A METHOD FOR THE EFFICIENT MODELLING OF DELAMINATION IN LARGE STRUCTURES

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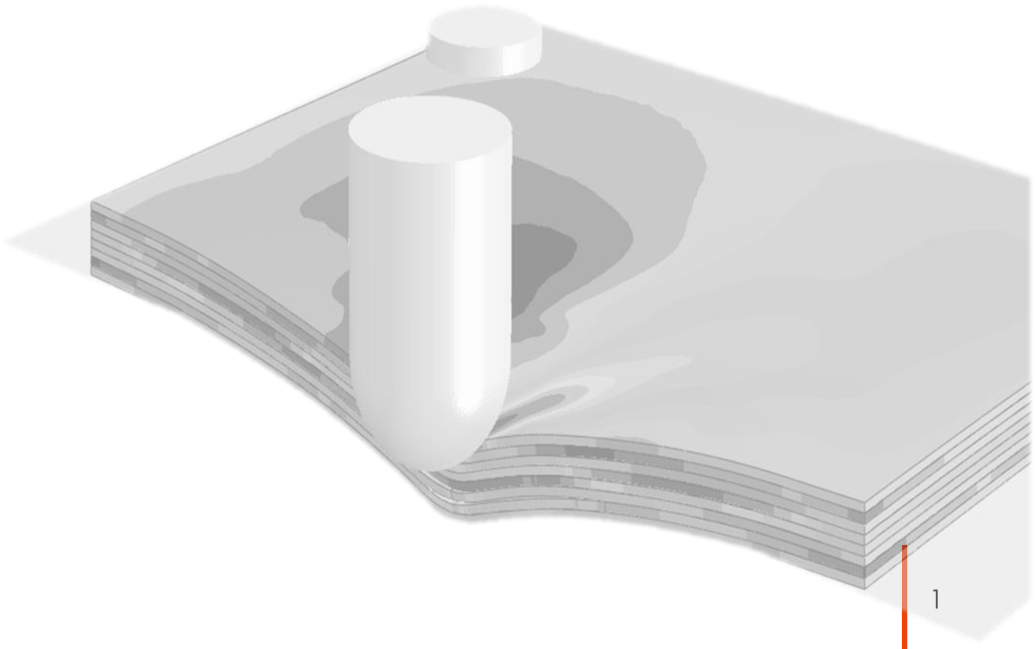
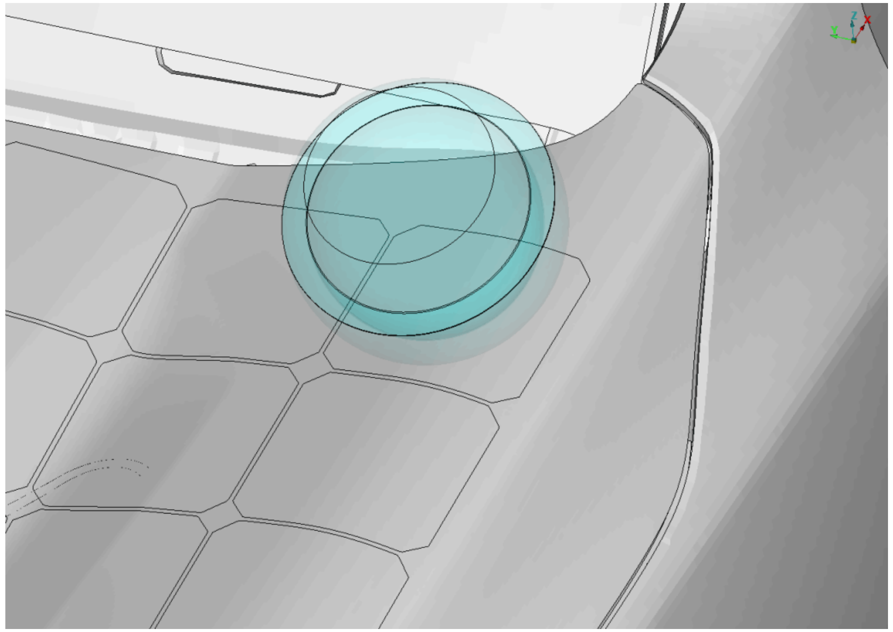
AMADE Day
27 January 2023



Introduction

- Need for the modelling of delamination **in large structures**, an example:



Headform impact (pedestrian safety)**:**

Energy: 212 Joules
Mass: 4.5 kg
Velocity: 9.7 ms^{-1}
Diameter: 165 mm

About **50 positions** to model on the hood.

Simulation time (26cpus):

Steel hood: 22 minutes
Composite hood: 8 hours

↓ **x 22** ⚠

Introduction

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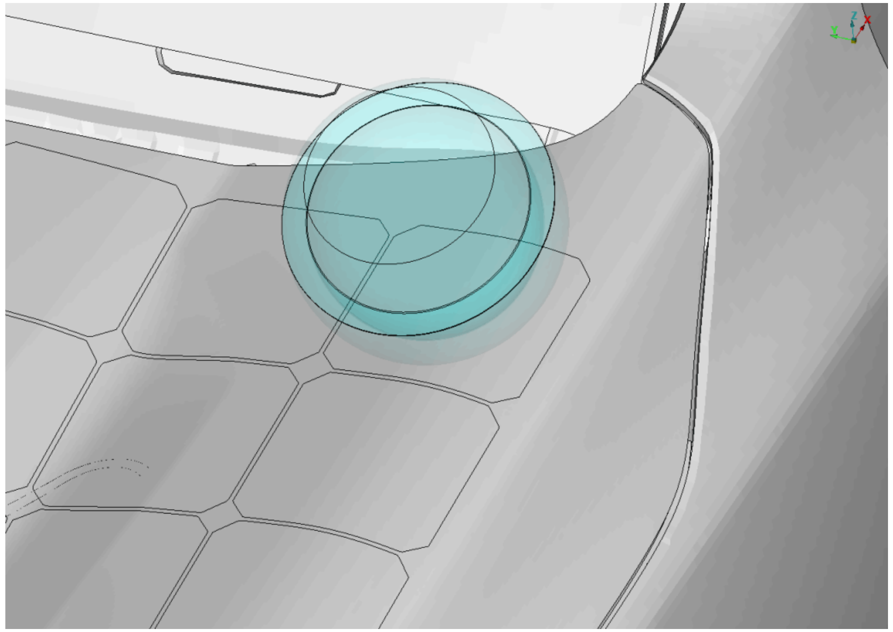
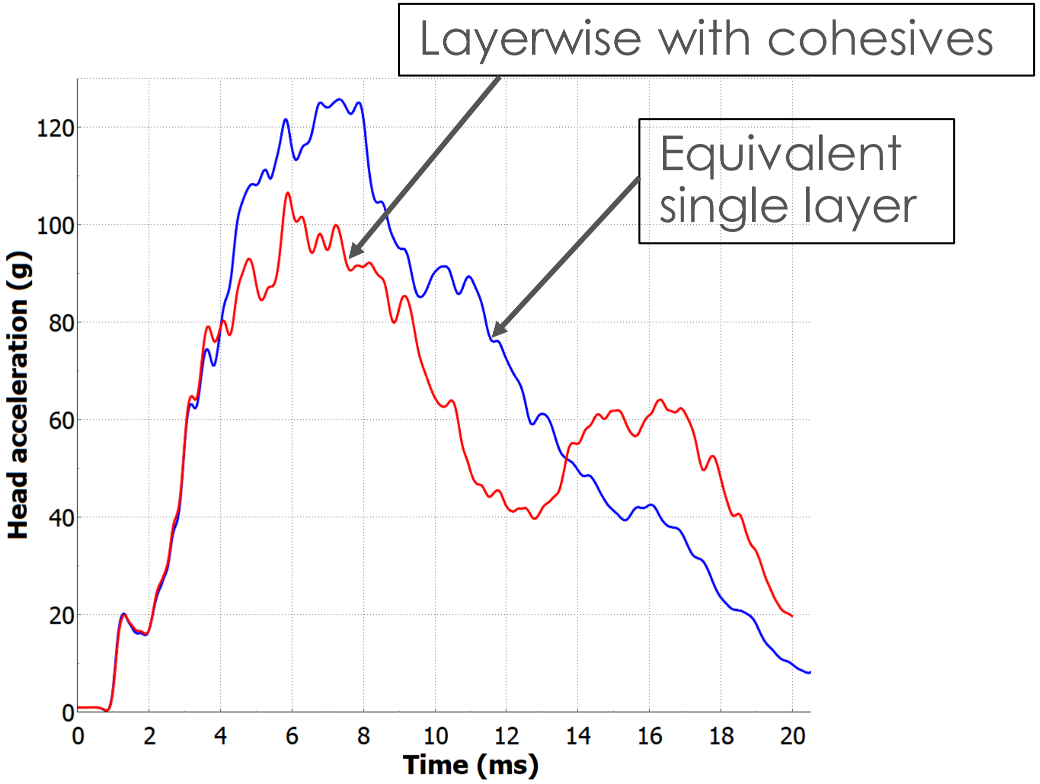




Simulation time (26cpus):

Steel hood: 22 minutes
Composite hood: 8 hours ↓ x 22 ⚠

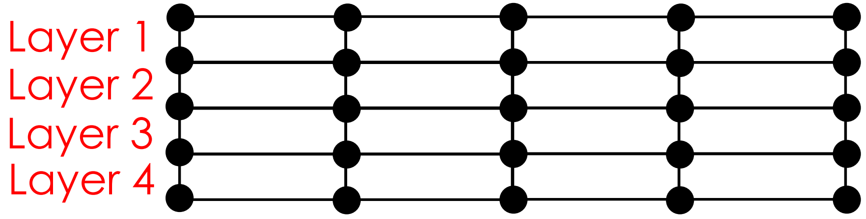
The "**Head injury criterion**" is halved !

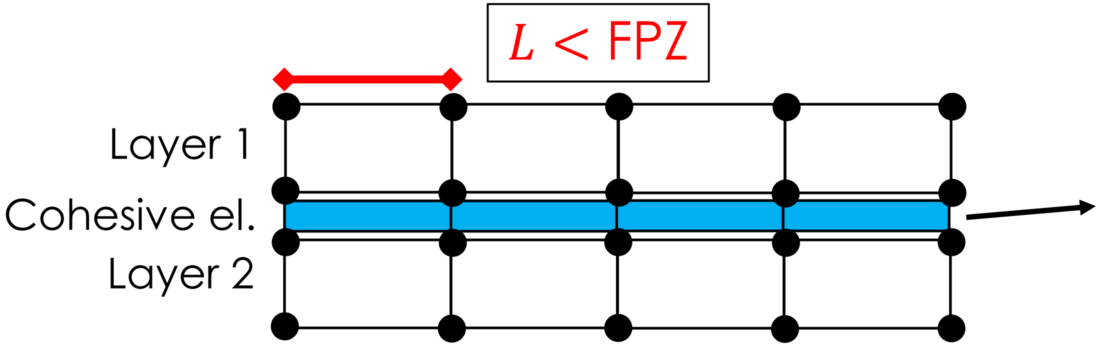
Delamination modelling (State of the art)

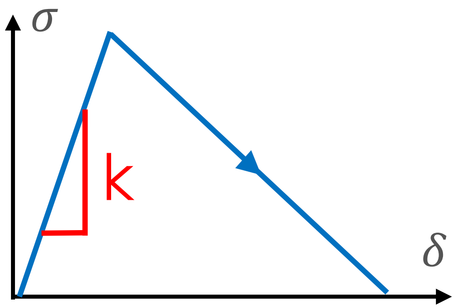
Failure detection → Crack nucleation → Crack propagation

Need: out-of-plane stress

Layerwise modelling | Cohesive Zone Modelling







Thickness refinement
x N_{layers}

In-plane refinement
x 25
(e.g. 1 mm vs 5 mm)

Time increments
x 10
(e.g. 0.5×10^{-7} s vs 0.5×10^{-6} s)

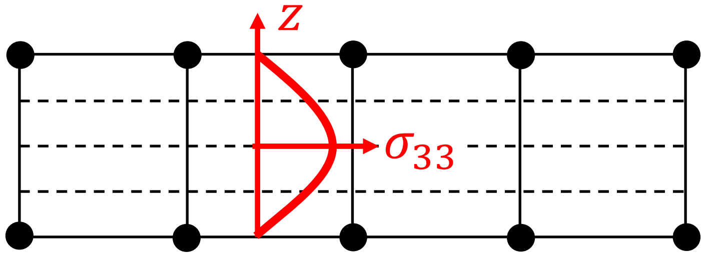
For a 10-layer laminate, the computational cost is increased by a factor ~ **2500 !!**

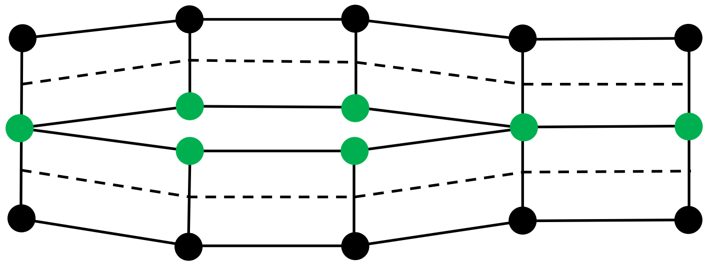
Present modelling strategy

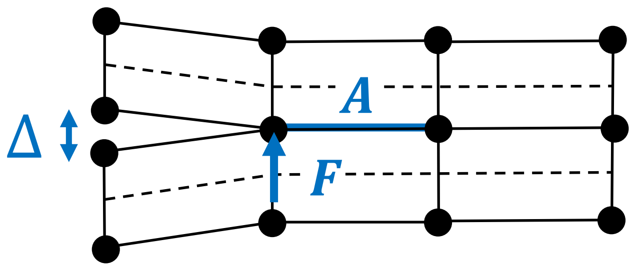
Failure detection → Crack nucleation → Crack propagation

Failure detection	Crack nucleation	Crack propagation
Equivalent single layer	Enrichment	ERR based propagation
Stress Recovery method	Adaptive modelling	VCCT+cohesive

$\sigma_{13}, \sigma_{23}, \sigma_{33}$







$\mathrm{FI}(\sigma_{13}, \sigma_{23}, \sigma_{33}) > \text{limit}$

└→ Enrichment

● Extra node

$ERR(\Delta, \boldsymbol{F}, A) > G_c$ → propagation

Present modelling strategy

Failure detection → **Crack nucleation** → **Crack propagation**

Failure detection	Crack nucleation	Crack propagation
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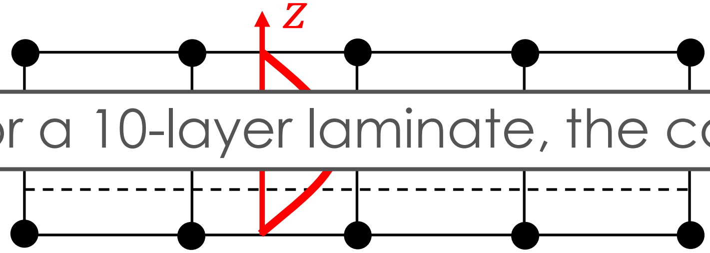
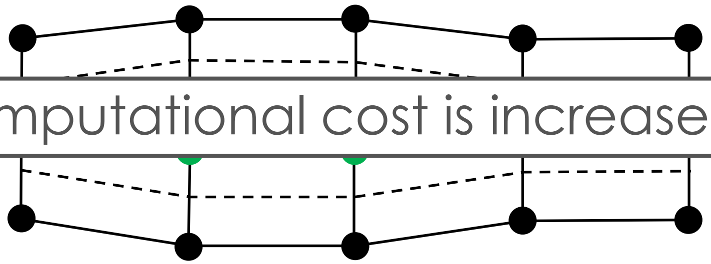
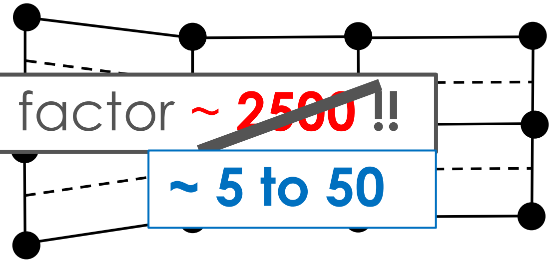
$\sigma_{13}, \sigma_{23}, \sigma_{33}$	● Extra node	$ERR(\Delta, \boldsymbol{F}, A) > G_c$







For a 10-layer laminate, the computational cost is increased by a factor ~ ~~2500~~ !!

