CHALMERS
UNIVERSITY OF TECHNOLOGY

EFFICIENT (AND ROBUST) ANALYSIS OF PROGRESSIVE FAILURE IN FIBRE-REINFORCED POLYMERS

MARTIN FAGERSTRÖM
DIV. MATERIAL AND COMPUTATIONAL MECHANICS,
DEPT. INDUSTRIAL AND MATERIALS SCIENCE,
CHALMERS UNIVERSITY OF TECHNOLOGY

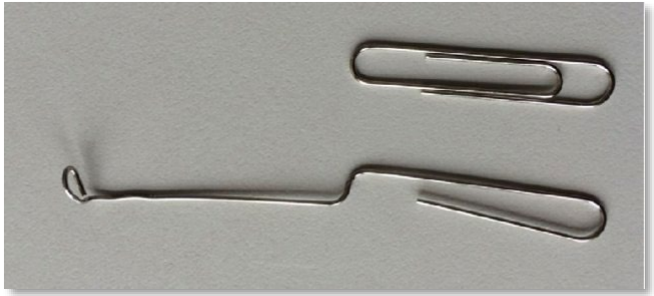

VOLVO
AUTOMOTIVE ELECTRIFICATION
https://www.autoevolution.com/

SUSTAINABLE AVIATION

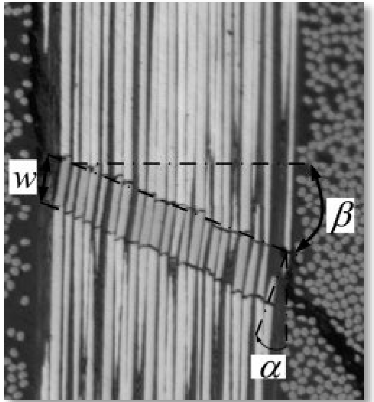
https://www.airbus.com/

What is “failure”?

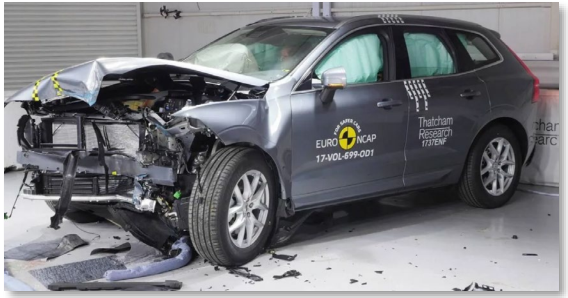
“When and how a component or structure is deforming and eventually failing to fulfil its intended function”



T.T. Ng, 2016



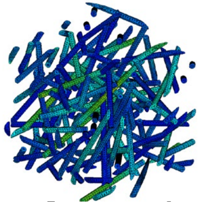
R. Gutkin, 2010

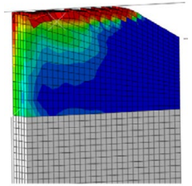


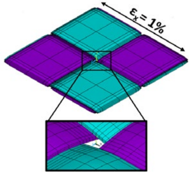
www.motor1.com

There are challenges on all scales!

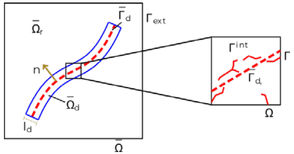
- **How to properly model damage and fracture on the micro- or mesoscale?**
  - Sérgio Costa, Hana Zrida, Mohsen Mirkhalaf, …

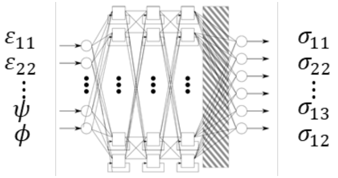




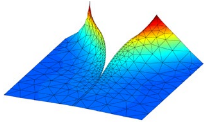


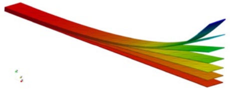
- **How to efficiently link the microscale behaviour to macroscale performance?**
  - Erik Svenning, Mohsen Mirkhalaf, Ehsan Ghane, …

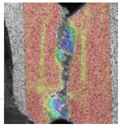


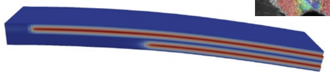


- **How to efficiently model damage and crack propagation on the macroscale?**
  - Salar Mostofizadeh, Jim Brouzoulis, Johannes Främby, Pierre Daniels, Carolyn Oddy, Camiel Adams, Elias Börjesson, …



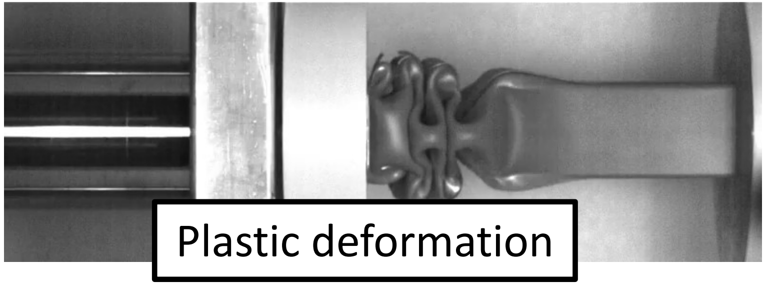


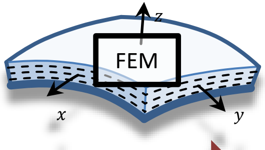




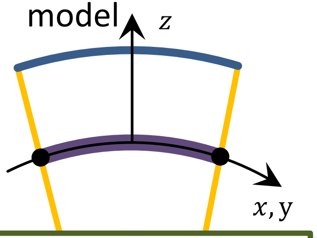
Automotive crash simulations

METAL CRASH BOX





Single-layer model

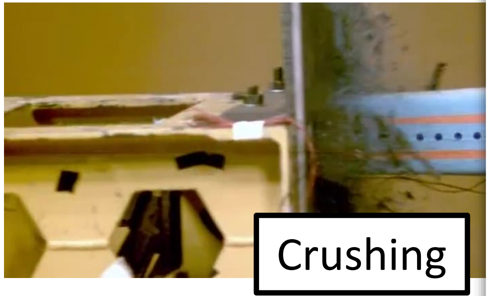


Entire thickness represented by one <u>shell</u> element.

