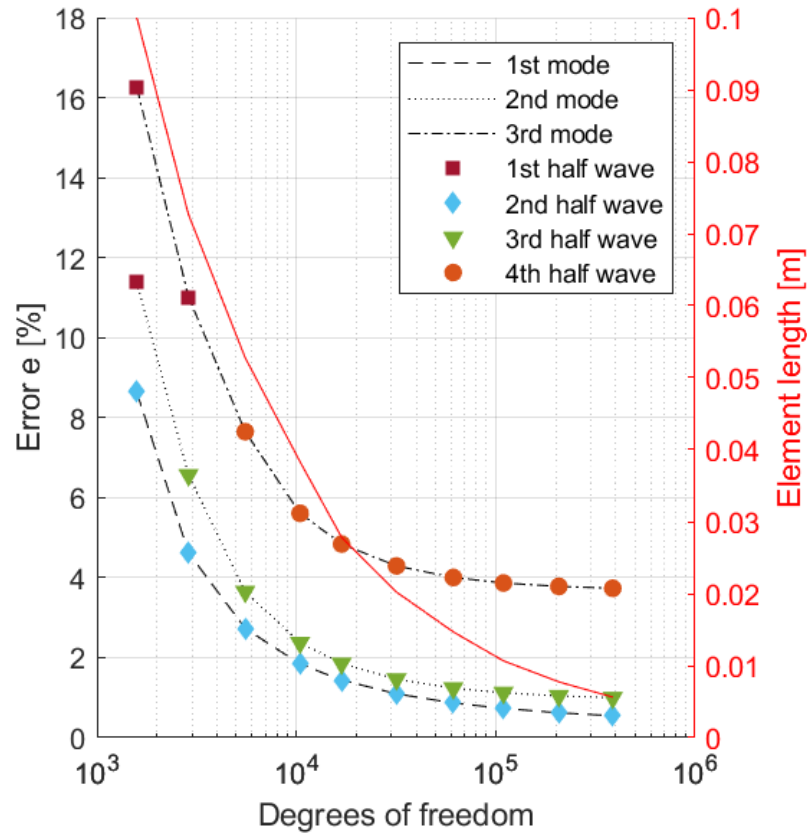


# 20-node layered solid elements. Error compared to reference

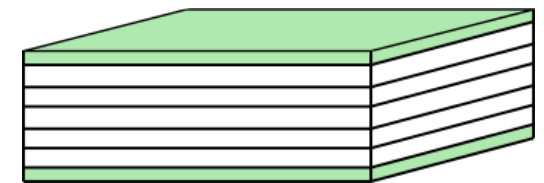
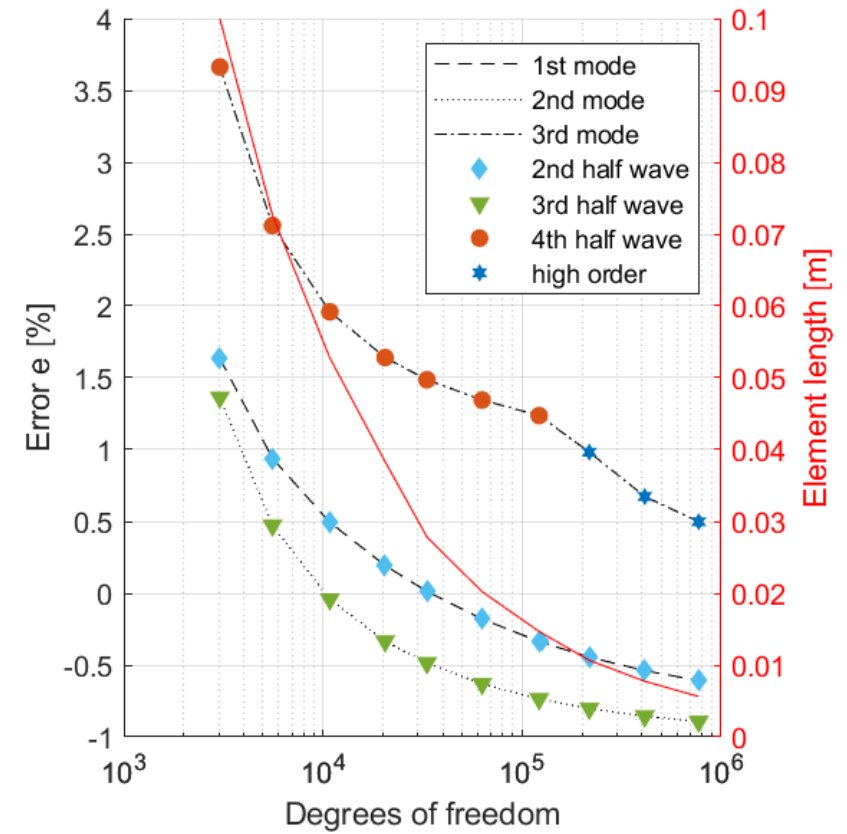
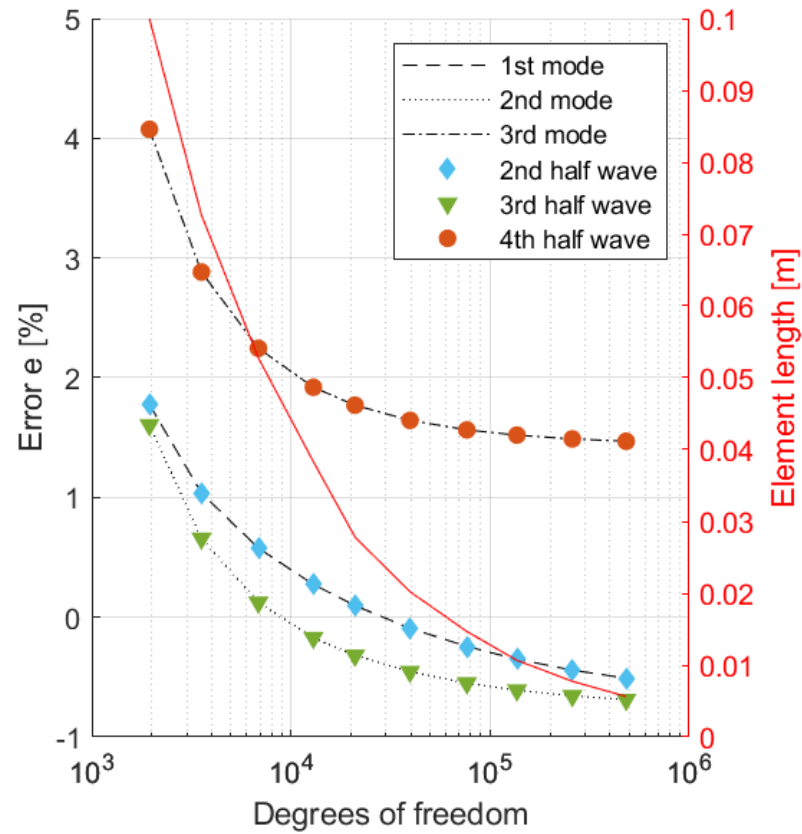
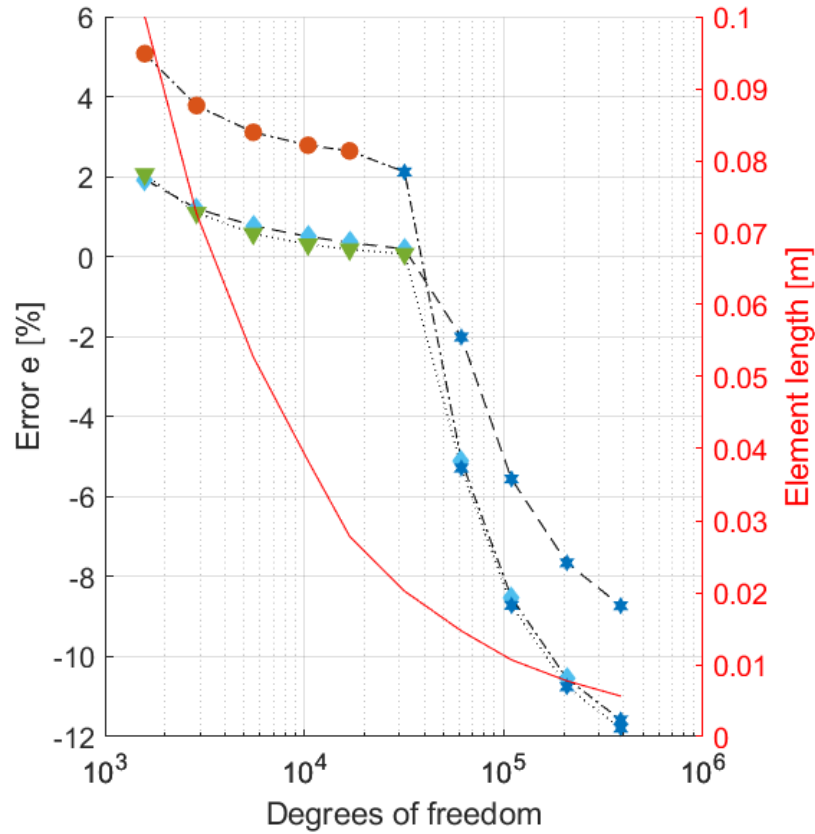