~ 5 to 50

Thickness refinement	**In-plane refinement**	**Time increments**
~~x N_{layers}~~	~~x 25 (1 mm)~~	~~x 10 (0.5×10^{-7} s)~~
x 1 (no failure) **x $N_{layers}/2$** (progressive failure*)	**x 1** (5 mm) **x 4** (2.5 mm)	**x 5** (1.0×10^{-7} s)

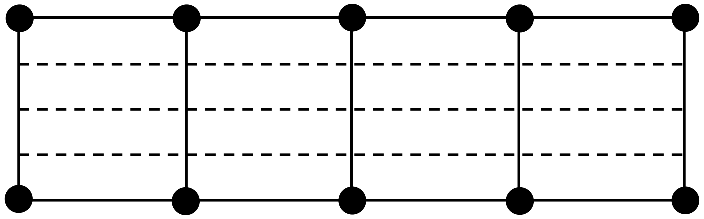
Failure detection → Crack nucleation → Crack propagation

Failure detection

Equivalent single layer

Stress Recovery method

$\sigma_{13}, \sigma_{23}, \sigma_{33}$



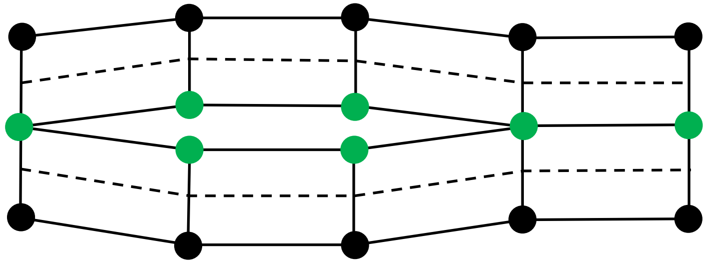
Composite Structures (2020)

Crack nucleation

Enrichment

Adaptive modelling

● Extra node



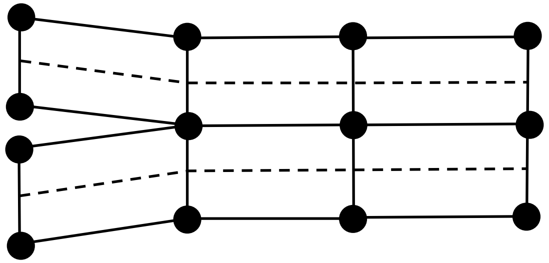
Främby(2020), Eng. Fract. Mech.

Crack propagation

ERR based propagation

VCCT+cohesive

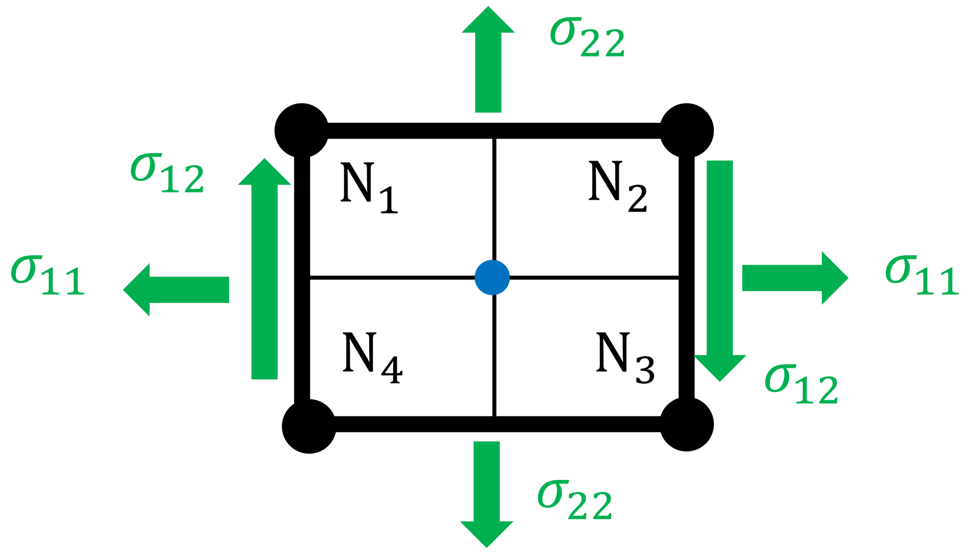
$ERR(\Delta, \boldsymbol{F}, A) > G_c$



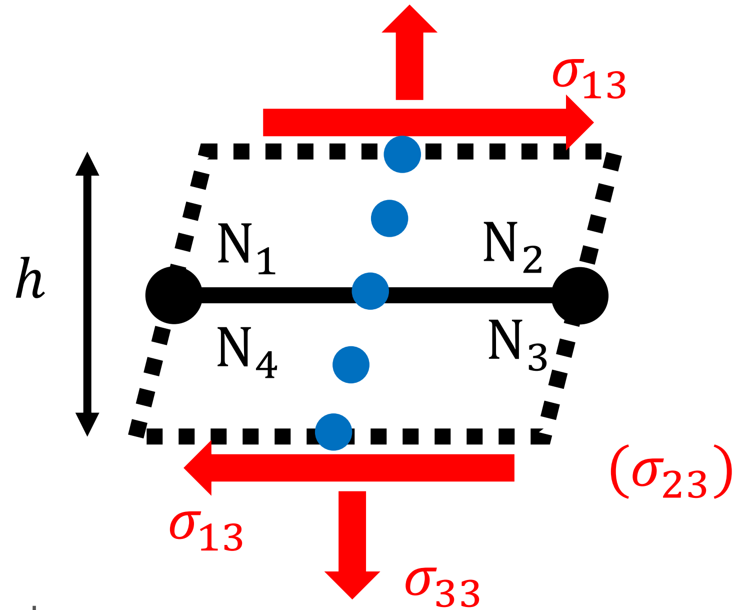
Stress Recovery Basics

- Linear Shell elements (ESL based on FSDT) present:

Good quality of in-plane stresses



Poor quality of transverse stresses



● Integration points

Stress Recovery Basics

- Linear Shell elements (ESL based on FSDT) present:

Several authors have proposed using the **stress equilibrium equations :**

$$\sigma_{11,1} + \sigma_{12,2} + \sigma_{13,3} = 0$$
$$\sigma_{13,1} + \sigma_{23,2} + \sigma_{33,3} = 0$$

→

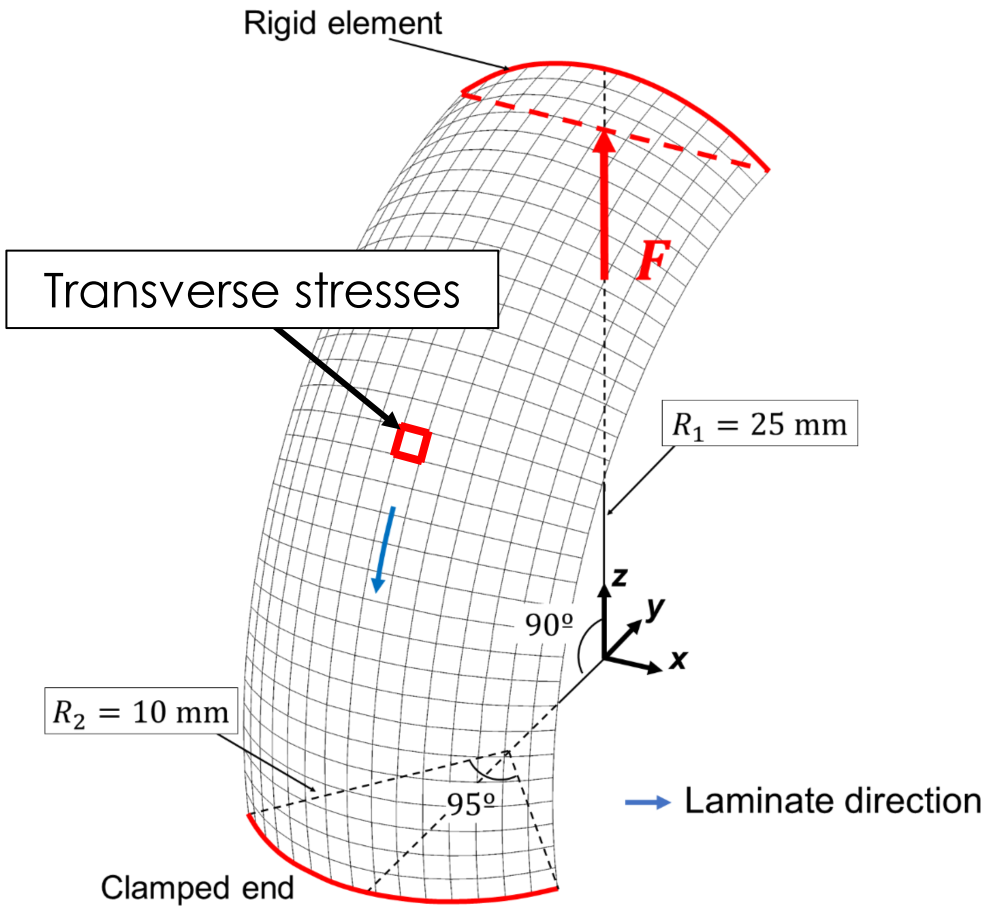
$$\sigma_{13} = -\int_{-\frac{h}{2}}^{z} \sigma_{11,1} + \sigma_{12,2} dz + C_1$$
$$\sigma_{33} = \iint_{-\frac{h}{2}}^{z} \sigma_{11,11} + \sigma_{22,22} + 2\sigma_{12,12} dzdz + C_3$$

These equations have been generalized for **arbitrarily curved geometries**.

An **efficient formulation**, based on the shell **forces and moments** is used.

σ_{13}, σ_{23} and σ_{33} are recovered in a post-processing step.

Doubly-curved example: Bending



- Laminate:

$$[(0; 90; 45; -45)_2; -45; 45; 90; 0; -45; 45; 0_8; 90; 0]$$

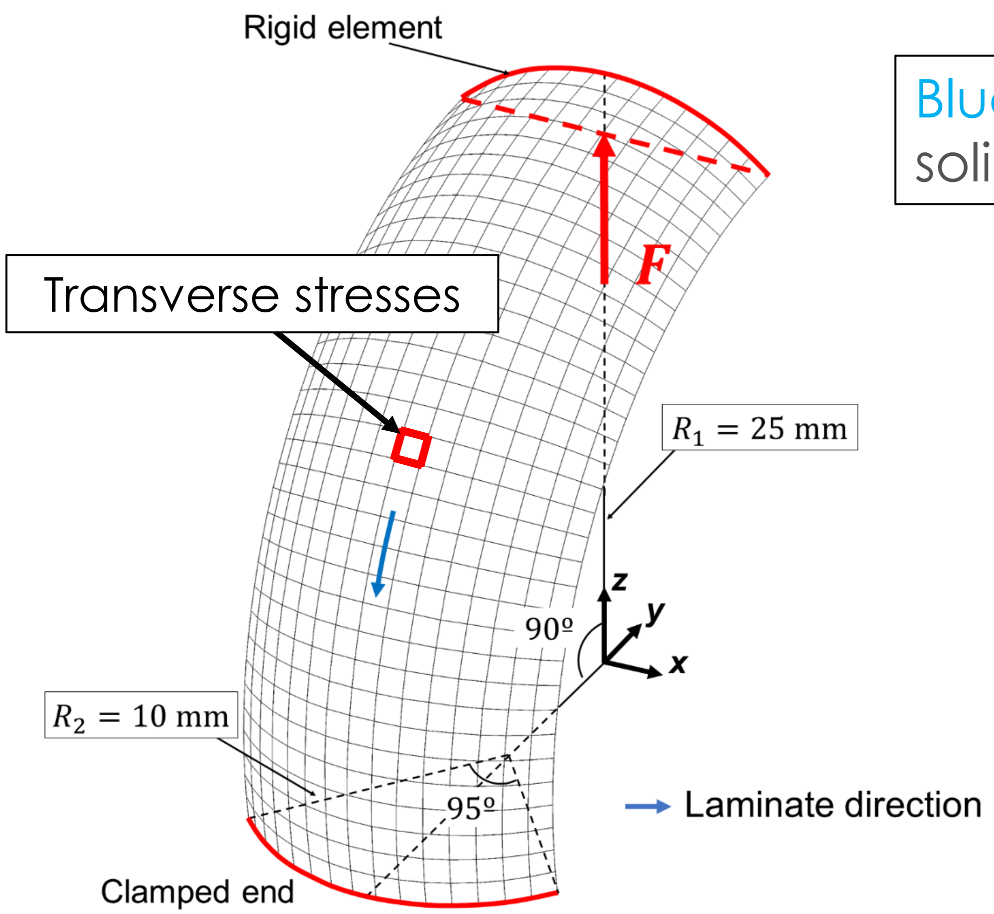
- Layer thickness : 0.25 mm
- Total thickness : 6 mm