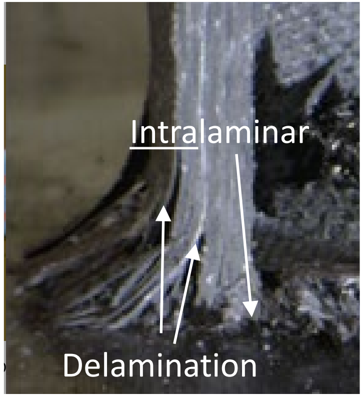
Computationally efficient

Not for composites (can't model delamination)

COMPOSITE CRASH BOX

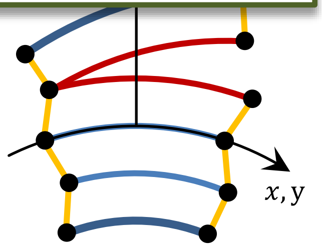


Courtesy of **Engenuity**: https://www.youtube.com/watch?v=VdP5a4k6



Grauers, Olsson & Gutkin (2014), *Compos Struct*

<u>Research scope:</u>
Develop **accurate** and **efficient** shell models for FE simulation of failure in composites



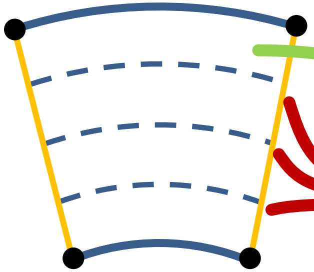
Each ply represented by separate element layer.

Interface modelled by cohesive elements

Accurate prediction (includes delaminations)

VERY computationally expensive

Modelling of crash behaviour in future lightweight vehicles – steps 1 & 2



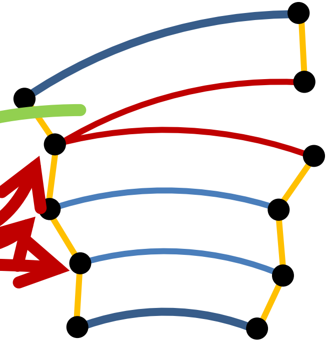
Single-layer model

RISE + Chalmers

Intralaminar (smeared-crack) material model

Adaptively refine model **when-where needed**

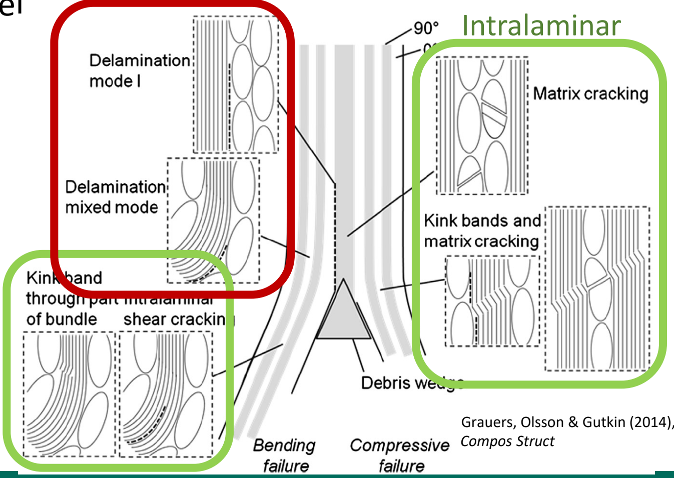
Chalmers



Layerwise model

Grauers, Olsson & Gutkin (2014). *Compos Struct*

Intralaminar



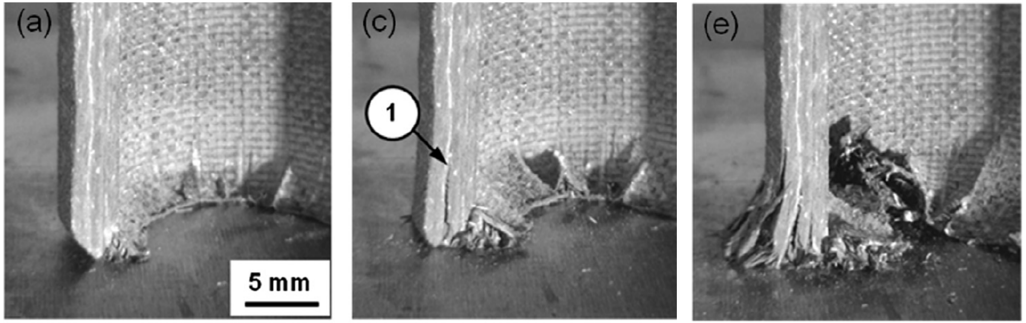
Grauers, Olsson & Gutkin (2014), *Compos Struct*

CHALMERS UNIVERSITY OF TECHNOLOGY · RISE · VINNOVA · eXstream engineering · MSC Software · DYNA MORE NORDIC · HEXAGON · escenda · Gestamp · Autoliv · VOLVO · VOLVO · Altair · FS DYNAMICS · NEVS