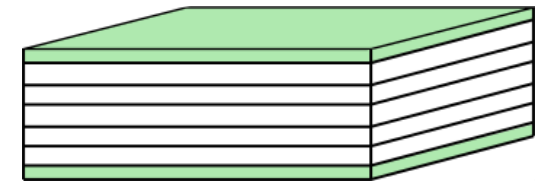
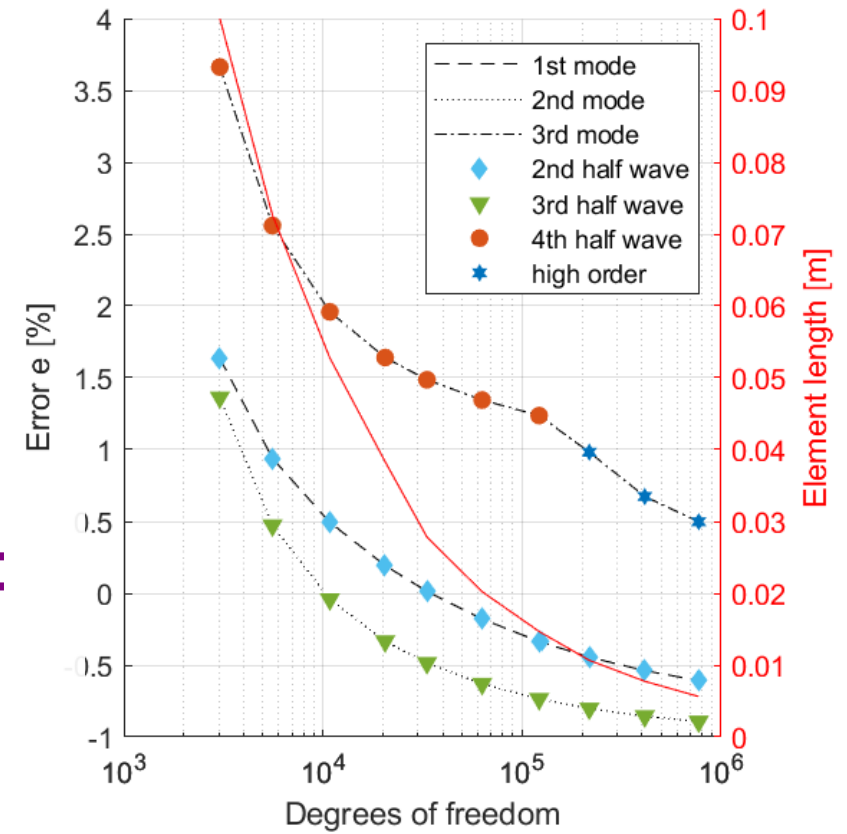
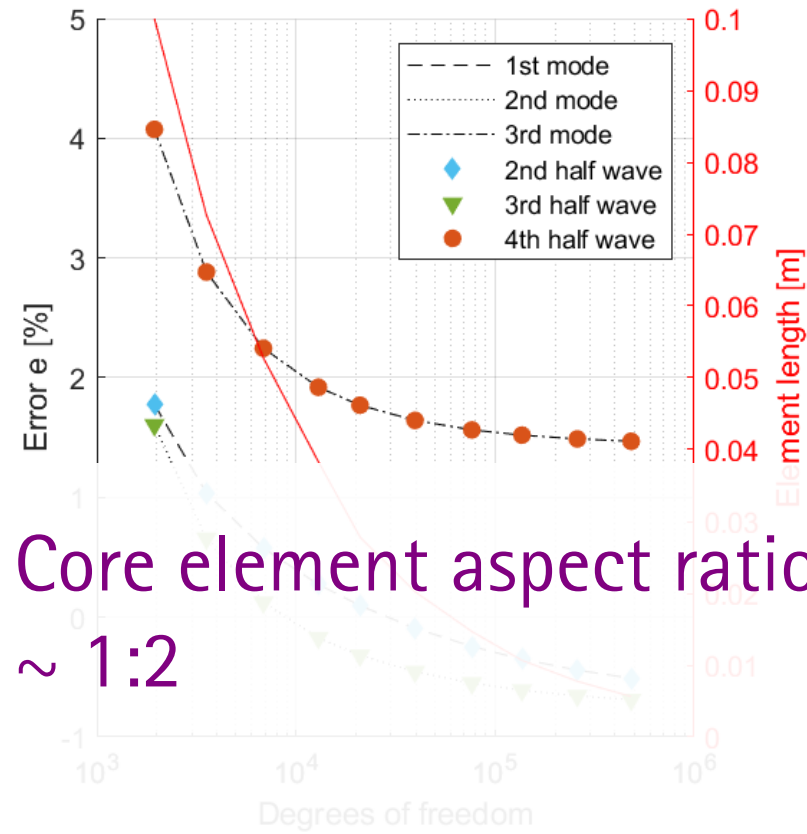
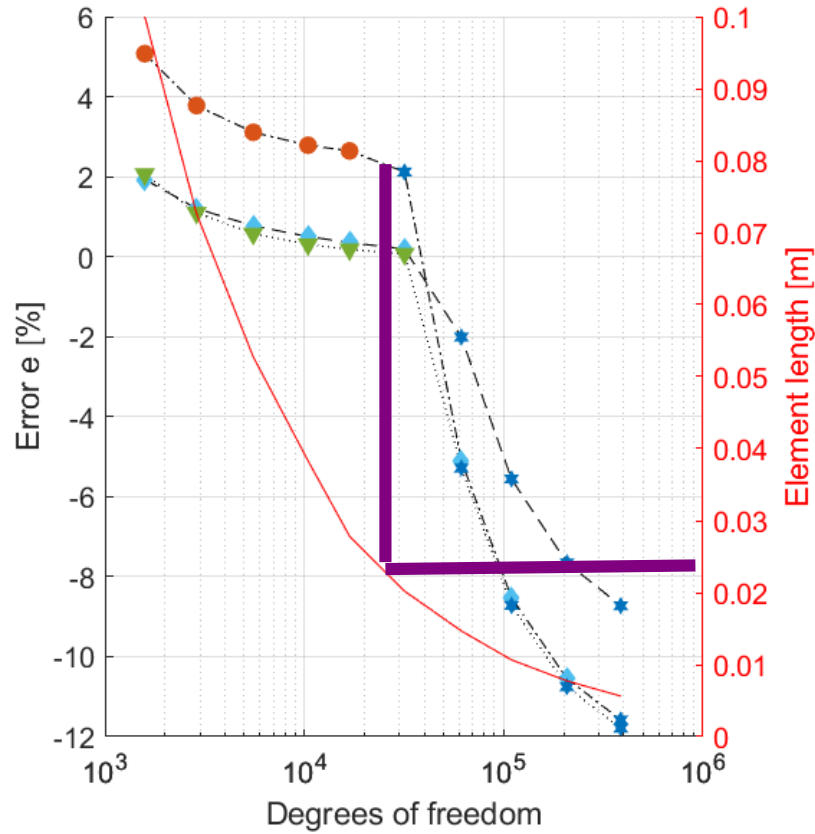
# 8-node layered solid elements. Error compared to reference