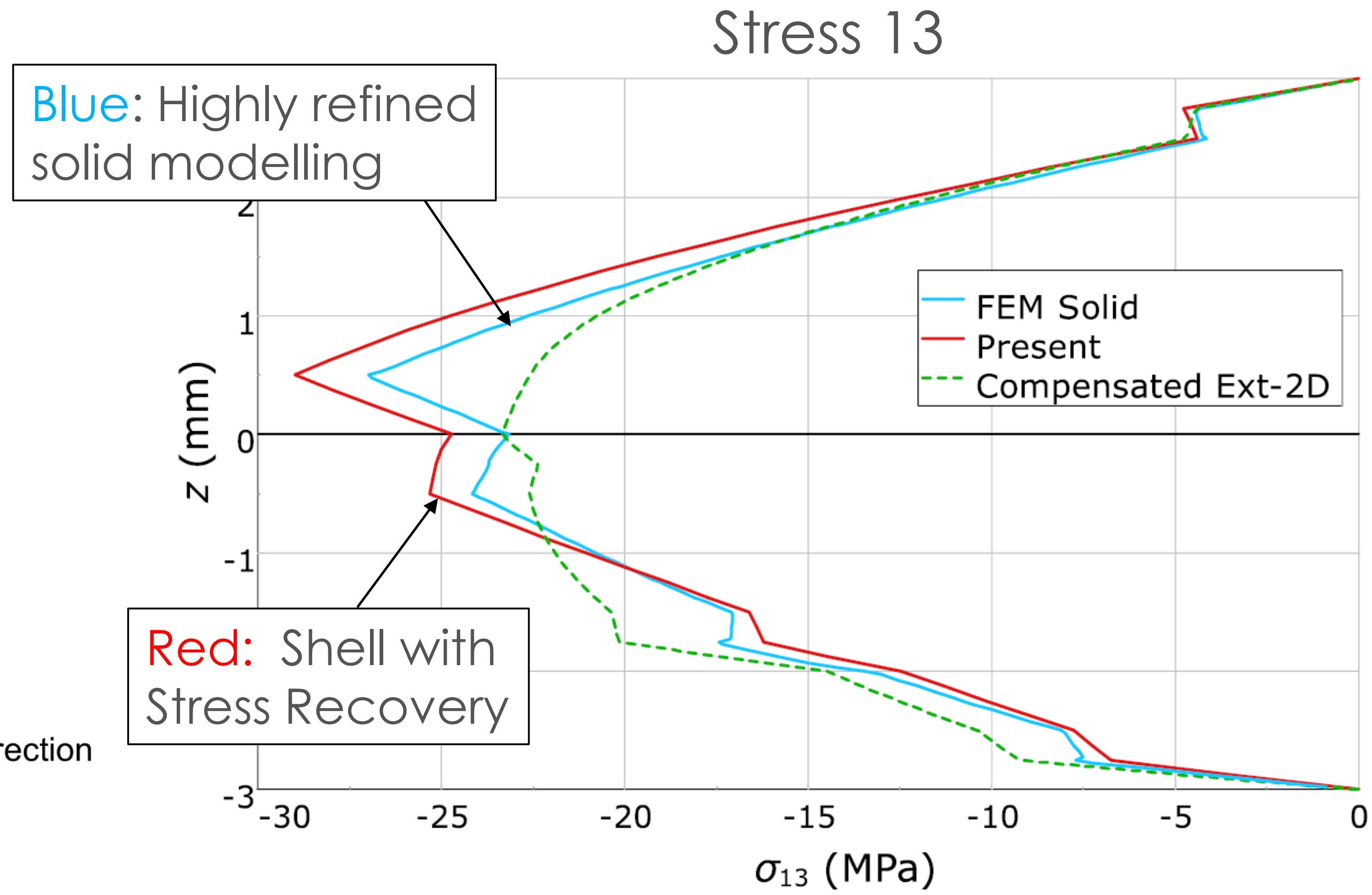
- Prototype material:

E_{11}	$E_{22} = E_{33}$	$G_{12} = G_{13}$
100 GPa	10 GPa	5 GPa

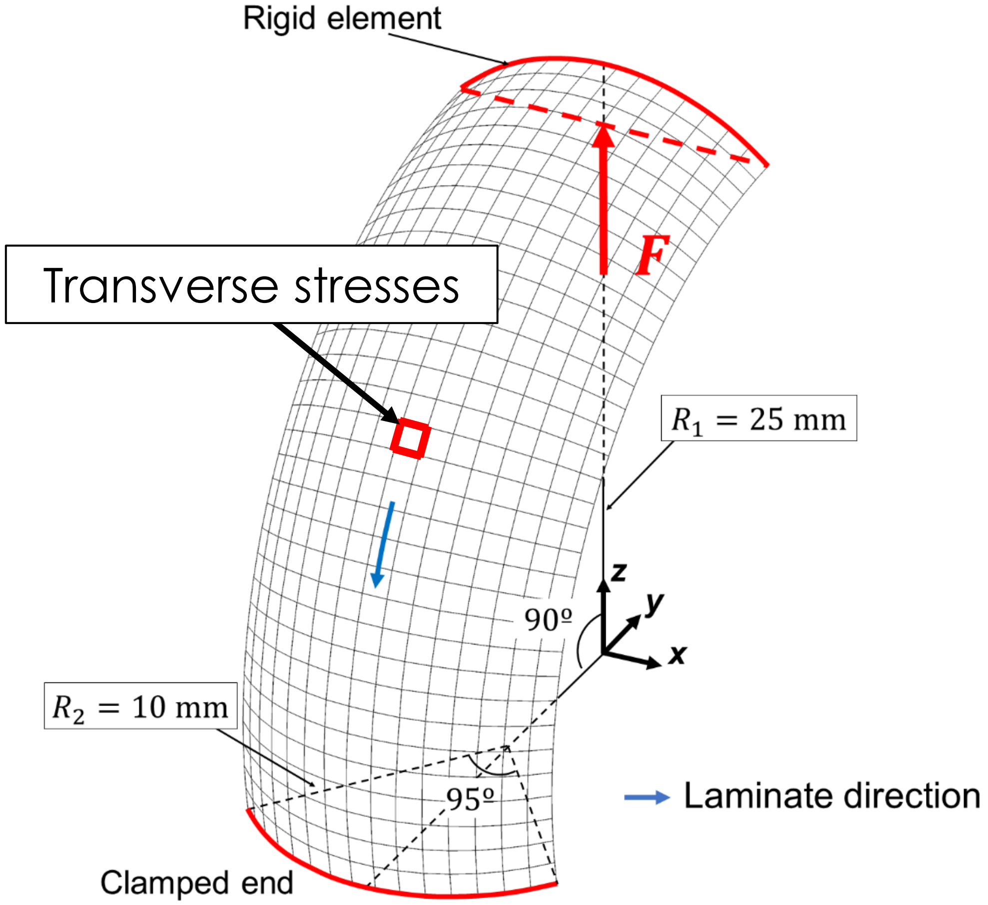
G_{23}	$\nu_{12} = \nu_{13} = \nu_{23}$
4 GPa	0.25