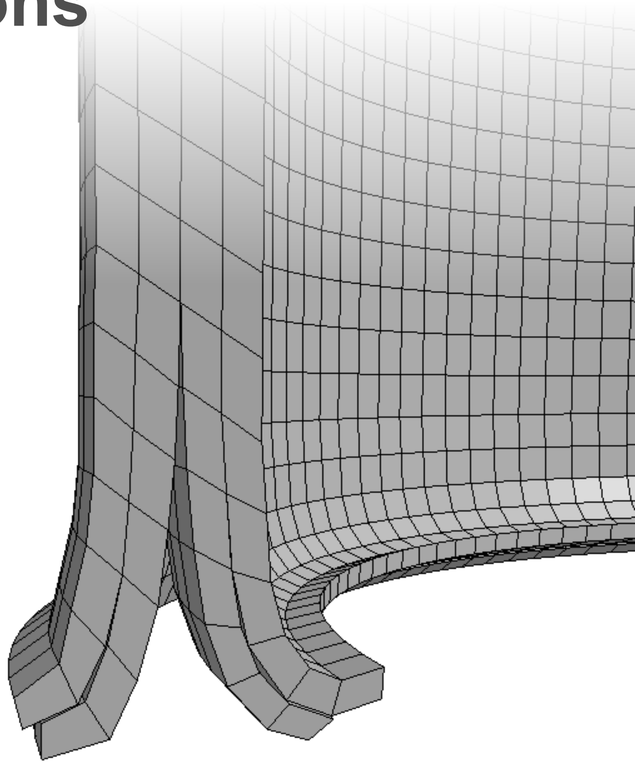
Adaptive method to model delaminations

Johannes Främby, Jim Brouzoulis, Jesper Karlsson & MF

1. Starts with one shell element through the thickness;
2. Identify potential refinement areas with refinement indicators;
3. Shell is locally refined through the thickness (weak refinement);
4. If necessary: cohesive interfaces introduced (strong refinement);
5. If delaminations propagate, refinements are expanded in plane.



Adapted from: Grauers, Olsson & Gutkin (2014). *Composite Structures*



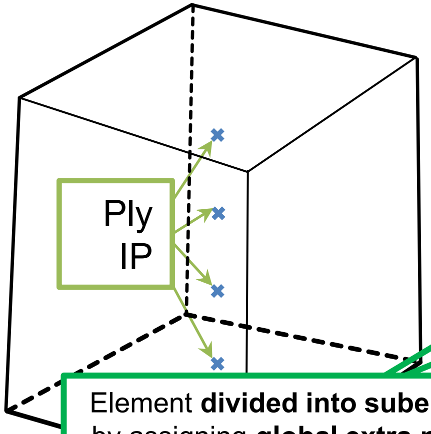
Adaptive LS-DYNA thick shell element

Johannes Främby, Jim Brouzoulis, Jesper Karlsson & MF

- No additional IP added, no IP-data mapping required.
- Refinement done during simulation. No restarts made.
- The time step is automatically updated. Also takes material orthotropy into account (allows for slender elements when $E_3 < E_1$)

Unrefined element

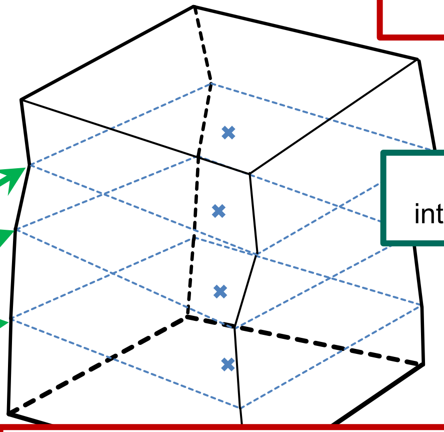
User element: 8 noded thick shell
ELFORM 3 and 5



Element **divided into subelements** by assigning **global extra nodes** to represent the ply interfaces.

Augmented FEM – Ling et al (2009). *Int. J. Fract.*

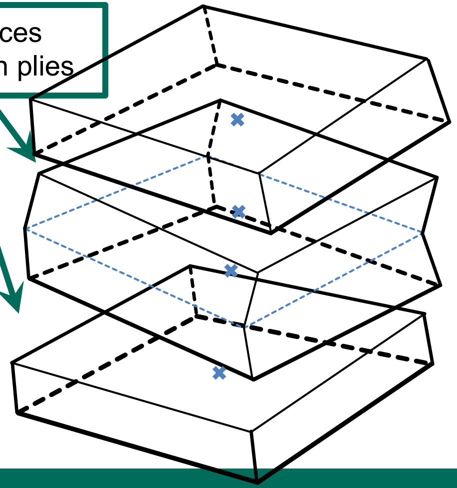
Weak refinements
(increase resolution)



When subelements are introduced, the nodal masses are adjusted appropriately.

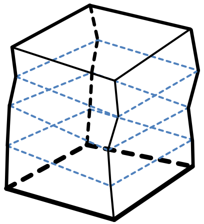
Strong refinements
(model delaminations)

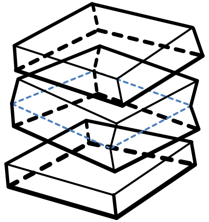
Cohesive interfaces introduced between plies



Refinement indicators/damage initiation criteria

Johannes Främby, Pierre Daniel, Jim Brouzoulis & MF





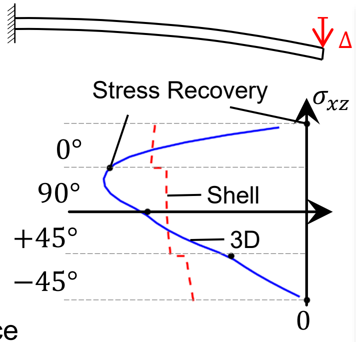
Weak refinements (increase resolution)

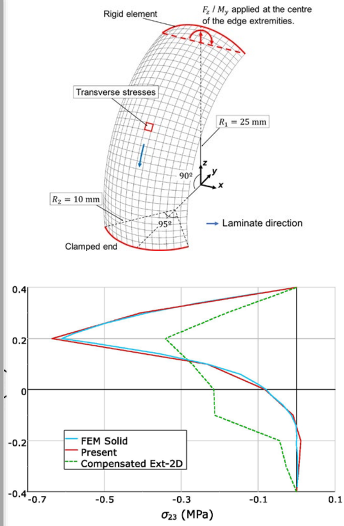
- Evaluate ply failure indices.
- Requires an educated guess of the refined stress state.
  - Stress recovery technique can assist.
    Främby et al (2017). *IJNME*. - **flat**
    Daniel et al. (2019), *Composite Structures* – **doubly curved**

Strong refinements (model delaminations)

- Evaluate delamination failure index.
- Monitor formation of intralaminar cracks.