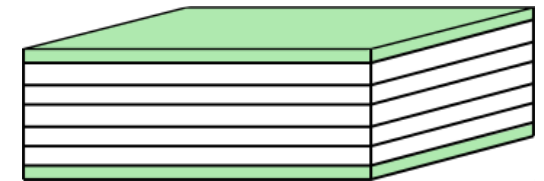
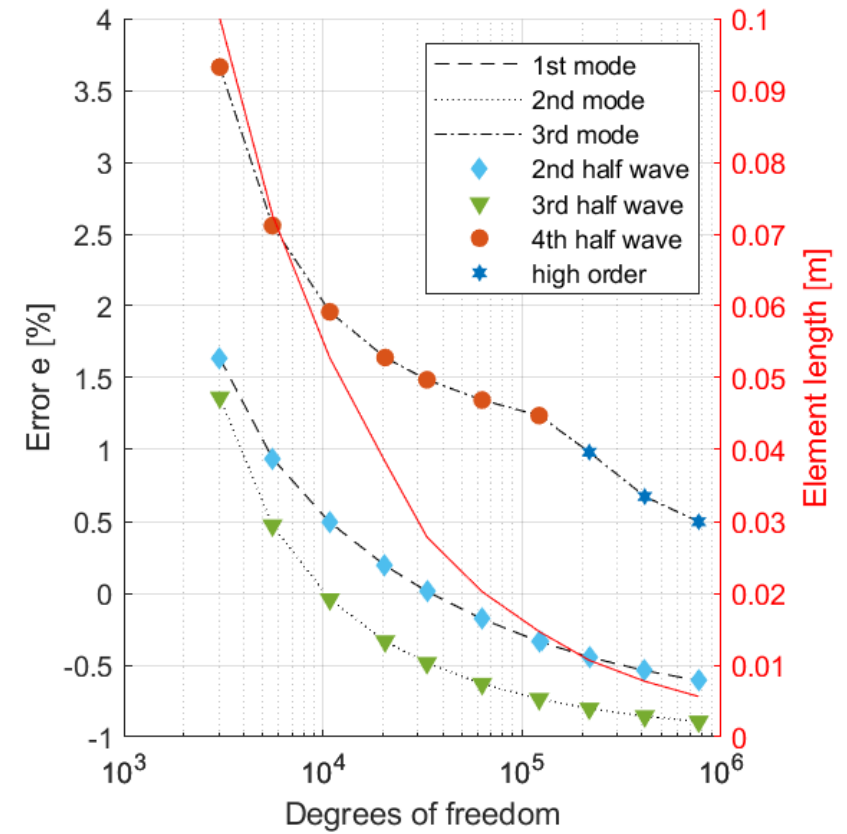
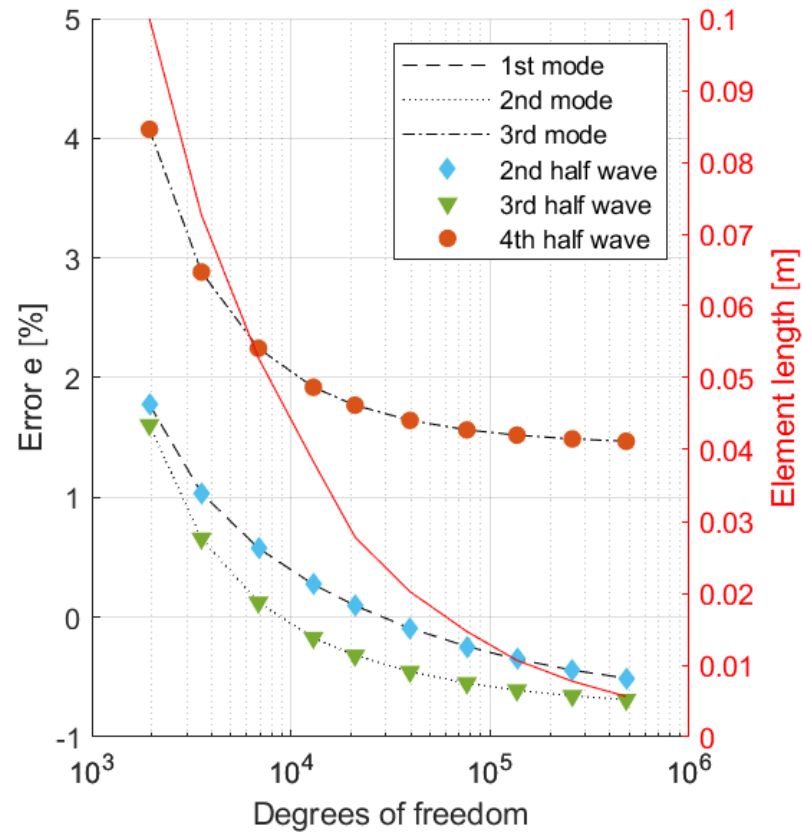
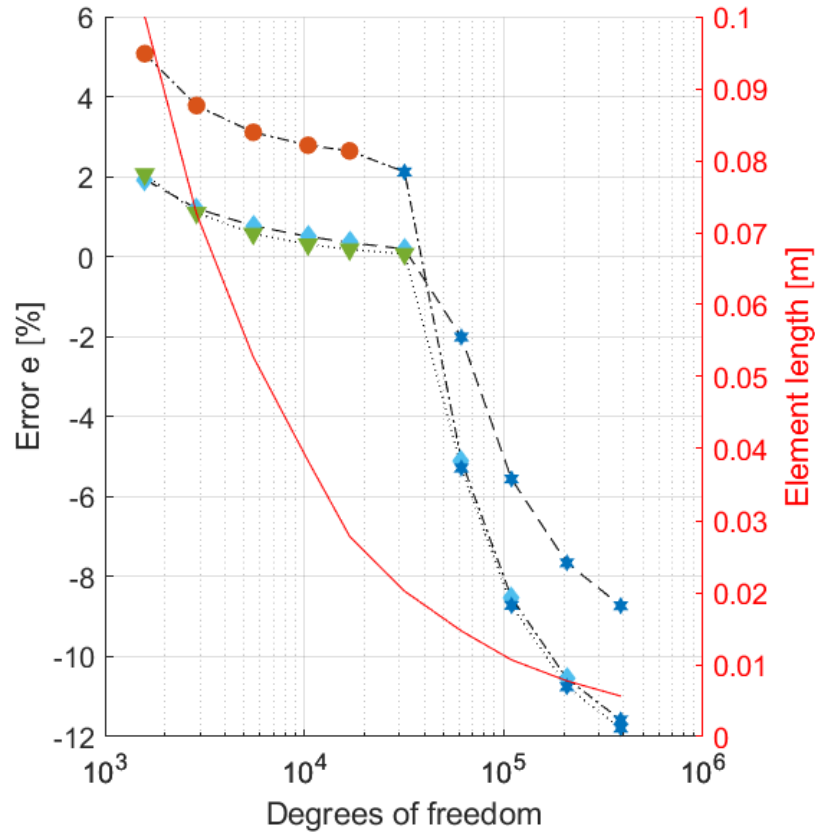
# 8-node solid shell elements. Error compared to reference