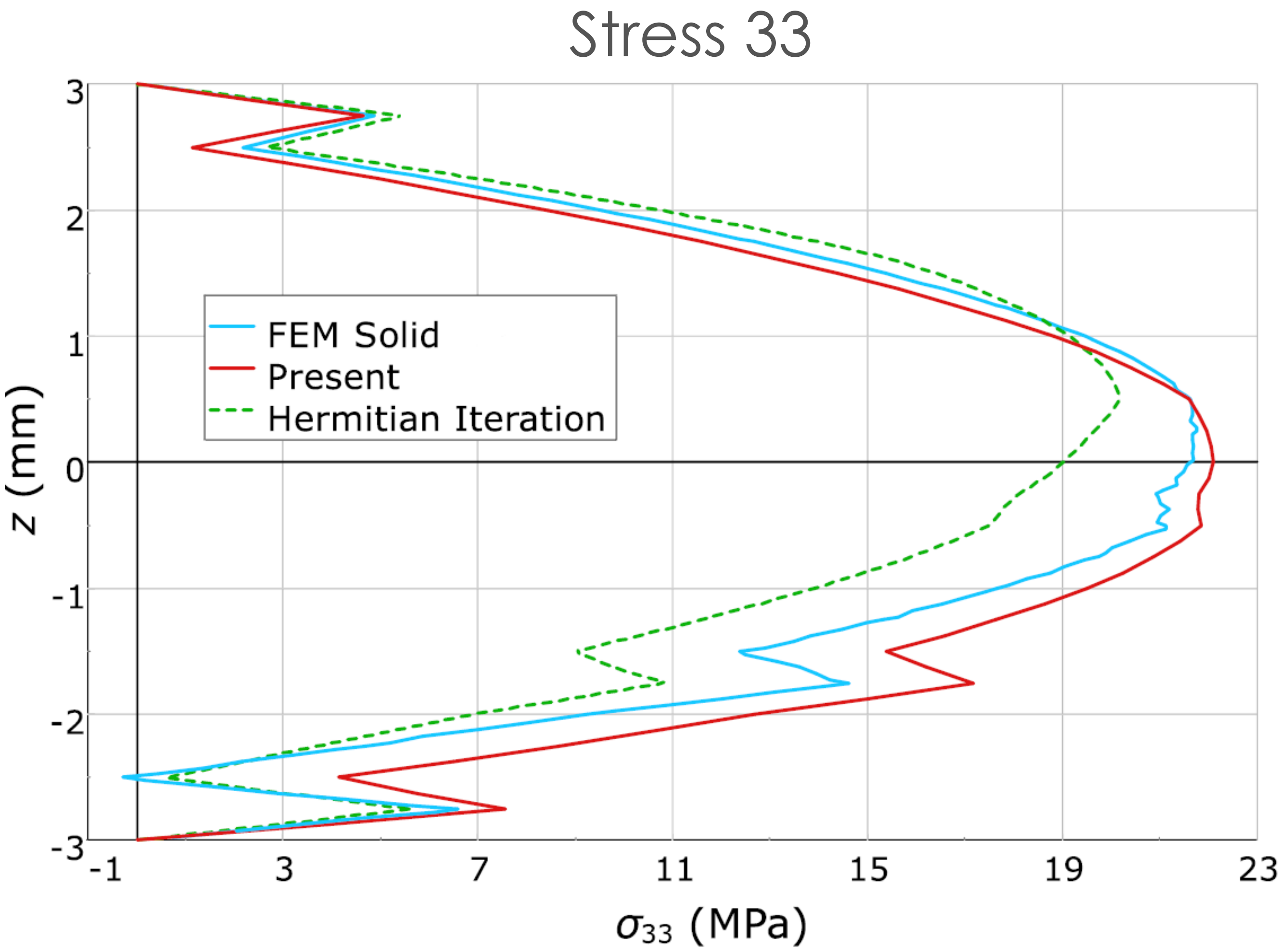
Doubly-curved example: Bending



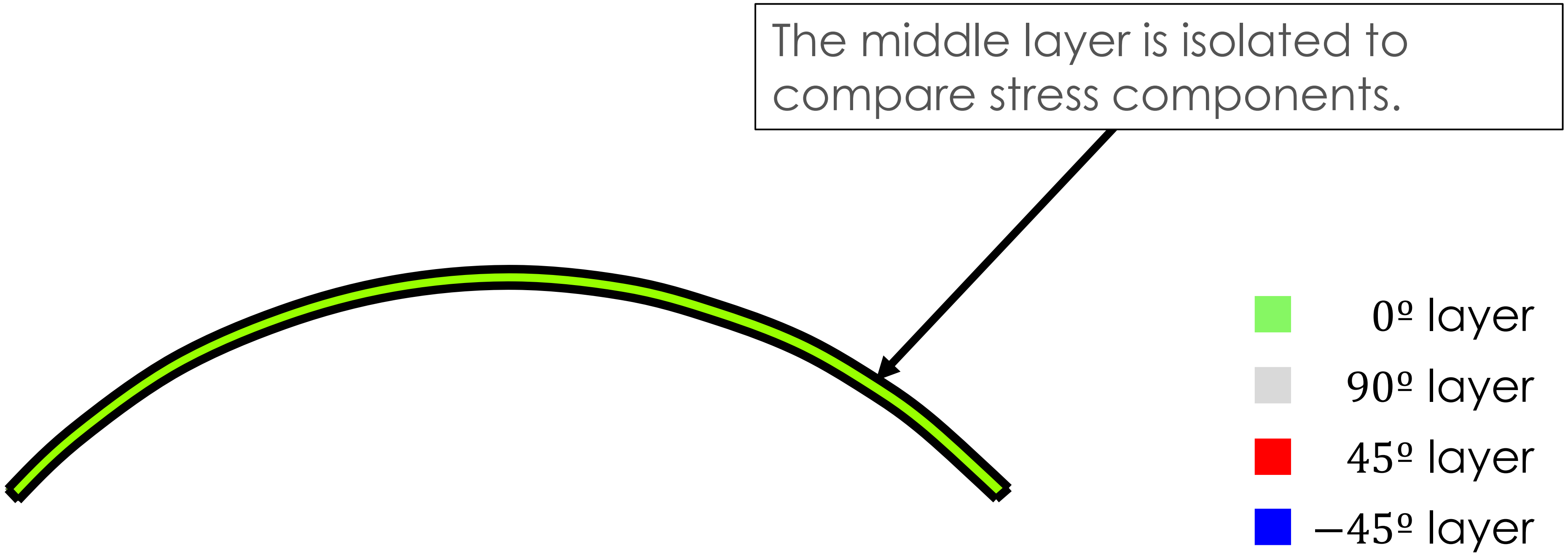


Doubly-curved example: Bending





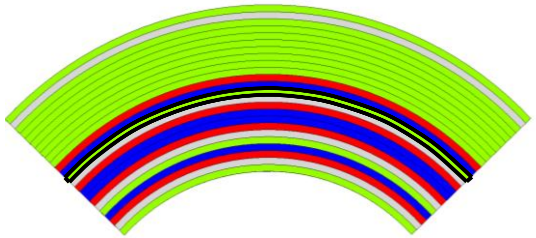
Doubly-curved example: Bending

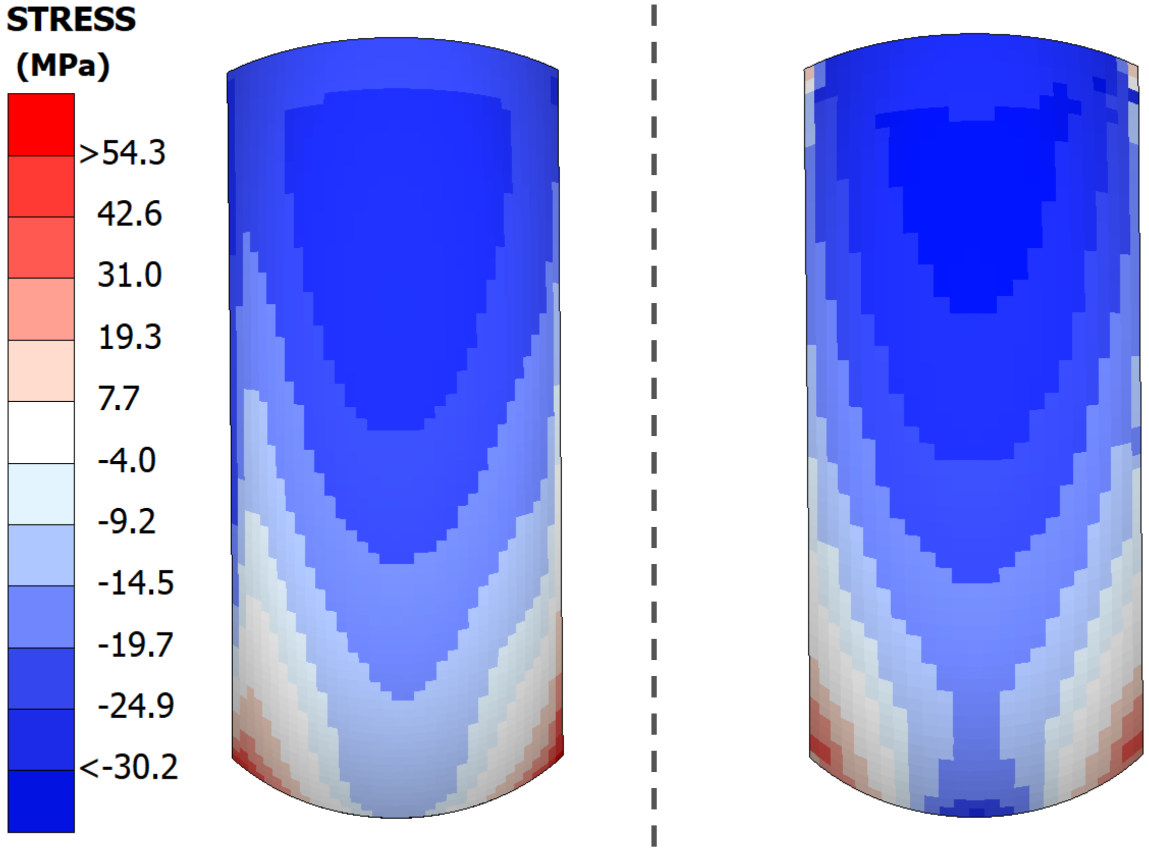


Doubly-curved example: Bending

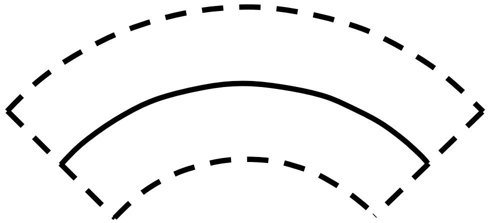
Stress 13

Solid





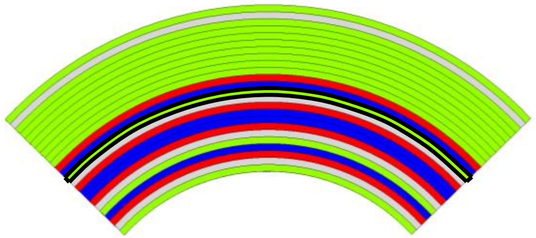
Shell

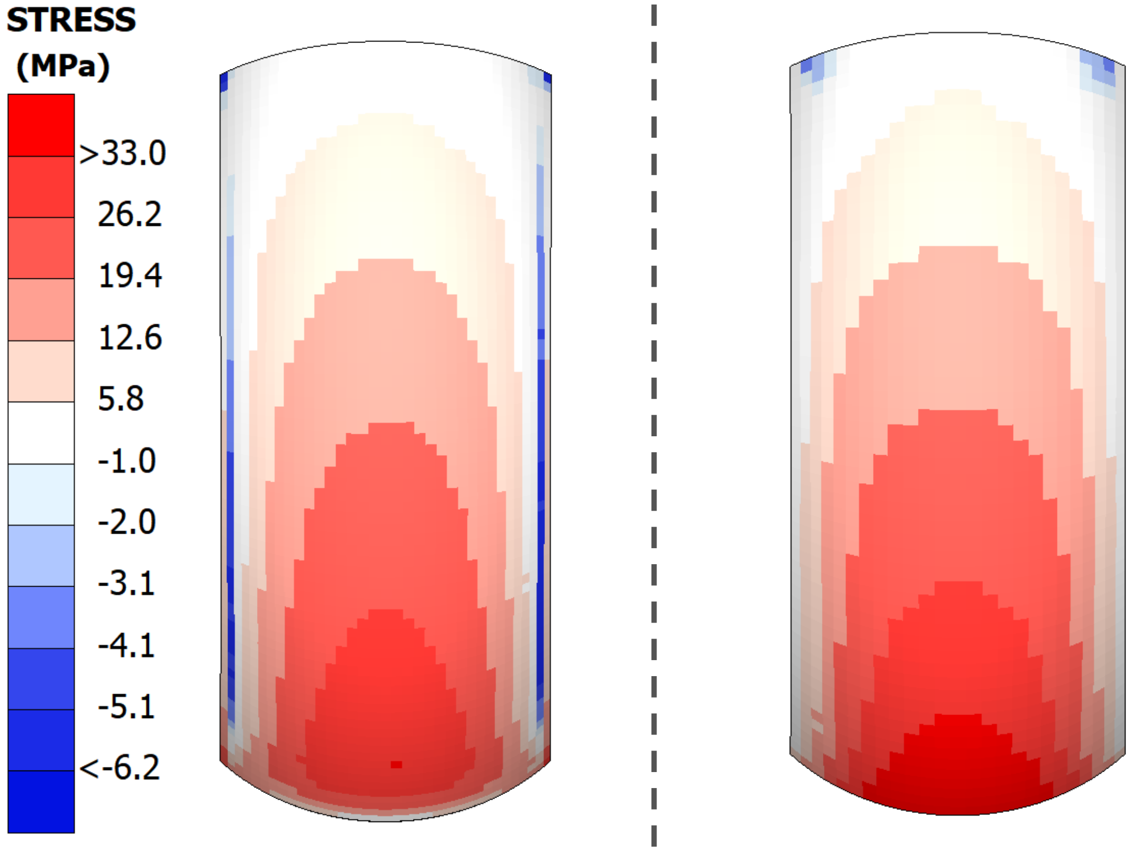


Doubly-curved example: Bending

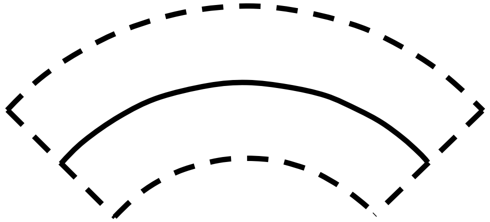
Stress 33

Solid





Shell



Doubly-curved example: Bending

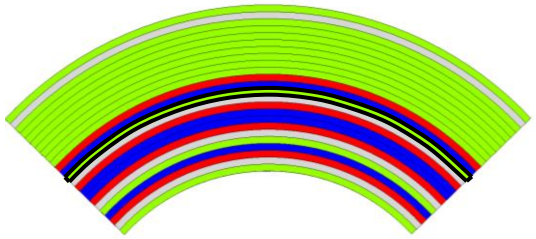
$$\frac{\langle\sigma_{33}\rangle^2}{{X_I}^2} + \frac{{\sigma_{13}}^2 + {\sigma_{23}}^2}{{X_{II}}^2}$$

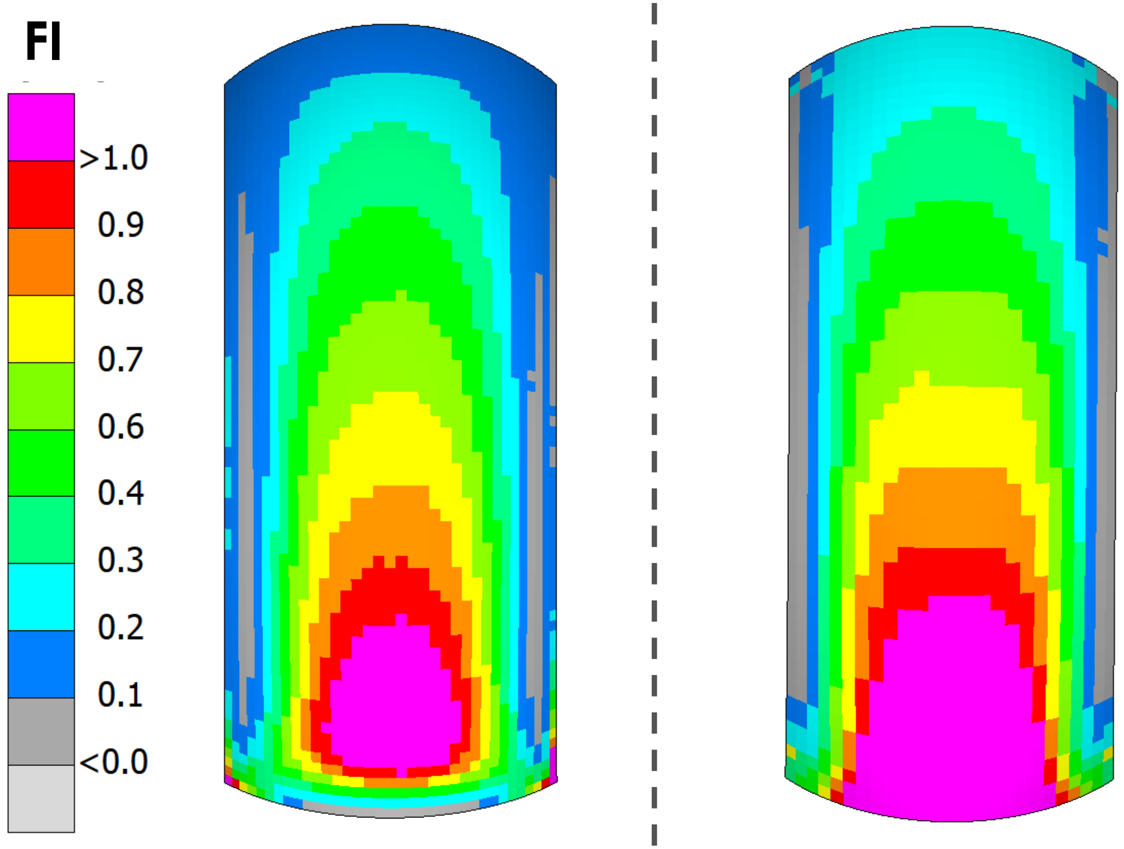
$$X_I = 30 \text{ MPa}$$

$$X_{II} = 60 \text{ MPa}$$

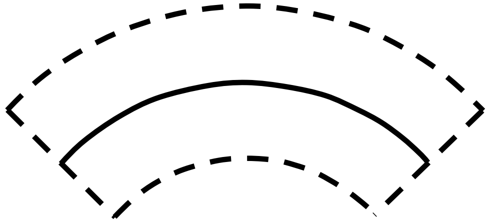
Delamination Criterion

Solid





Shell



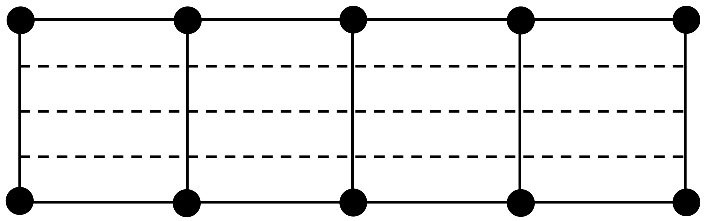
Failure detection → Crack nucleation → Crack propagation

Failure detection

Equivalent single layer

Stress Recovery method

$\sigma_{13}, \sigma_{23}, \sigma_{33}$

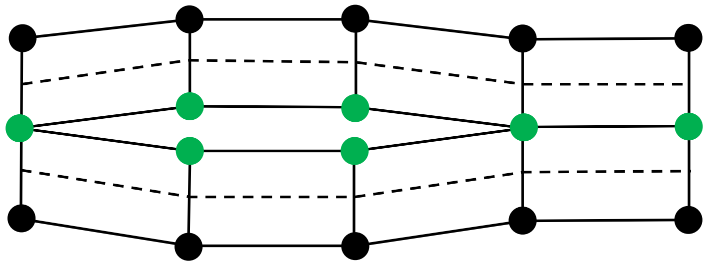


Crack nucleation

Enrichment

Adaptive modelling

● Extra node

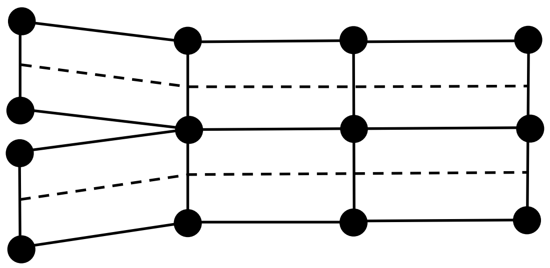


Crack propagation

ERR based propagation

VCCT+cohesive

$ERR(\Delta, \boldsymbol{F}, A) > G_c$



Composite Part A (2023)

VCCT criterion

- An initial crack is present: will it propagate?
- The Energy Release Rate (ERR) is computed:

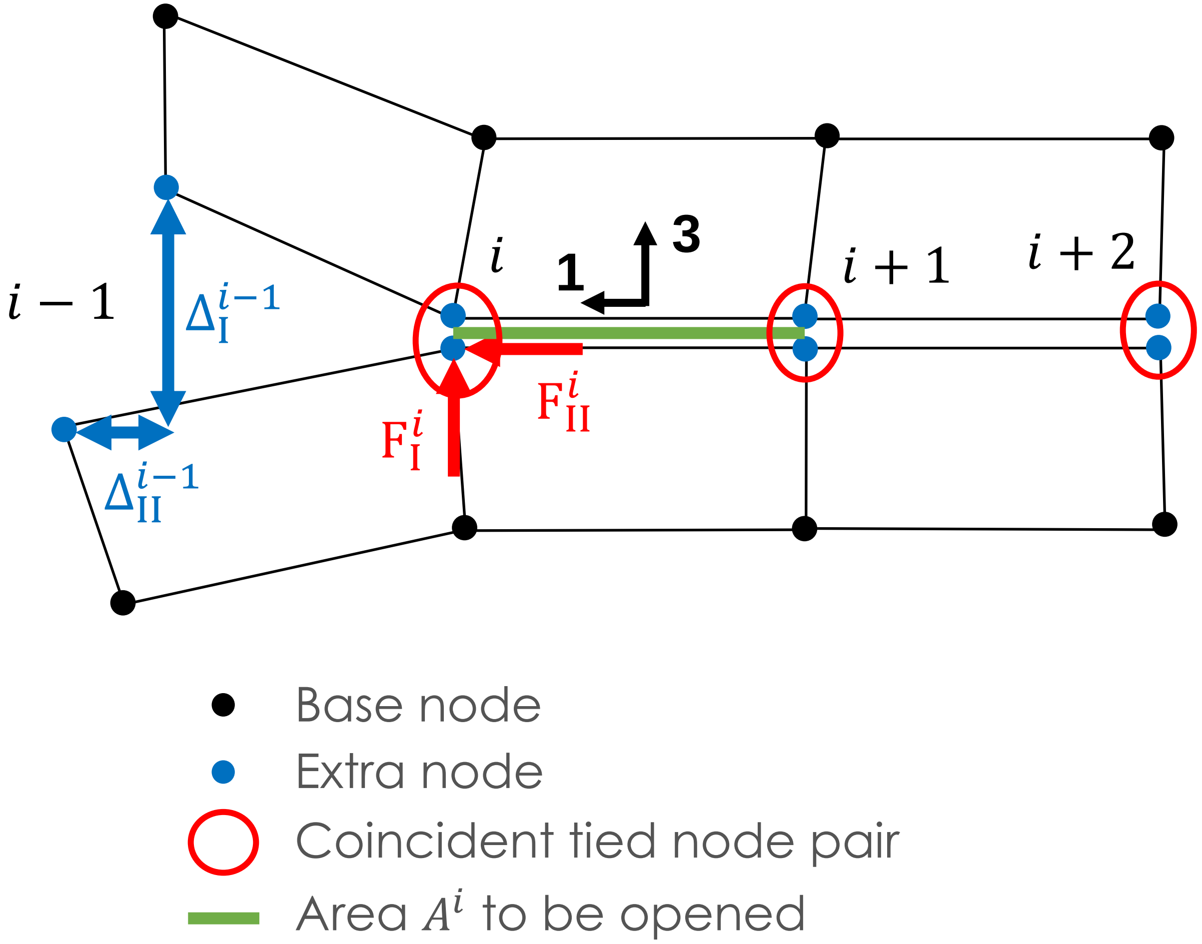
$$G_I = \frac{1}{2A^i} F_I^i \langle \Delta_I^{i-1} \rangle \quad ; \quad G_{II} = \frac{1}{2A^i} F_{II}^i \Delta_{II}^{i-1}.$$

$$G_T = G_I + G_{II}.$$

if $G_T > G_C$ (Benzeggagh-Kenane)