Refinements should be done before failure initiates!

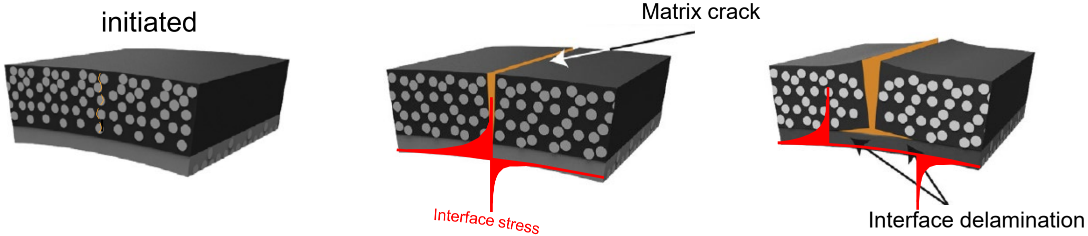




Transverse matrix crack initiated

Fully evolved matrix crack.

Interface delamination



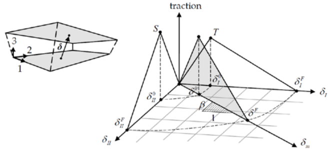
Adapted from: Mortell et al (2014). *Compos. Sci. Technol.*

Matrix Crack Induced Delaminations

Främby and Fagerström, Engineering Fracture Mechanics, 2021

Interlaminar interface (MAT138)

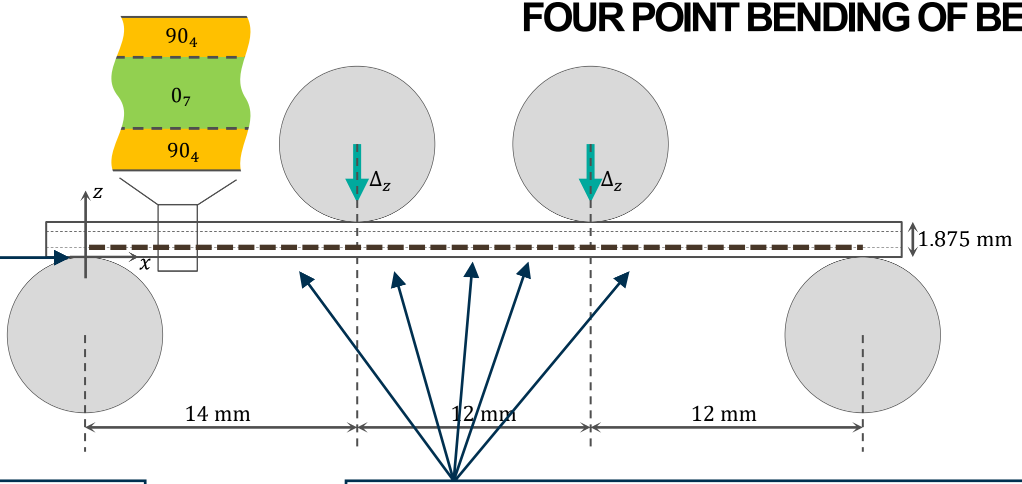
Bi-linear mixed mode CZ model



K	[N/mm²]	10^6
σ_{N0}	[MPa]	105
σ_{S0}	[MPa]	140
G_{Ic}	[J/m²]	432
G_{IIc}	[J/m²]	1002
x_{MU}	-	1.0

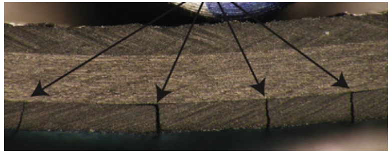
Reiner *et al* (2016). *J. Compos. Mater.*

FOUR POINT BENDING OF BEAM



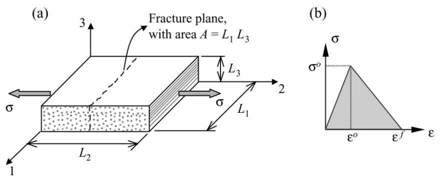
Comparison to

- Reference model with explicit matrix crack;
- Experiment by Mortell et al.