# 8-node solid shell elements. Error compared to reference



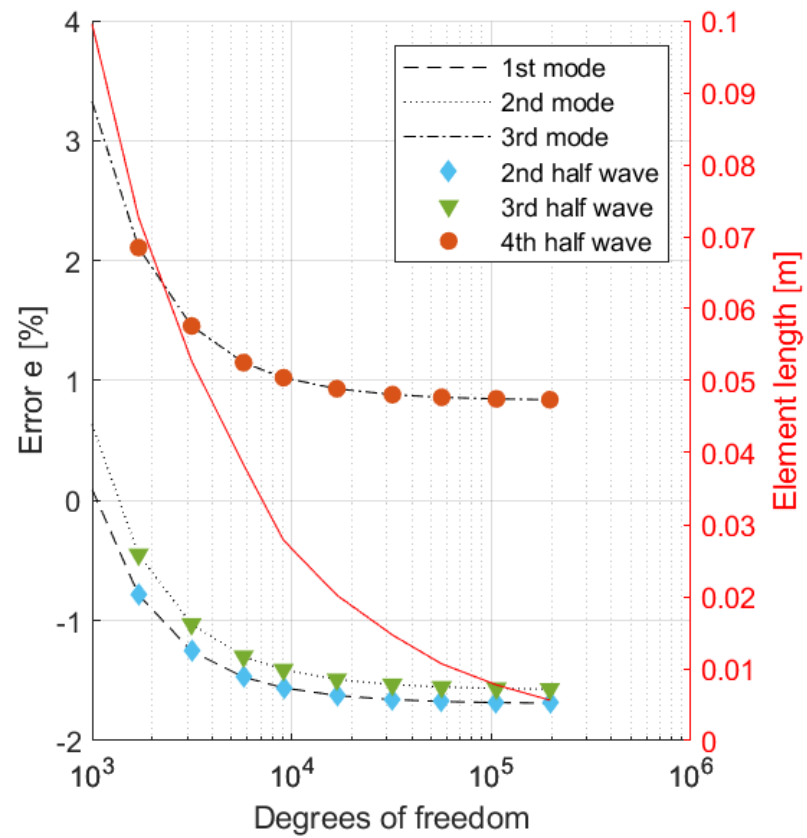
# 8-node solid shell elements. Error compared to reference