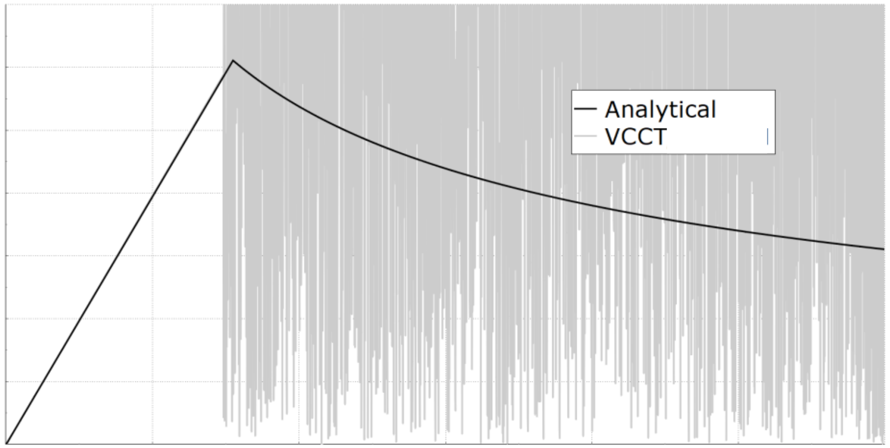
The tied at node i is released.

McElroy(2016). NASA/TP–2016-219211.

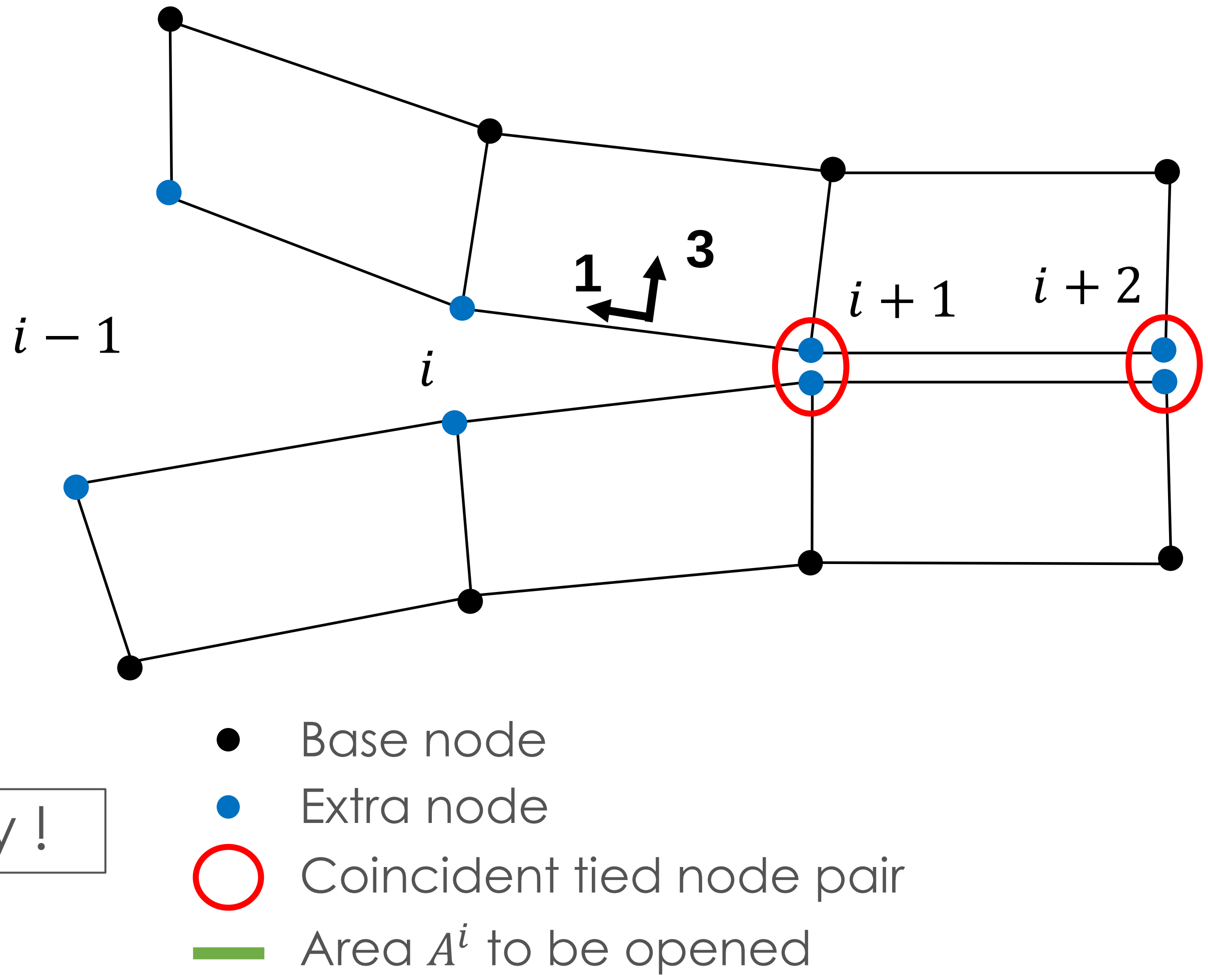


VCCT criterion

- An initial crack is present: will it propagate?

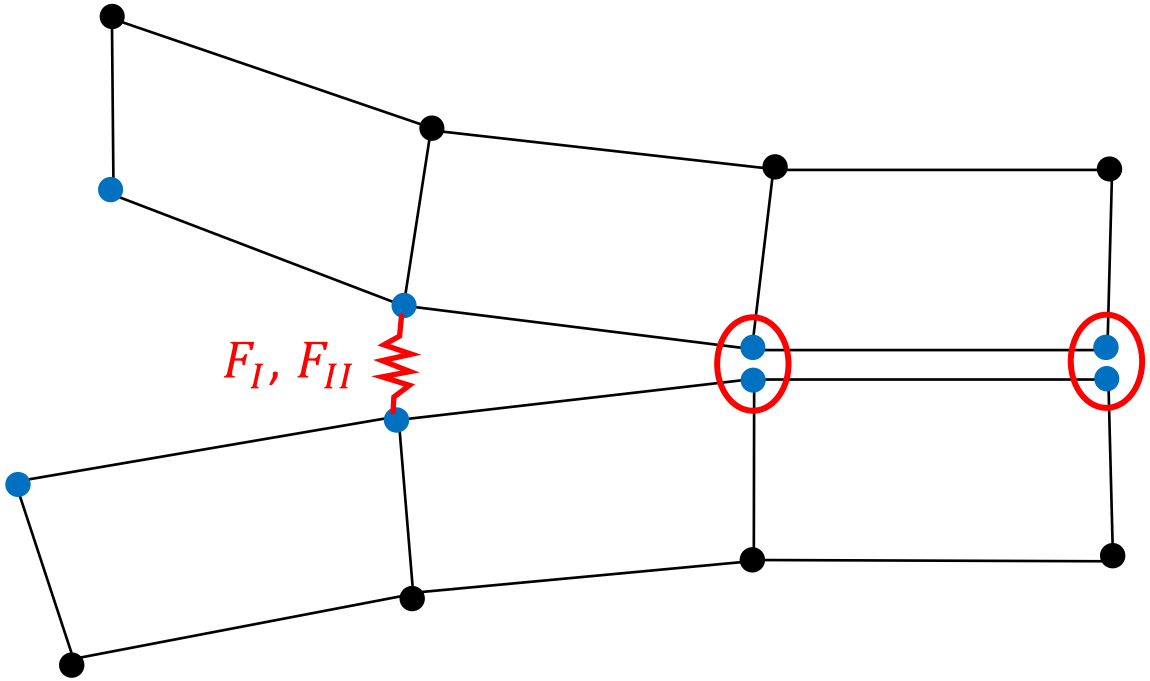


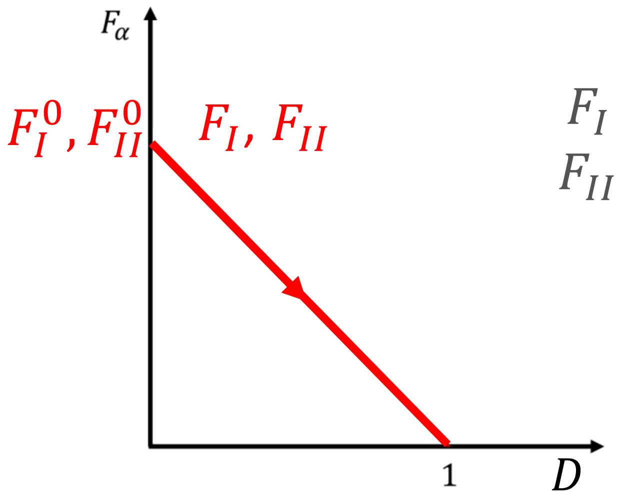
An energy absorption mechanism is necessary !



Cohesive law

- When the VCCT criterion is met the force at the interface decreases:





$$F_I = F_I^0(1 - D)$$
$$F_{II} = F_{II}^0(1 - D)$$

The damage variable D ensures that the energy $G_c A$ is dissipated

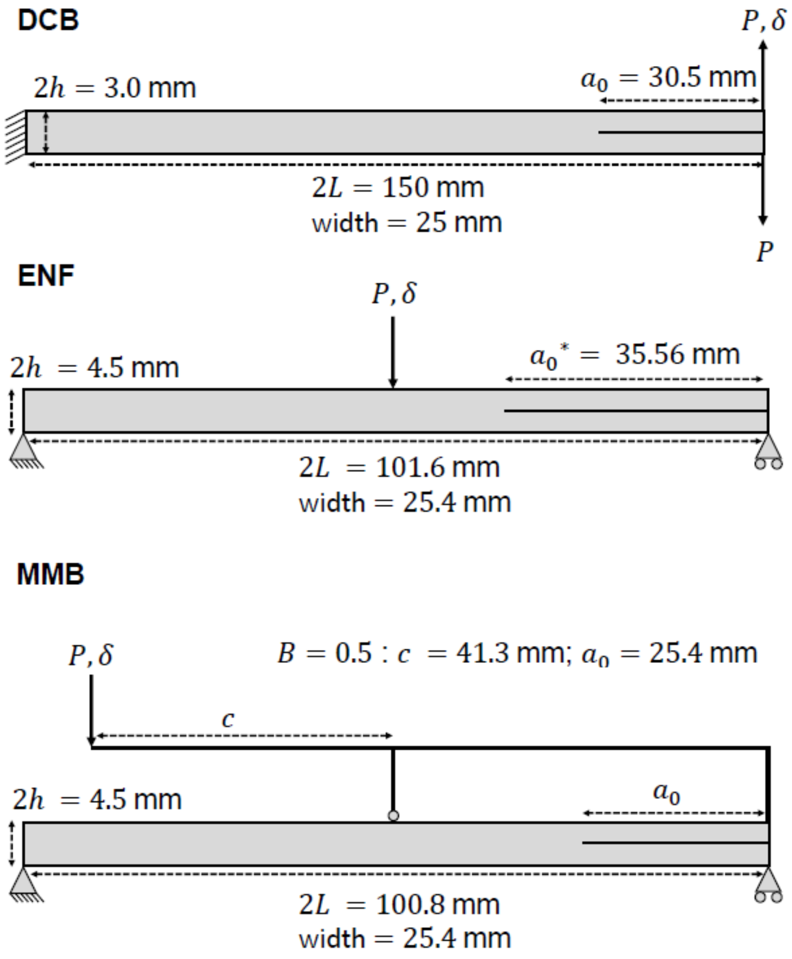
Validation: DCB, ENF, MMB

- Benchmark dimension and material from:

  Krueger (2015), J. Compos. Mater.