Mortell et al (2014), *Compos. Sci. Technol.*

Smeared intralaminar crack modelling



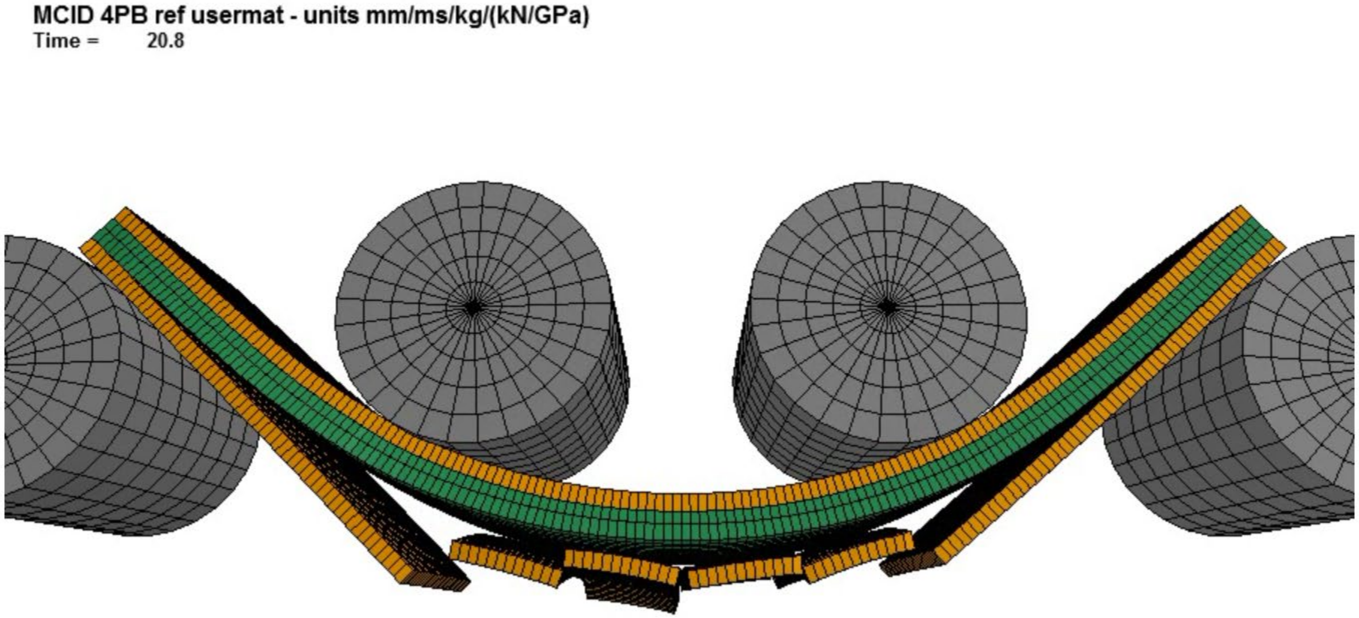
Pinho *et al* (2006). *Comp Part A*.

HTA/6376		
E_1	[GPa]	140
E_2, E_3	[GPa]	10
G_{12}, G_{13}	[GPa]	5.2
G_{23}	[GPa]	3.9
ν_{21}, ν_{31}	–	0. 0214
ν_{32}	–	0.5
Y_T	[MPa]	62
$G_{Ic,mt}$	[J/m²]	432