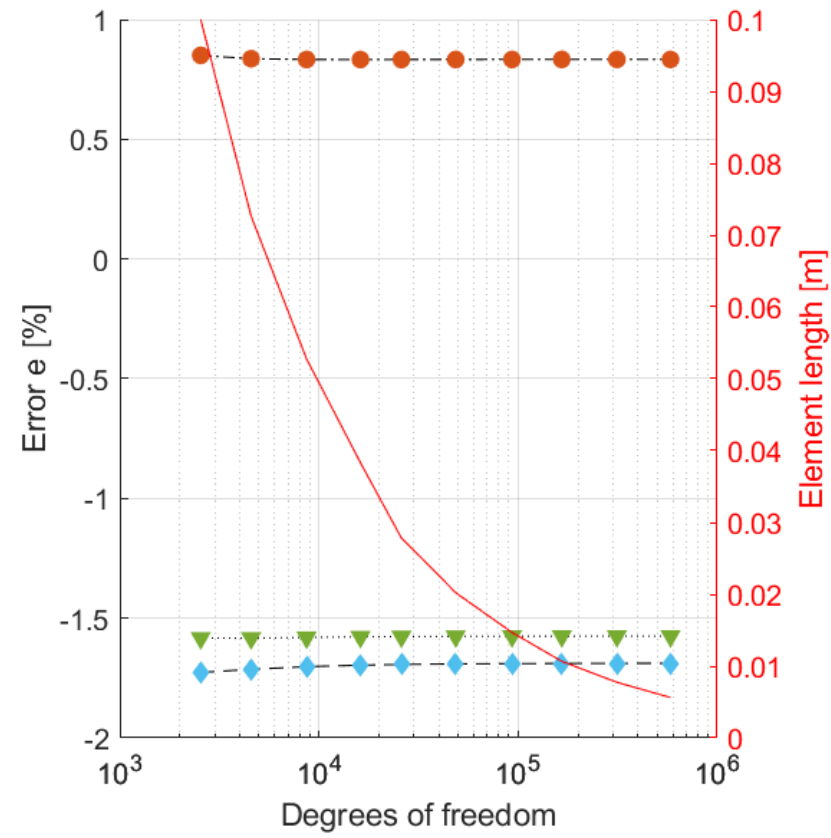
# Shell elements

## Error compared to reference

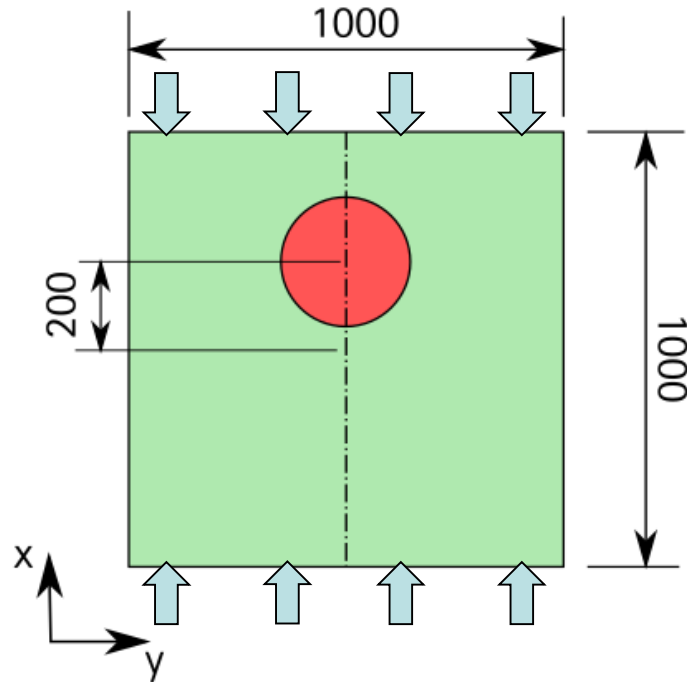
4-node shell



8-node shell



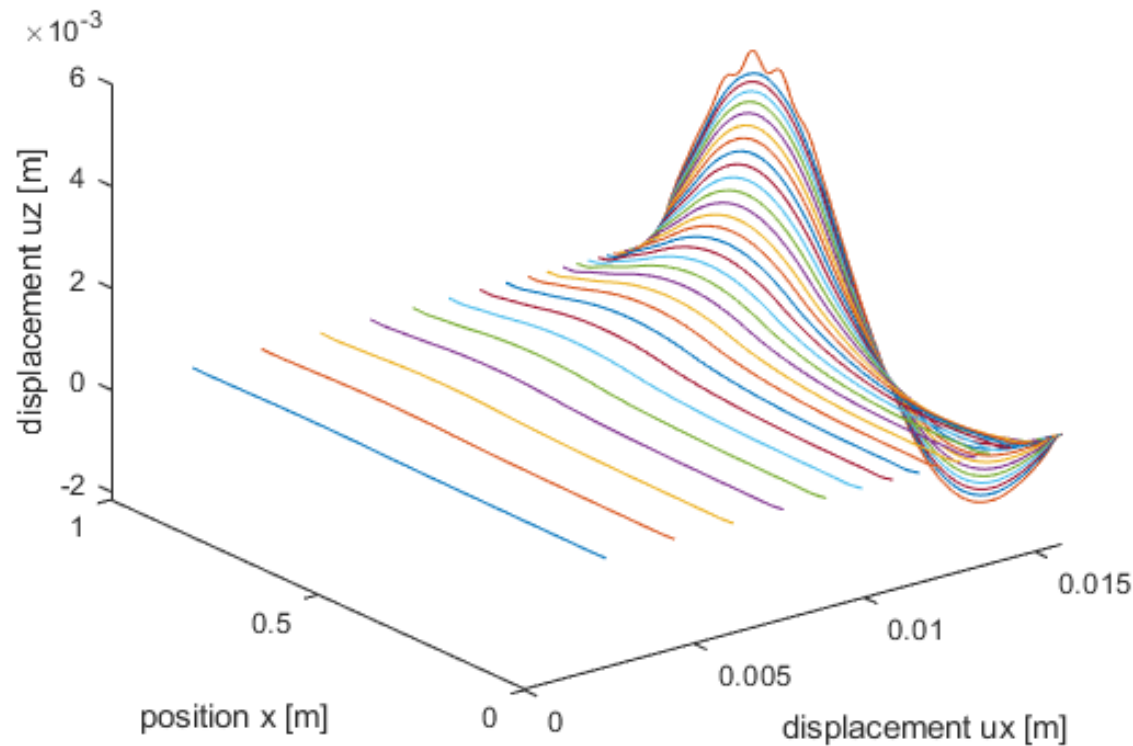
# Geometrically nonlinear buckling analysis of damaged panel with accompanying eigenvalue analysis