- Material Fracture Process Zone ≈ 0.80 mm

- Element length: 4 mm



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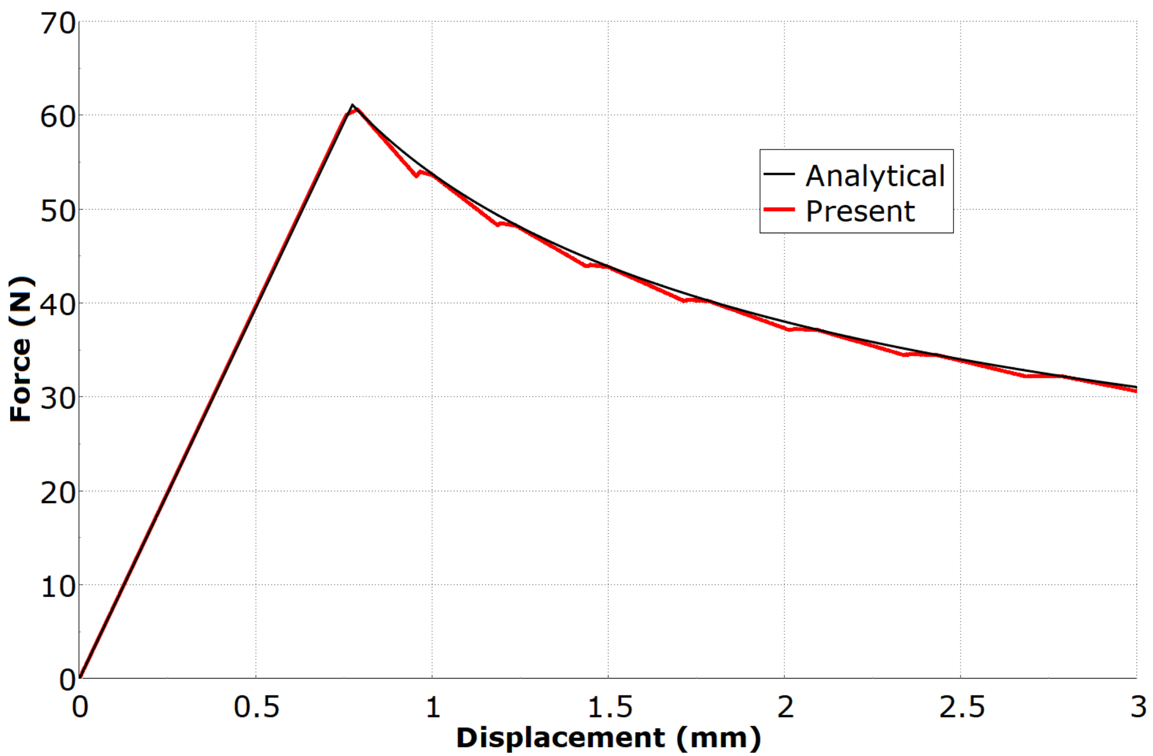

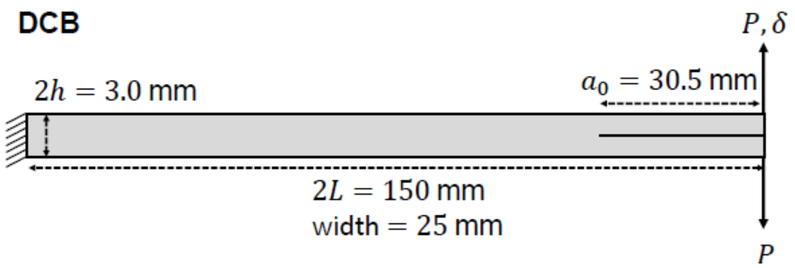

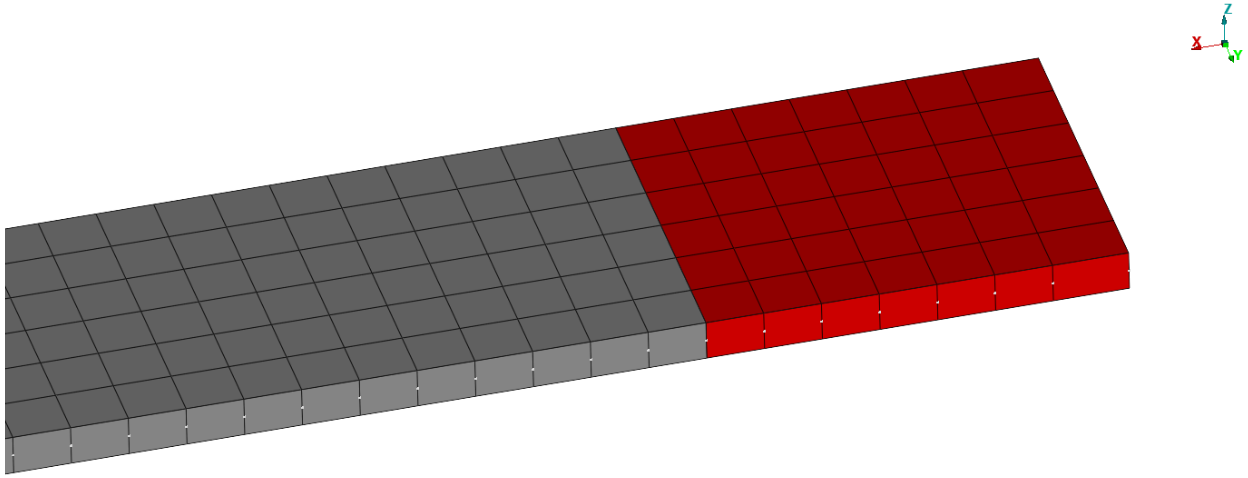

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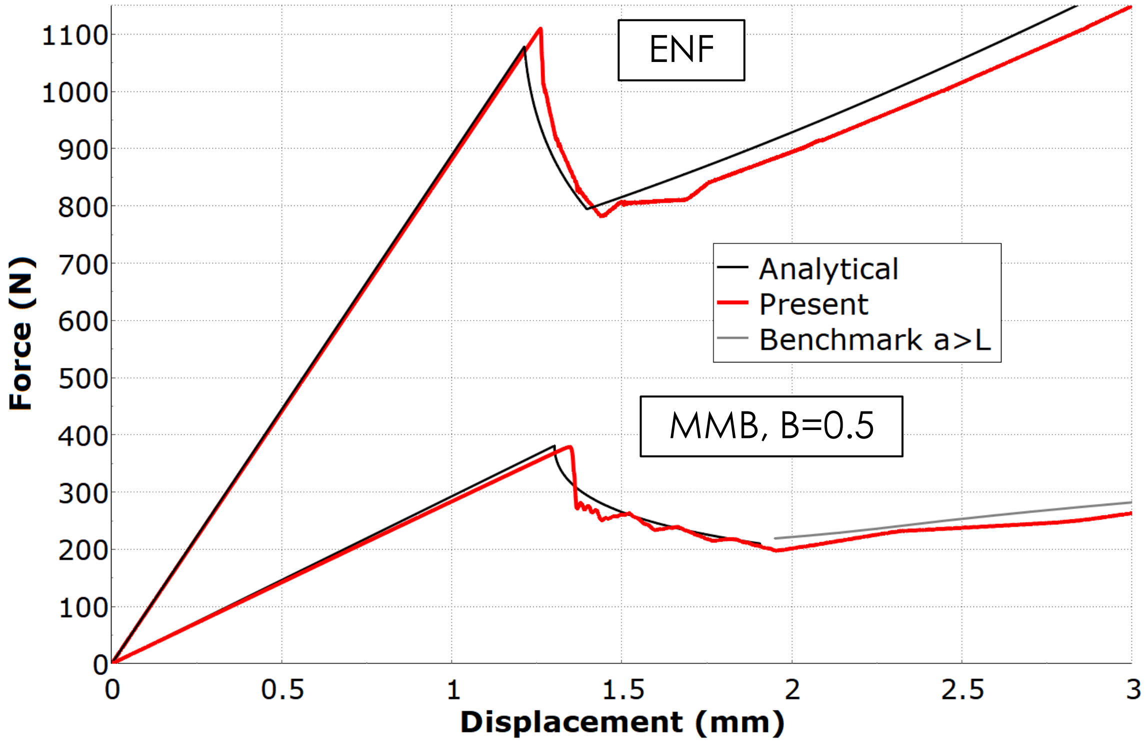
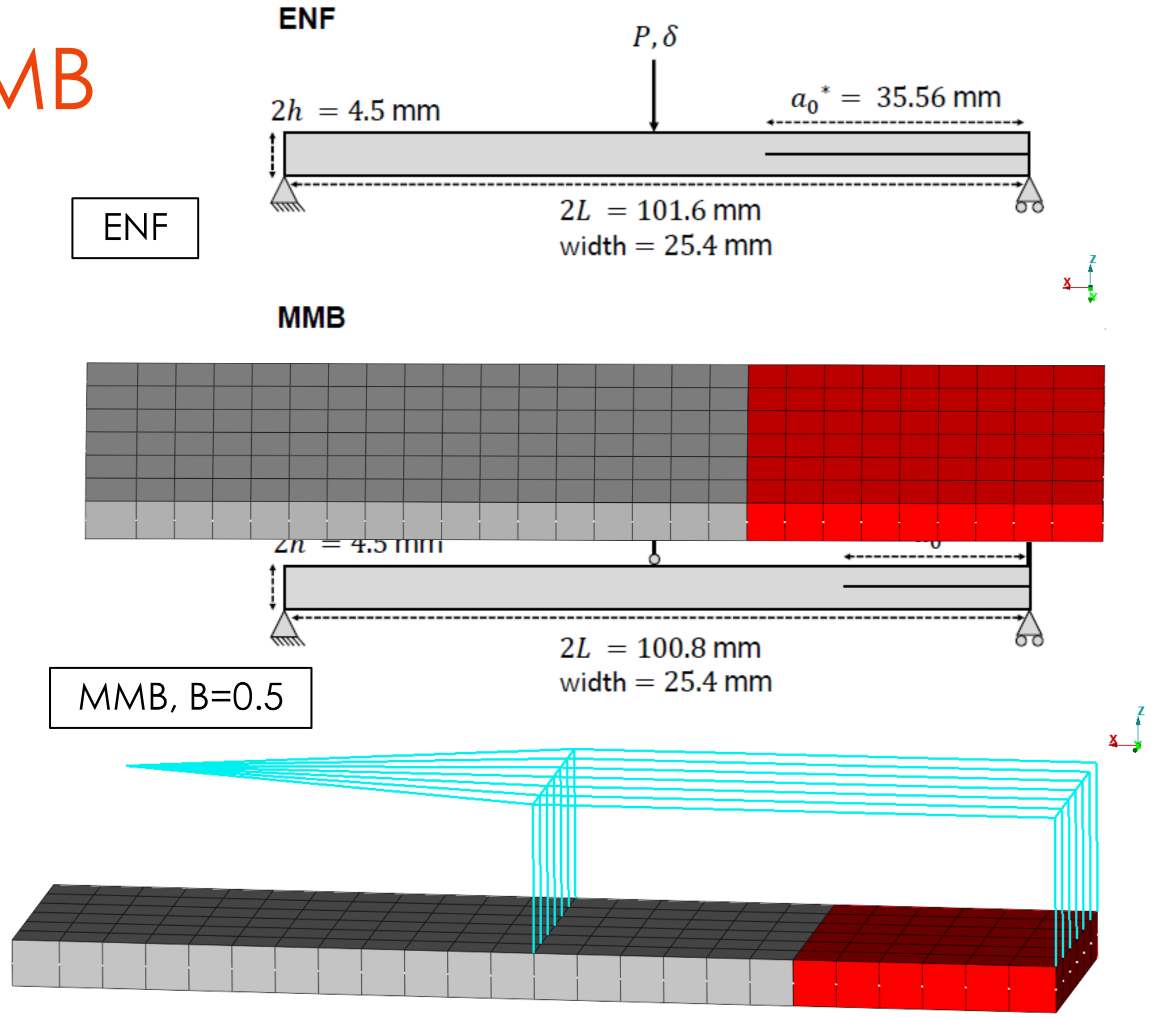
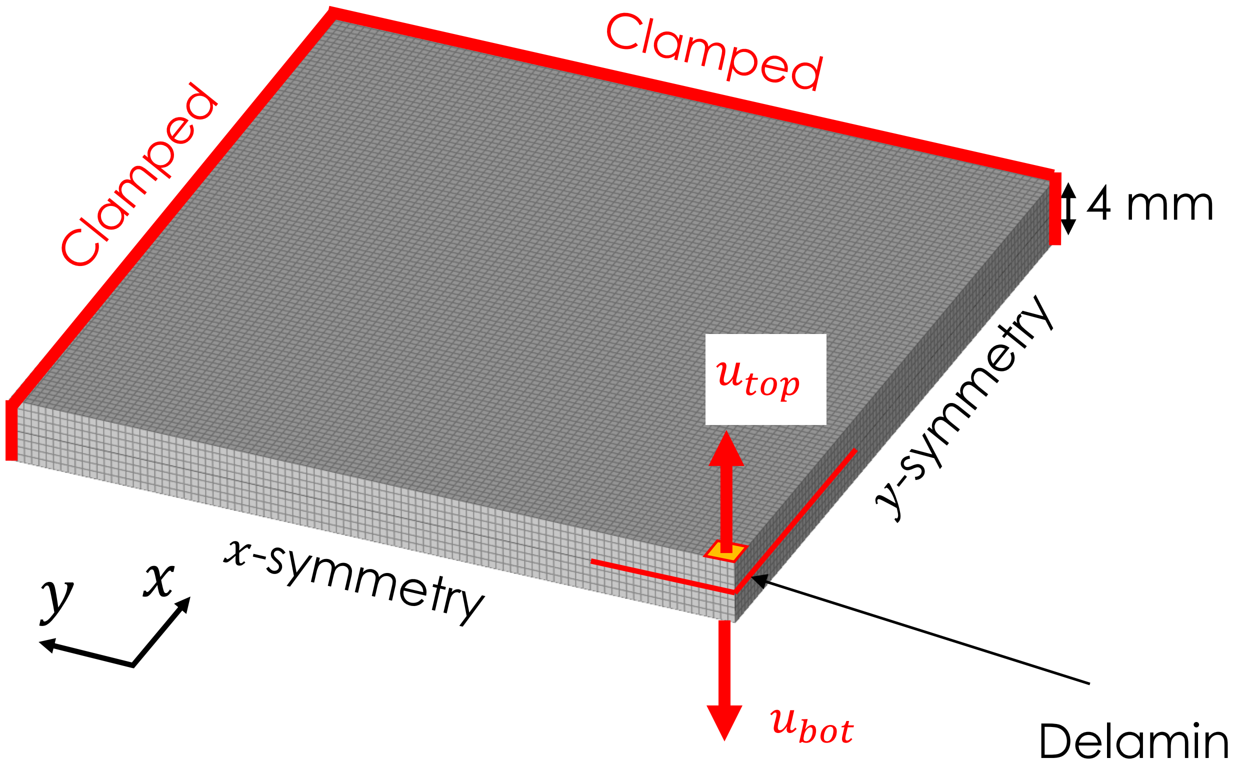
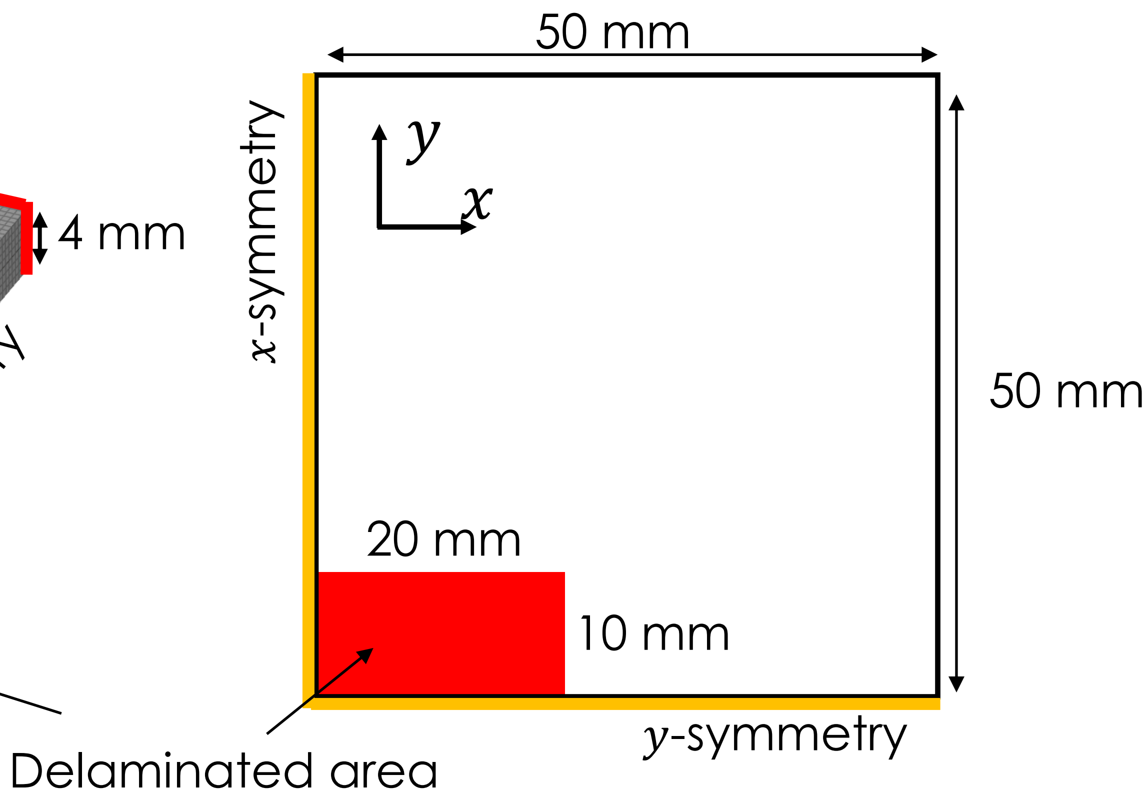