Reiner *et al* (2016). *J. Compos. Mater.*

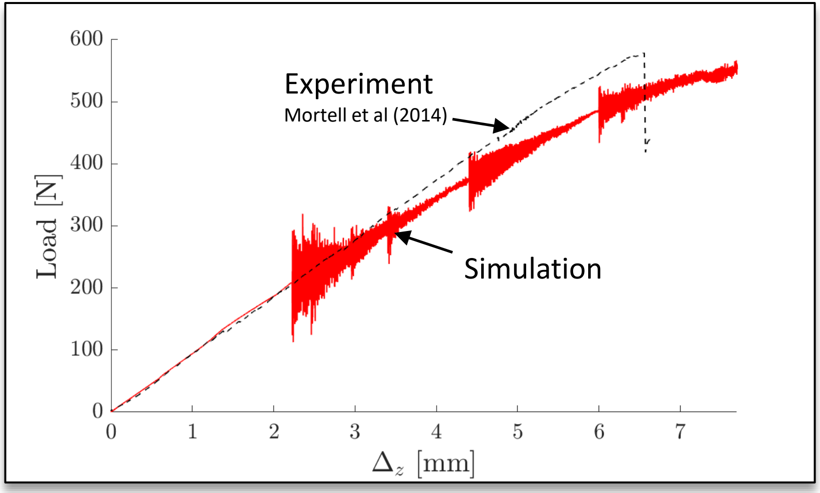
Matrix Crack Induced Delaminations

Främby and Fagerström, Engineering Fracture Mechanics, 2021



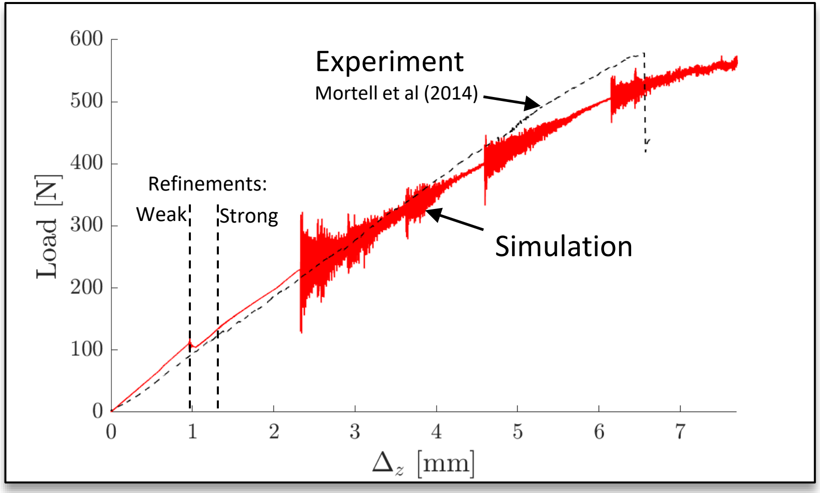
Reference model

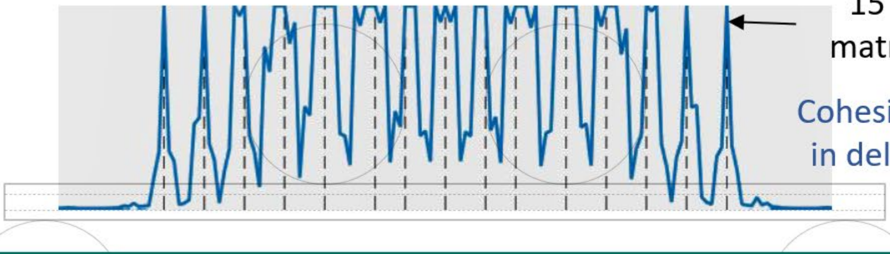
NON-ADAPTIVE REFERENCE



ADAPTIVE

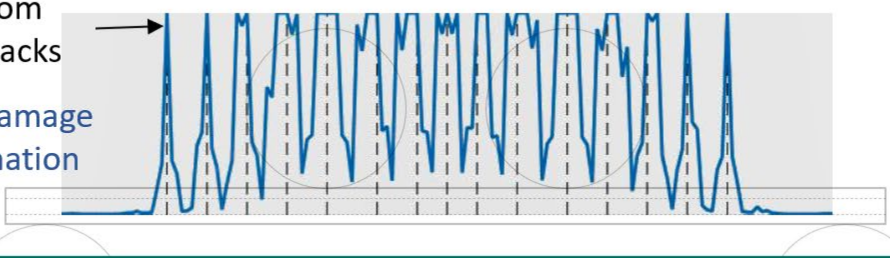
With stabilisation of weak refinement





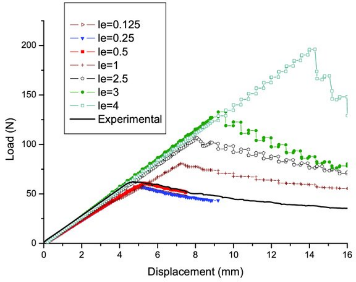
15 bottom matrix cracks

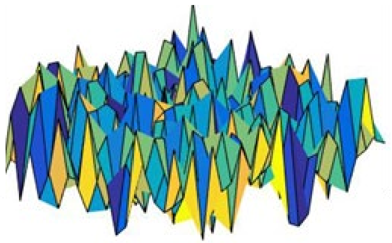
Cohesive damage in delamination



Efficient adaptive simulations of progressive failure

- **Adaptive modelling of delamination growth can be achieved by adding additional degrees of freedom on the fly**
  - Weak and strong discontinuities both have advantages
- **An adaptive strategy requires suitable refinement indicators**
  - Stress-based for initiations, damage-based for growth
- **What remains:**
  - The curse of cohesive zone modelling:
    Requires very small elements for brittle materials
  - Brittle failure requires robust solution methods

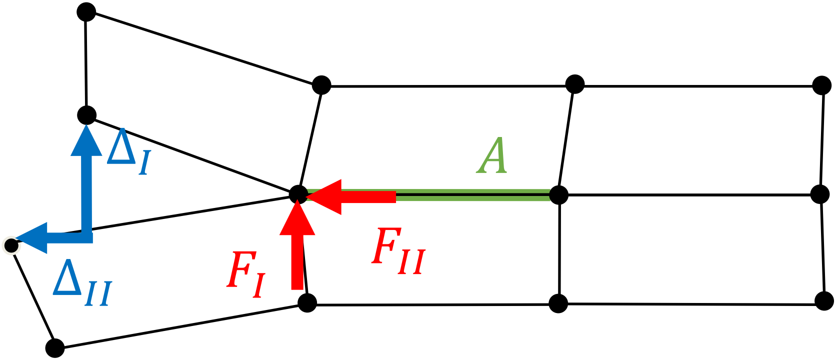




Mitigating the requirement on small in-plane element size

Pierre Daniels, Johannes Främby, MF and Pere Maimí: *Under review*

1. Use VCCT as propagation criterion



$$G_I = \frac{F_I \langle \Delta_I \rangle}{2A}$$

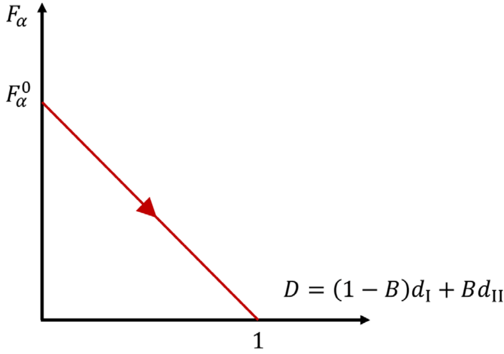
$$G_{II} = \frac{F_{II} \Delta_{II}}{2A}$$

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

If $G_T > G_C$ → The crack has grown

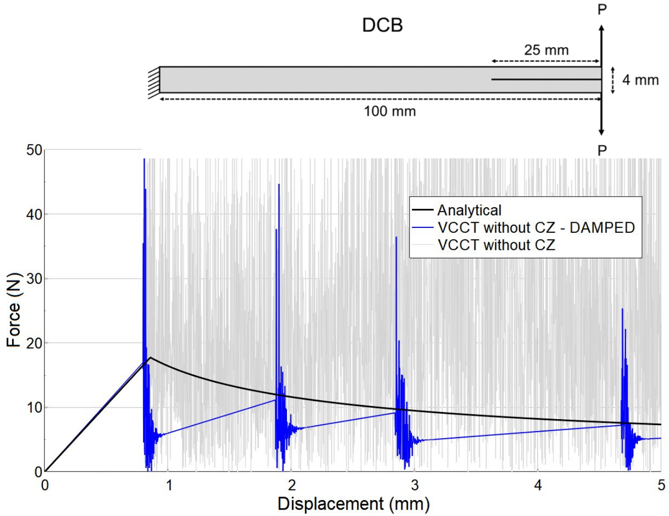
2. Use a cohesive zone like dissipative mechanism