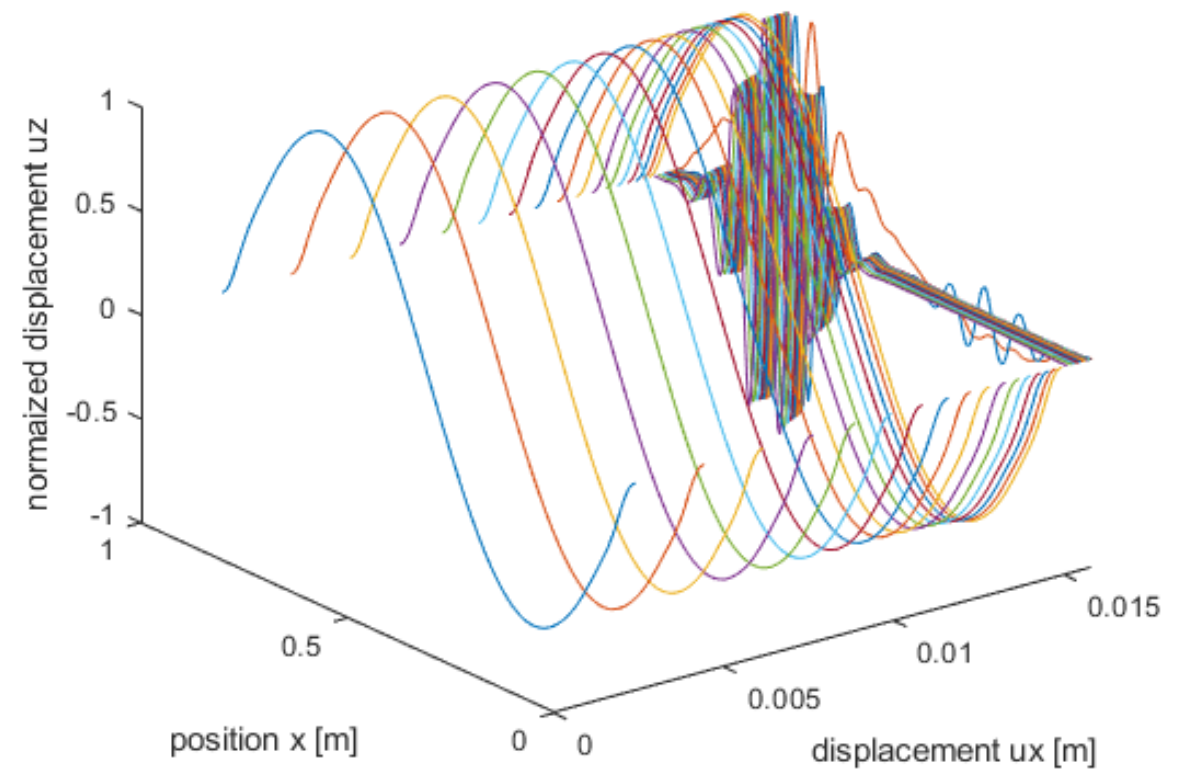
- Continuum elements only
- No geometrical imperfections
- Excentrical, circular damage of 300mm diameter in one face sheet
- Damaged is modeled by reducing elastic moduli by 10%
- Force is incremented by adding a fraction of remaining buckling load factor → converges right in the point of buckling
- Deformations and mode shapes are evaluated along center line

# Nonlinear buckling analysis of damaged panel with accompanying eigenvalue analysis. Results of $\sim 1 \cdot 10^6$ DOF mesh