Crack propagation

- Case from: De Carvalho (2022), NASA/TM-20220002081





Crack propagation

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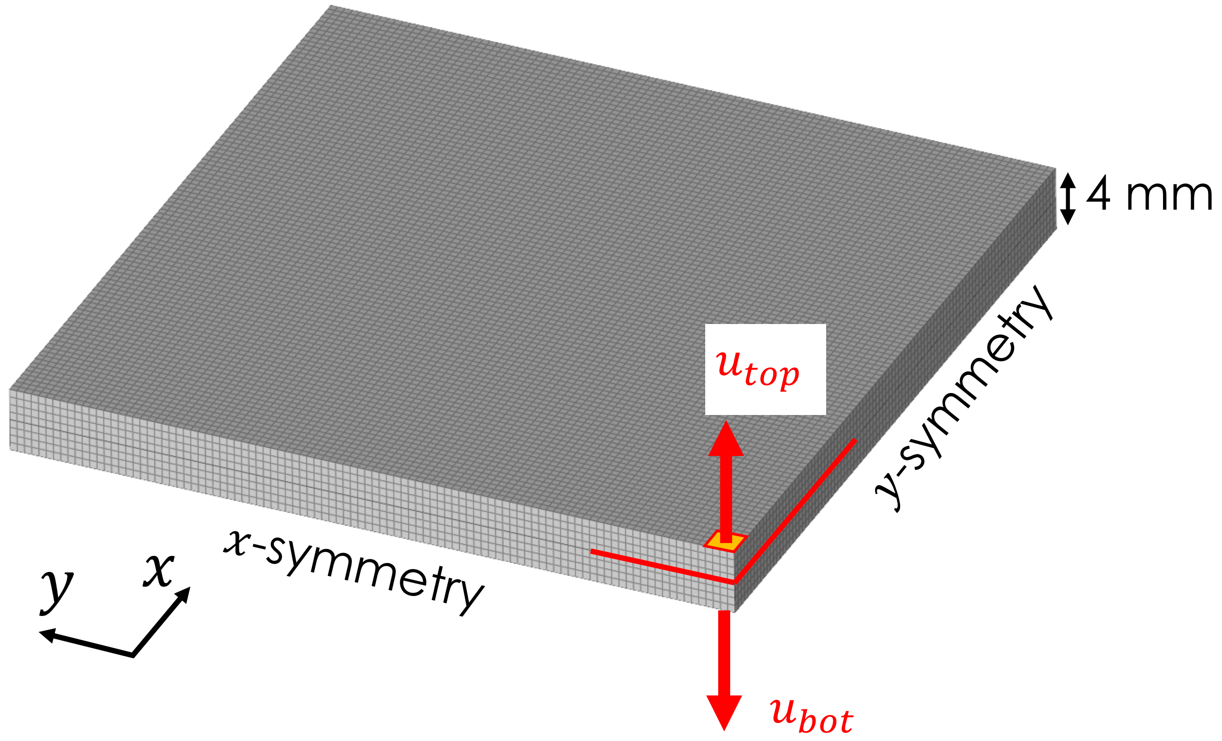
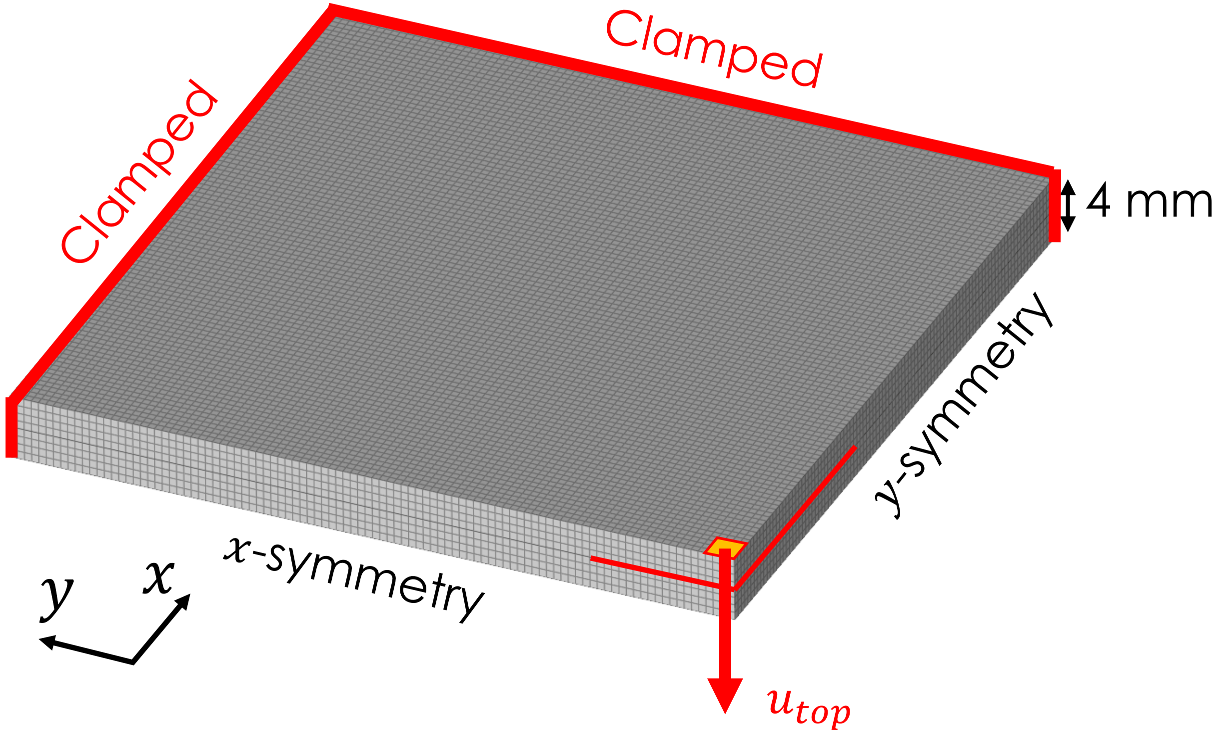


Case	u_{top}	u_{bot}	Edges
Mode I	positive	négative	free
Mode II	negative	-	clamped

Crack propagation

- Case from: De Carvalho (2022), NASA/TM-20220002081



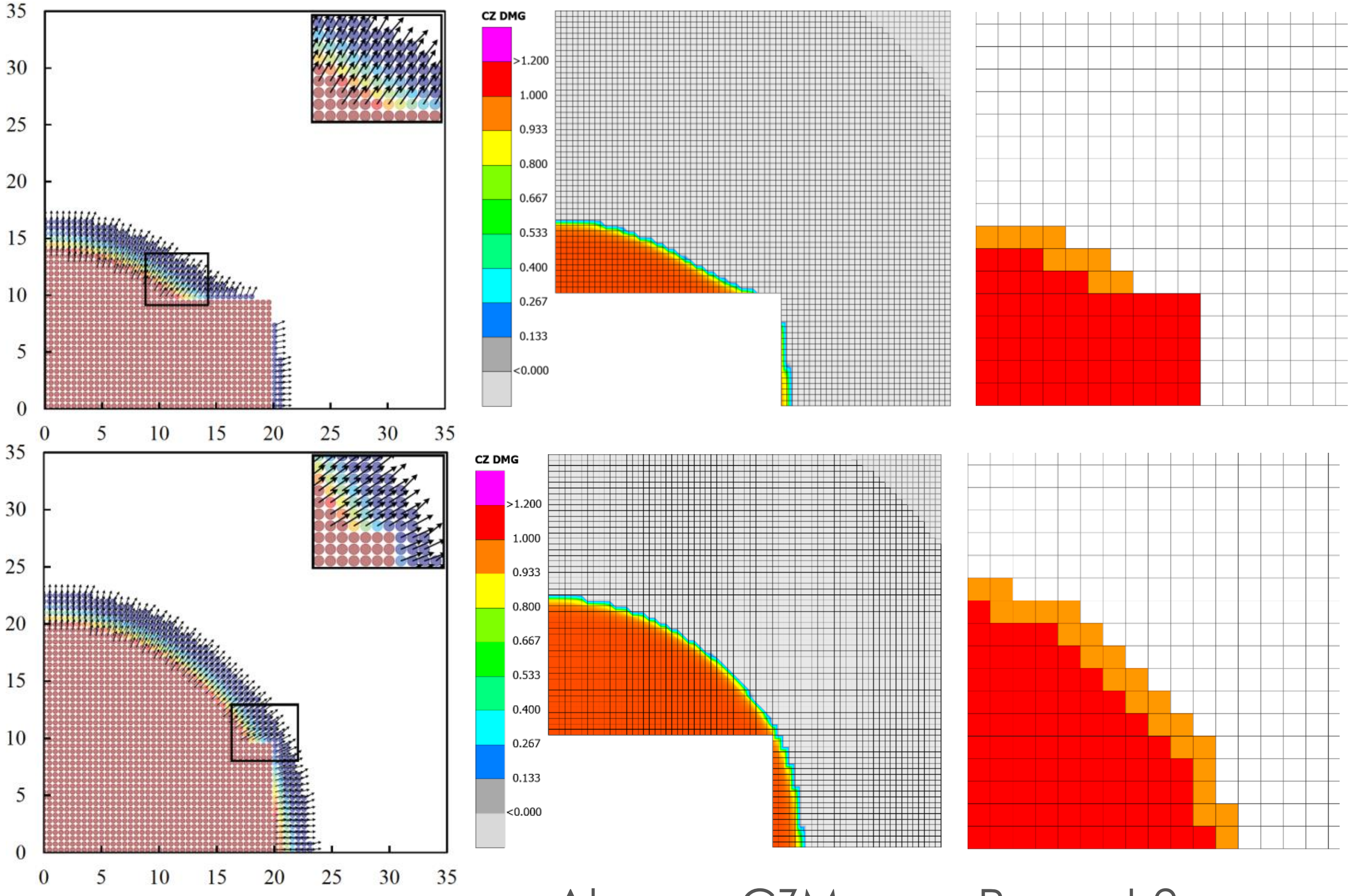
Case	u_{top}	u_{bot}	Edges
Mode I	positive	négative	free
Mode II	negative	-	clamped