$$F_\alpha = F_\alpha^0 (1 - D) \quad ; \quad (\alpha = I, II)$$

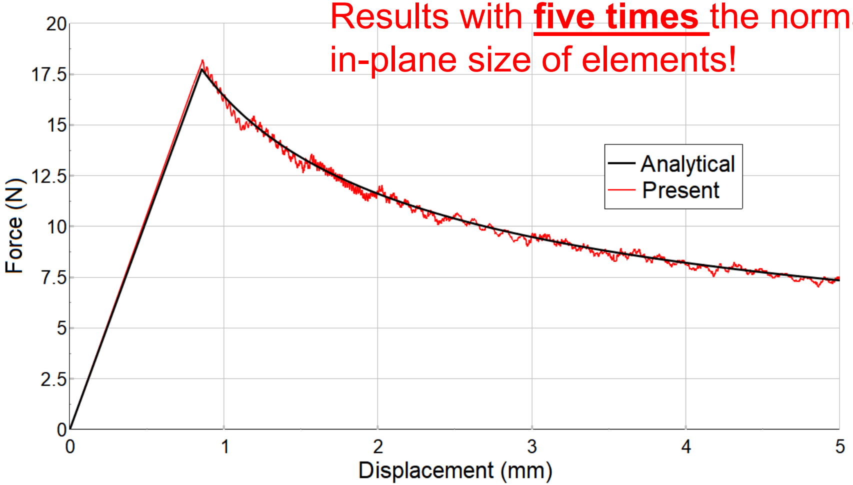


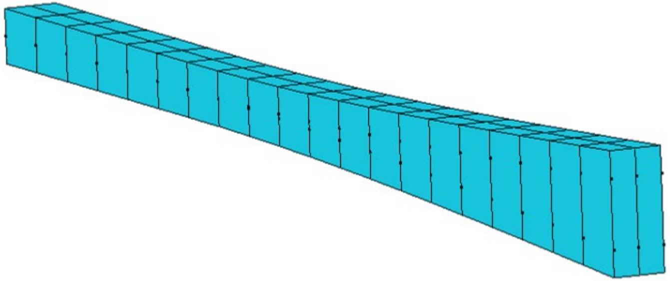
Mitigating the requirement on small in-plane element size

Pierre Daniels, Johannes Främby, MF and Pere Maimí: *Under review*



Results with **five times** the normal in-plane size of elements!





A novel dissipation-based path-following solver

Elias Börjesson, Joris Remmers and MF: *Computational Mechanics 2022*

- **Adding an additional unknown load factor λ to the system**

$$\boldsymbol{r}(\boldsymbol{a},\lambda) = \boldsymbol{f}^{int}(\boldsymbol{a}) - \lambda\hat{\boldsymbol{f}} = 0$$

External reference nodal load vector

- **Controlled by an additional equation φ constraining the total dissipation**

$$\varphi(\boldsymbol{a}) = \int_\Omega \Delta D dV - \Delta L = 0$$

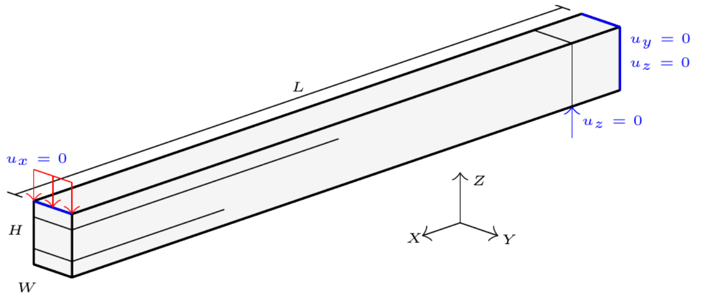
Max disspation during a load step

- **Almost too simple! But it works!**

Example - Multiple end loaded split

Elias Börjesson et al., Computers & Structures 2002

Note! Model is initially one shell through the thickness!

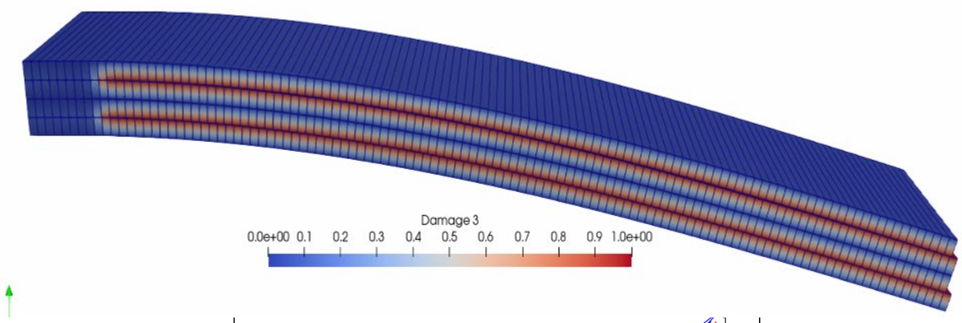


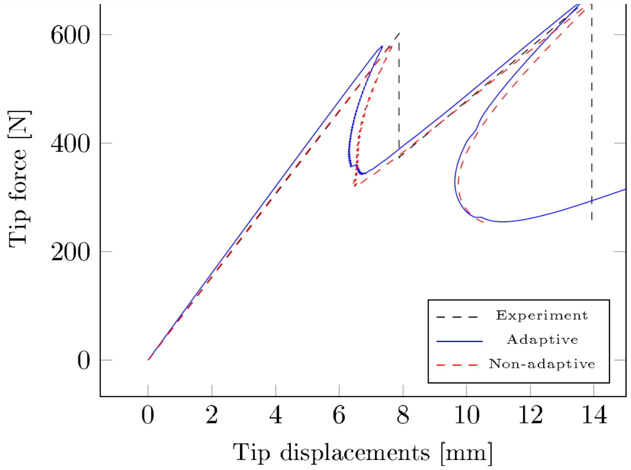
Geometry:
L = 110 mm, **W** = 20 mm, **H** = 8mm
Lower crack length: 32mm
Upper crack length: 56mm

Material IM7/8552 carbon-epoxy:
Homogenized material properties

$E_1 = E_2 = 61.65$ GPa	$G_{12} = 23.37$ GPa	$\nu_{12} = 0.3187$
$E_3 = 13.61$ GPa	$G_{13} = G_{23} = 4.55$ GPa	$\nu_{13} = \nu_{23} = 0.3161$