Displacement of center line

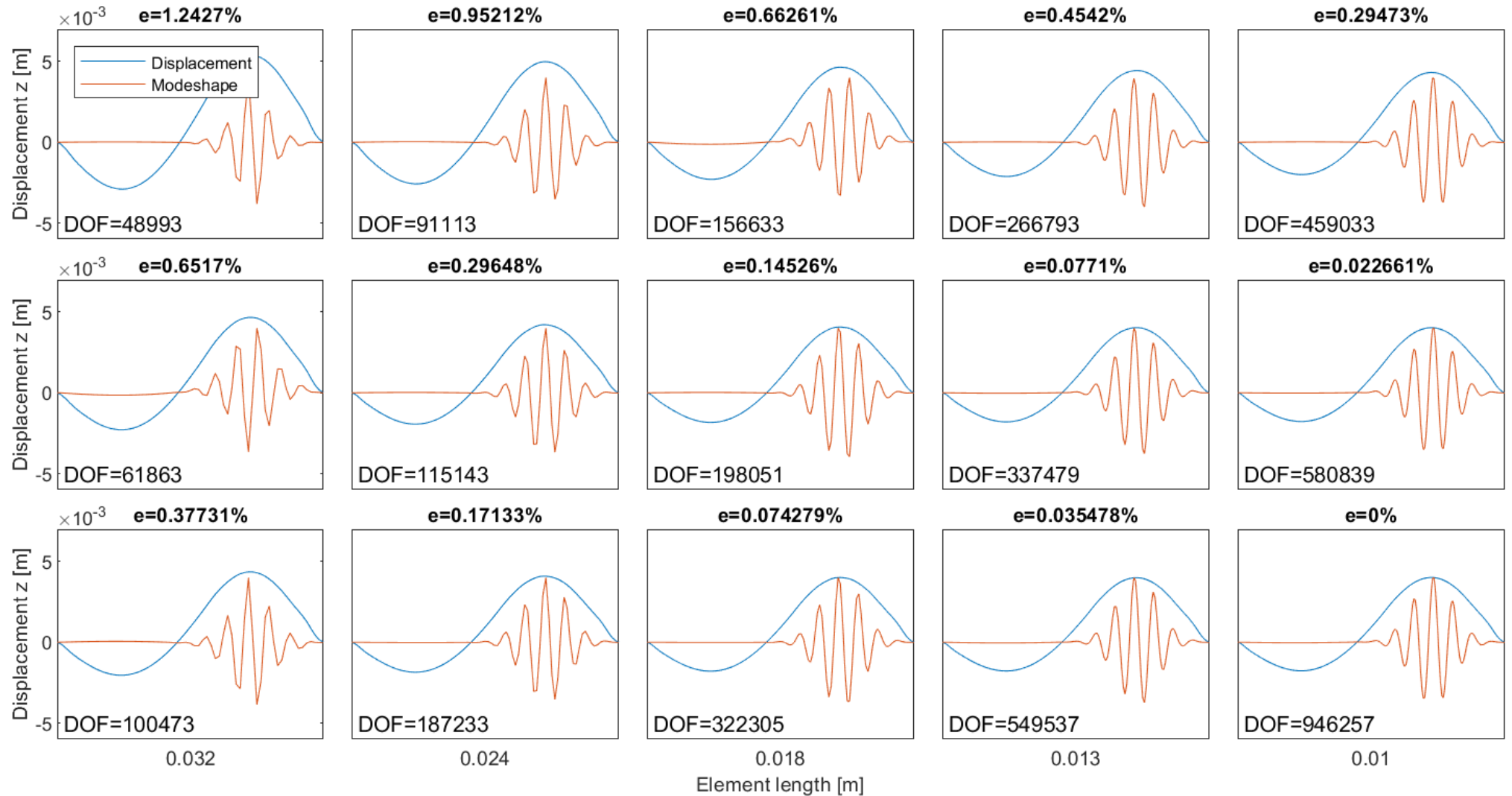
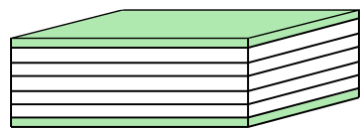
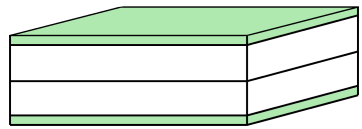
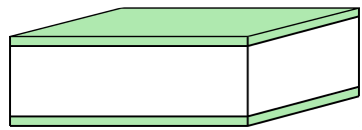


Mode shape of center line



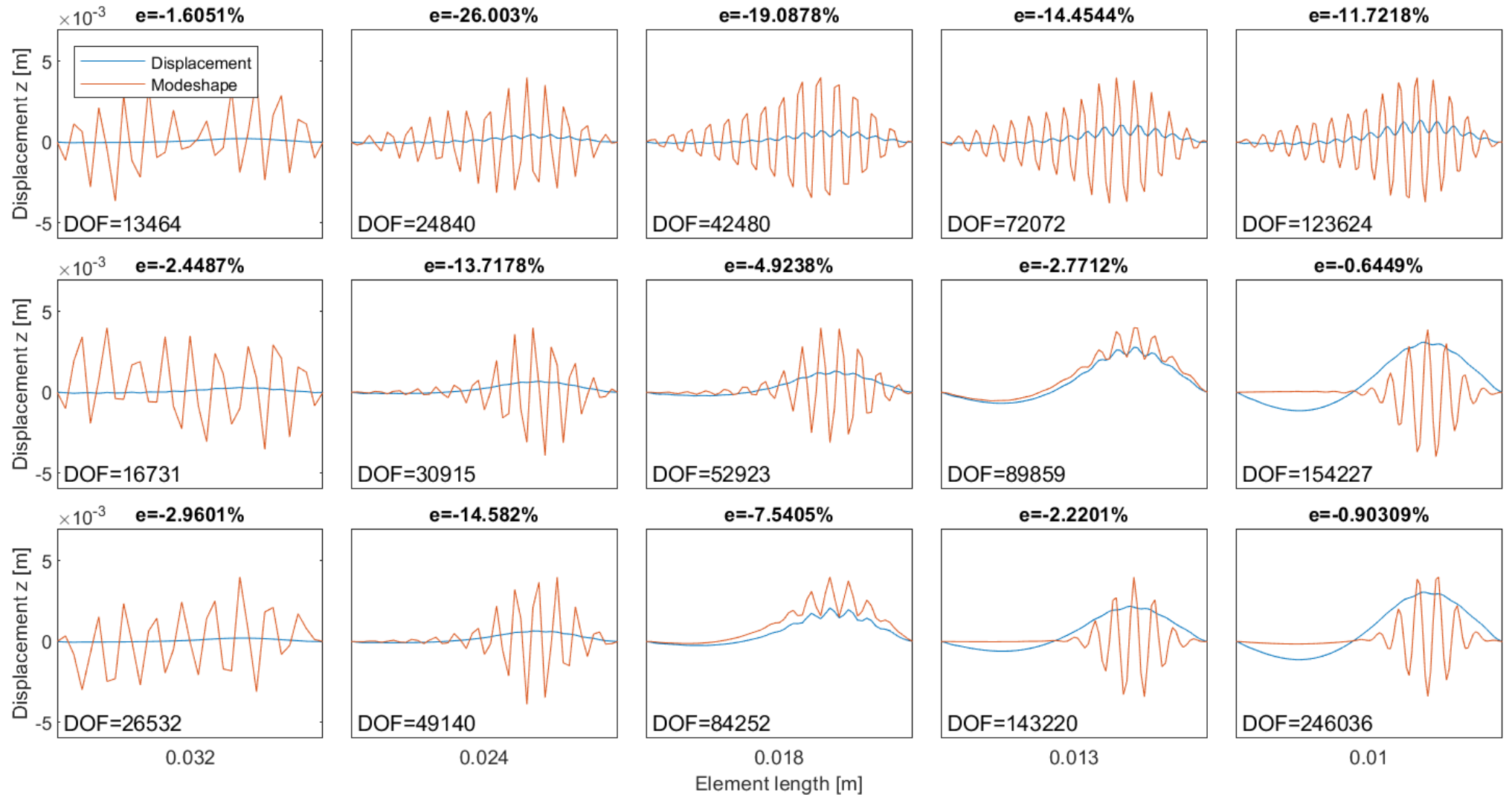
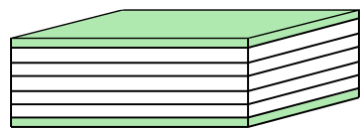
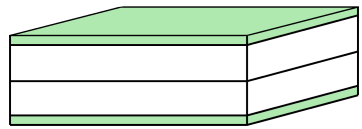
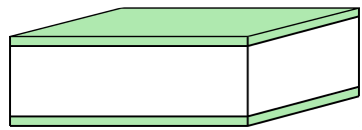