Crack propagation

Mode I

u_{top} = 0.1 mm

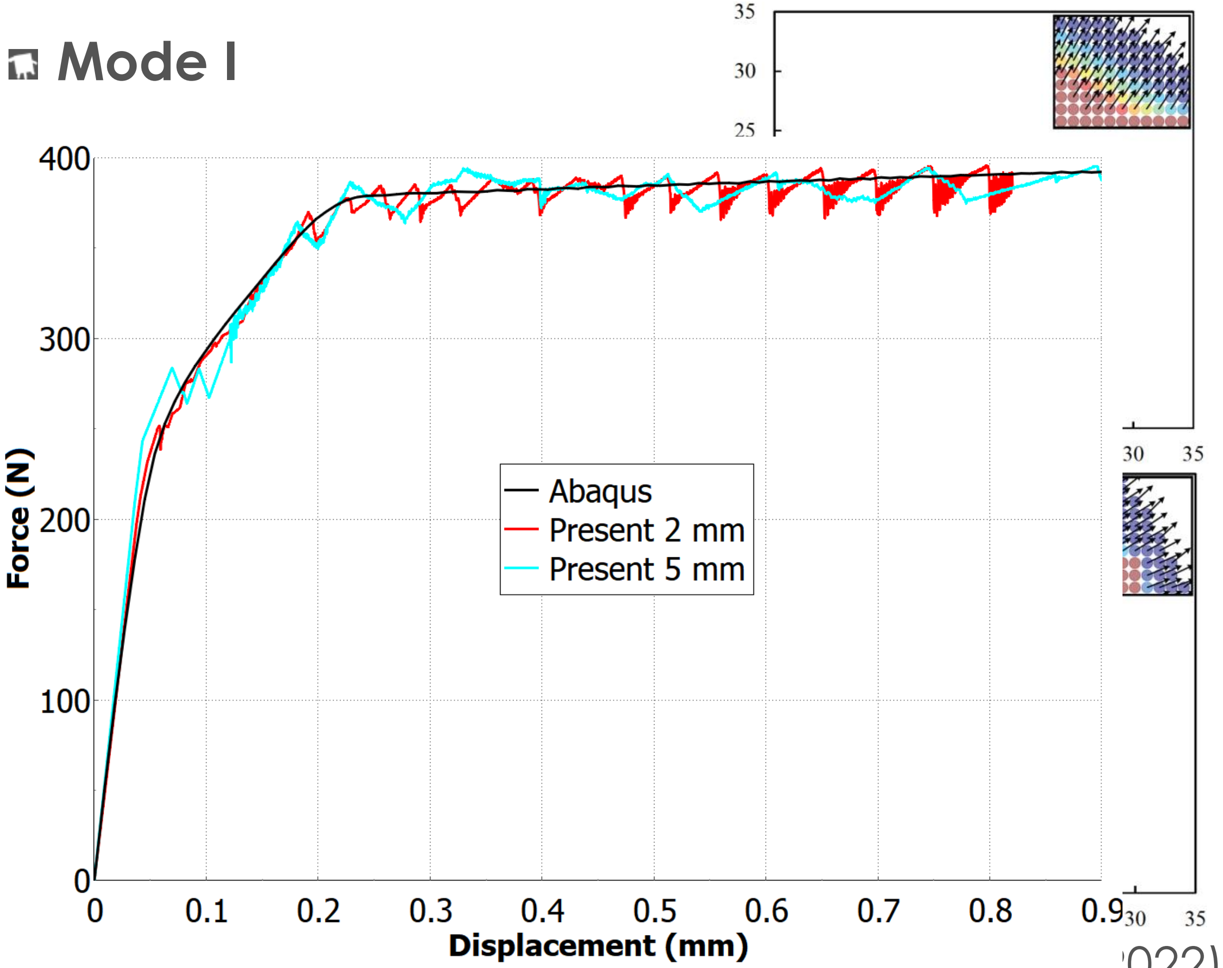
u_{top} = 0.2 mm



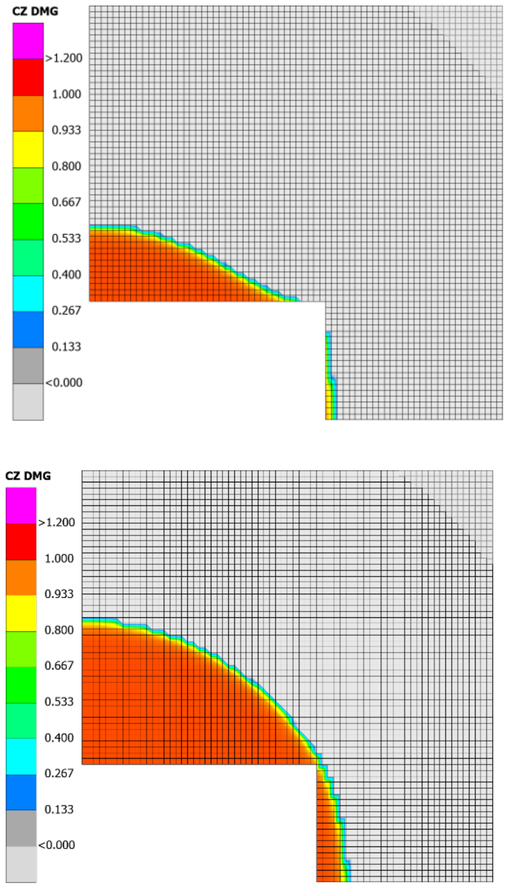
De Carvalho (2022) Abaqus CZM Present 2 mm

Crack propagation

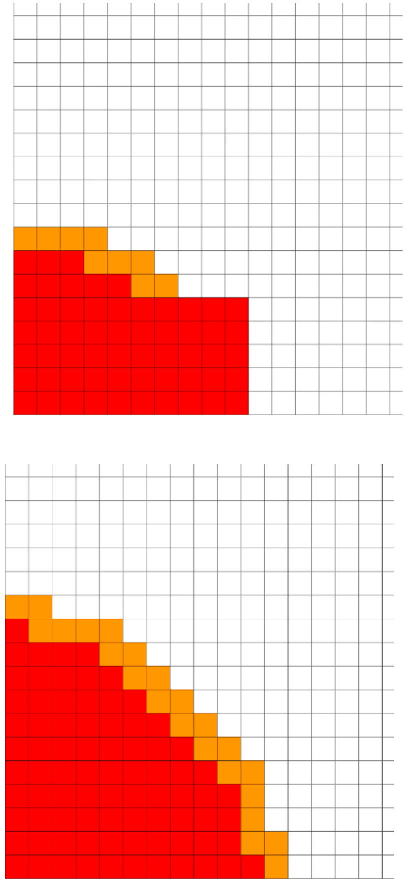
Mode I



De Carvalho (2022)



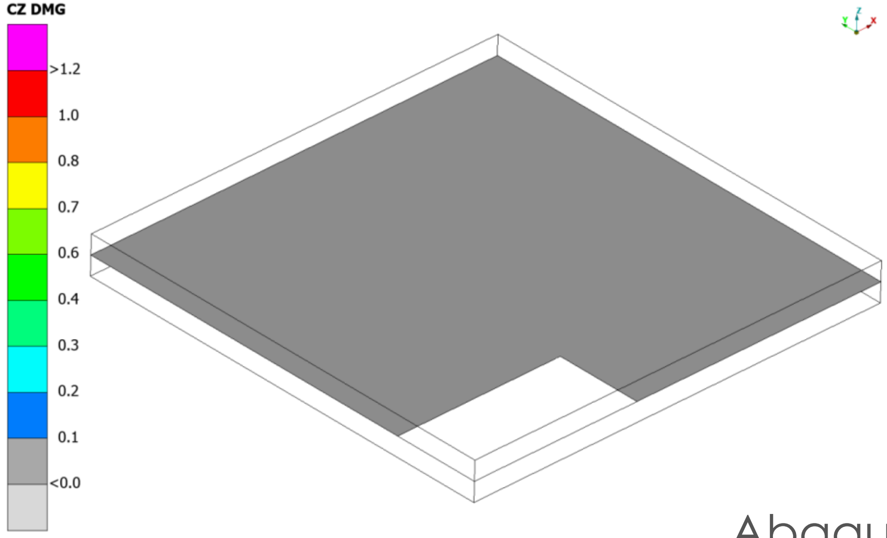
Abaqus CZM



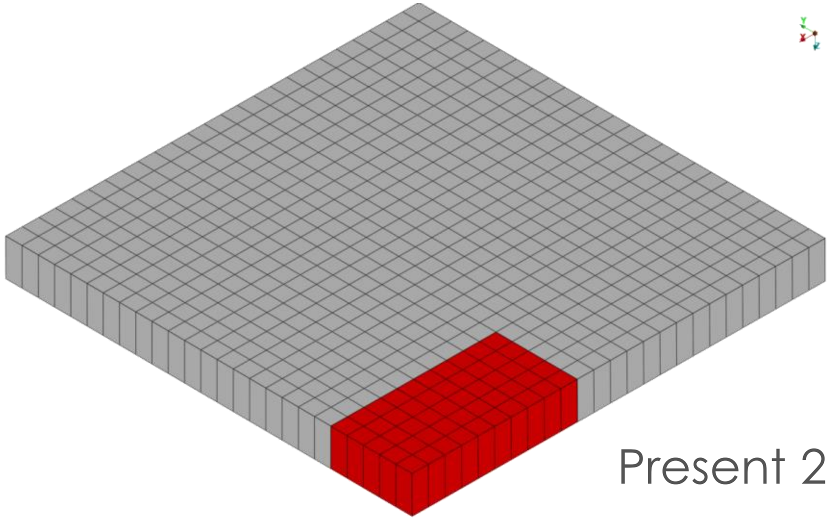
Present 2 mm

Crack propagation

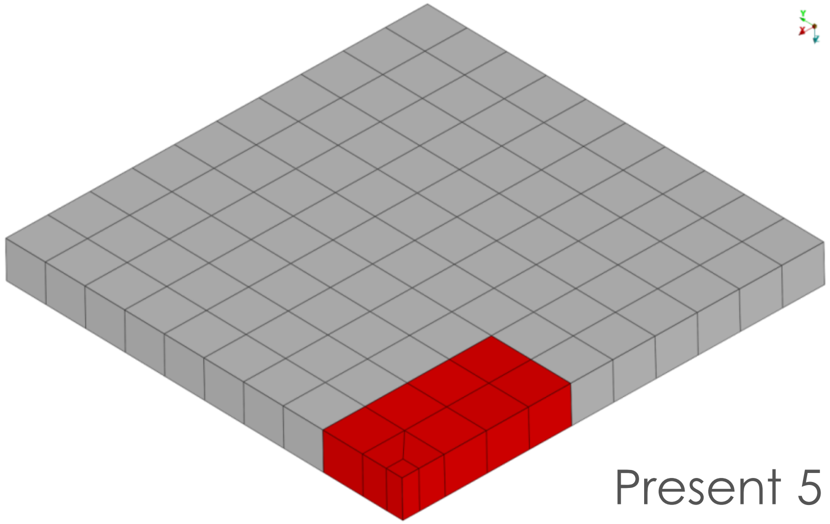
Mode II



Abaqus CZM



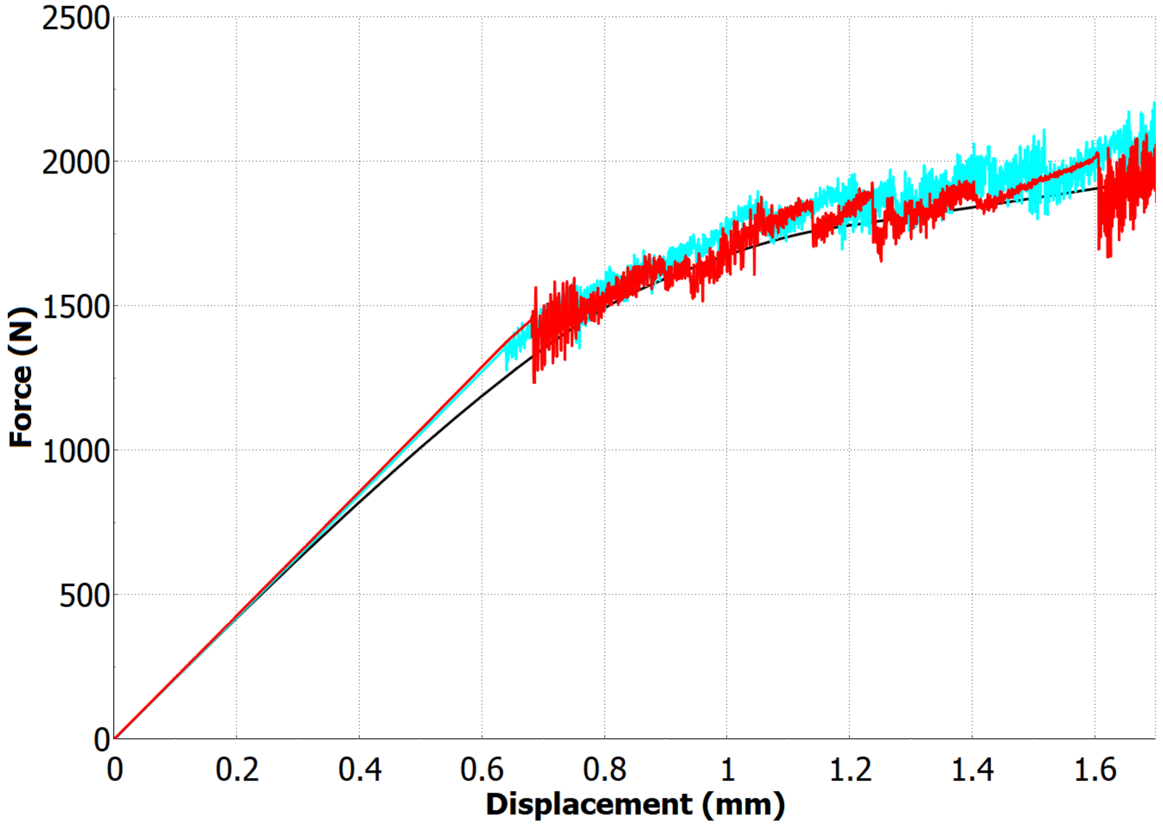
Present 2 mm

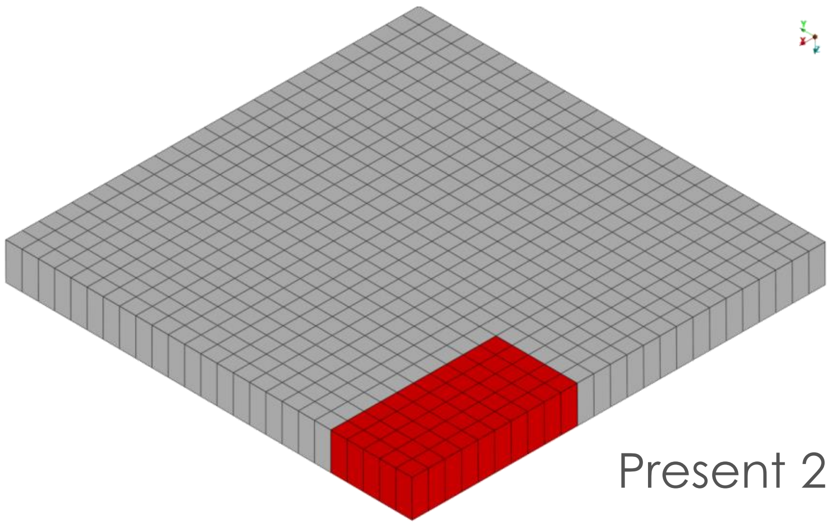


Present 5 mm

Crack propagation

- **Mode II**





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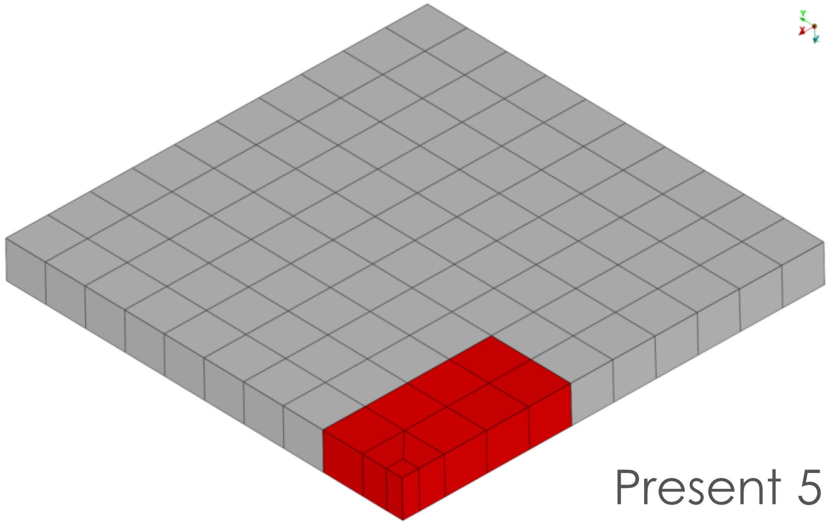

Present 5 mm

Conclusions

Stress Recovery (Delamination initiation)

- Accurate out-of-plane stresses can be obtained with ESL linear shells.
- The model can be refined where there is a risk of delamination.
- Can also be used as a post-processing tool.

VCCT-Cohesive approach (Delamination propagation)

- The method is able to model crack propagation in large elements.
- Does not introduce artificial stiffness.

Using these two methods,
delaminations can be modelled in large structures !

Project outlook

ACCIÓ grant (INNOTEC)

- Collaboration Btech – AMADE
- End of project: July 2024

Collaboration with Chalmers continues in the frame of the thesis.

Thank you!

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