# 20-node layered solid elements. Final center line displacement and mode shape

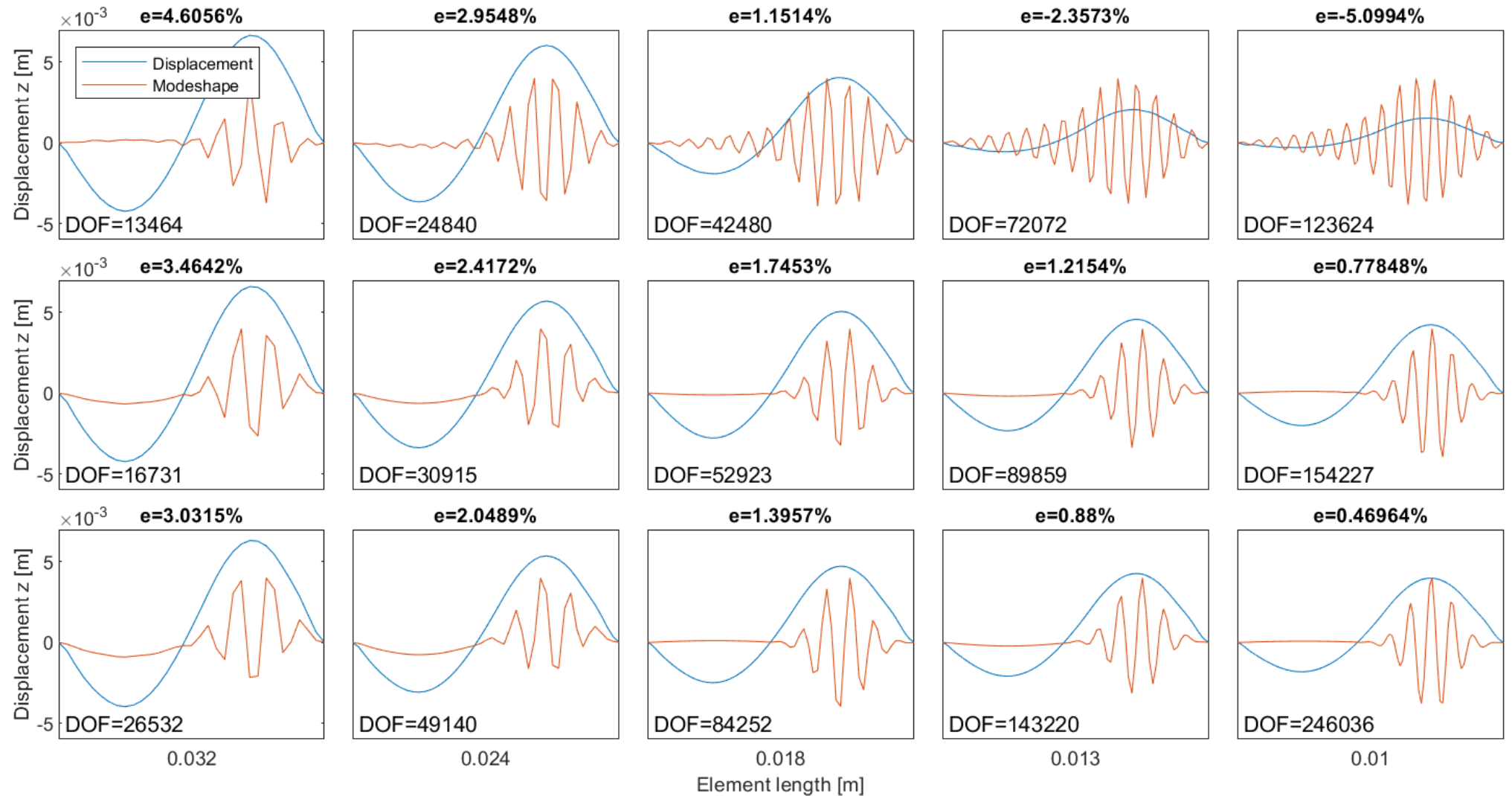
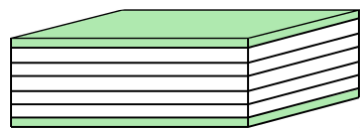
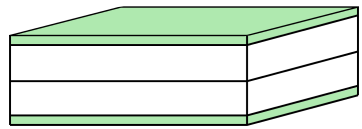
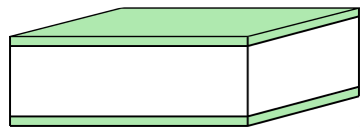




# 8-node layered solid elements. Final center line displacement and mode shape



# 8-node solid shell elements. Final center line displacement and mode shape



## Conclusions

- 20-node layered solids show best overall performance
- 20-node layered solids work in a wide range of aspect ratios
- 20-node layered solids show already good performance with one single element for each layer
  - same mesh topology works for various sandwich configurations
- When limited to 8-node elements, solid shell elements outperform layered solid elements
- Solid shell elements have a critical length to thickness aspect ratio of 1:2
  - when meshing thick core layers, core must be split in two elements or more
- 4-node and 8-node shell elements perform well in global buckling but can not model local effects

# Thank you for your attention



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on the basis of a decision  
by the German Bundestag

## References

- Wiedemann, J. 2007. *Leichtbau: Elemente und Konstruktion*. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.