Experiment by Yasaee et al., 2016

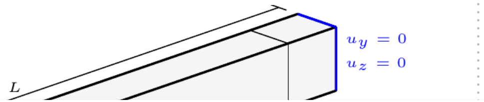




Example - Multiple end loaded split

Elias Börjesson et al., Computers & Structures 2002

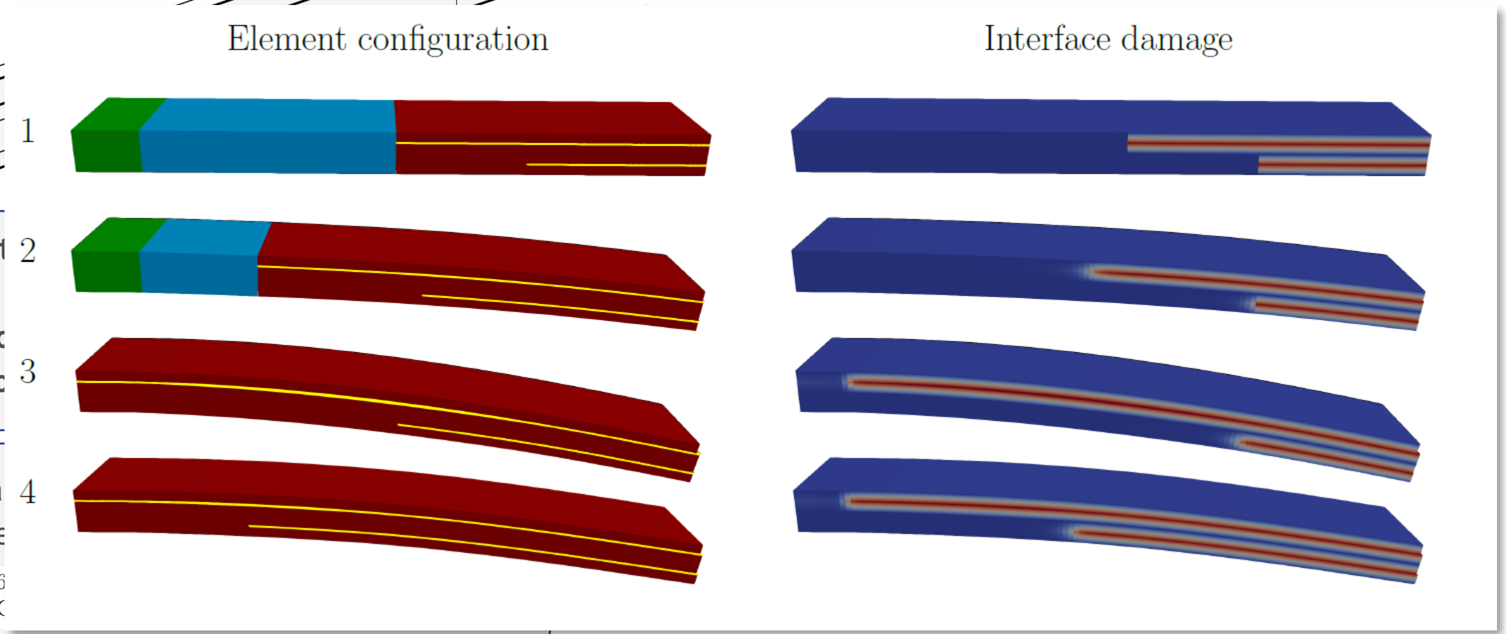
Note! Model is initially one shell through the thickness!



Geomet
L = 110
Lower c
Upper c

Materia
Homoge

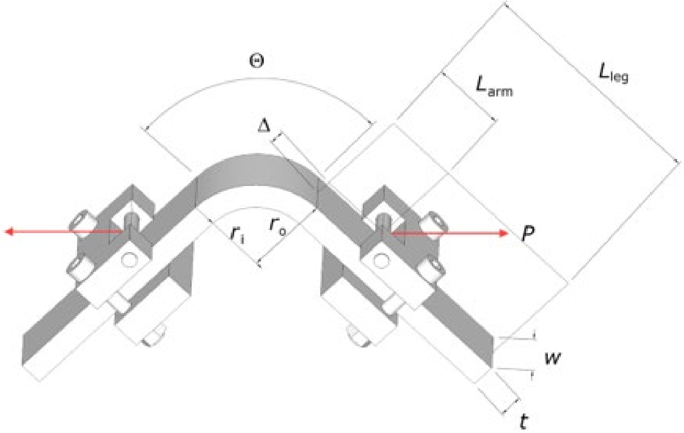
$E_1 = E_2 = 6$
$E_3 = 13.61$ (

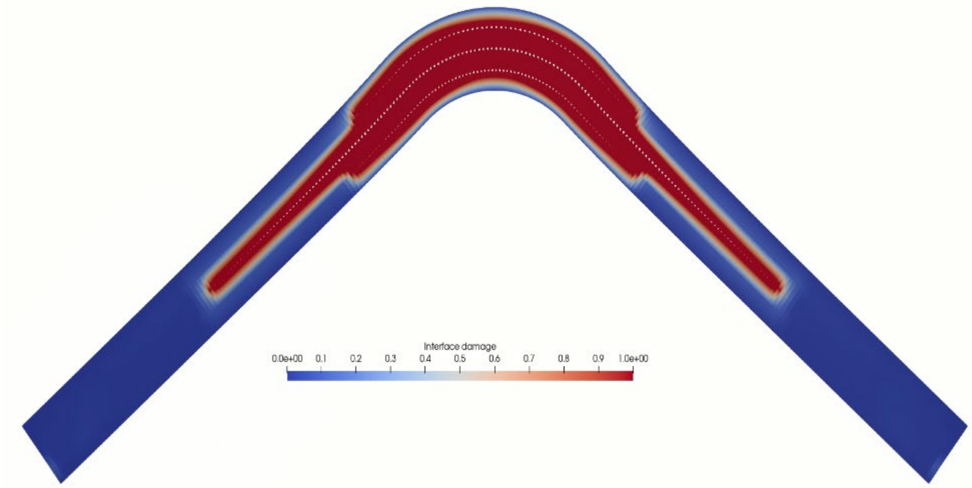


Experiment by Yasaee et al., 2016

Example - “NASA specimen”

Elias Börjesson, Joris Remmers and MF: *Computational Mechanics 2022*





Geometry:

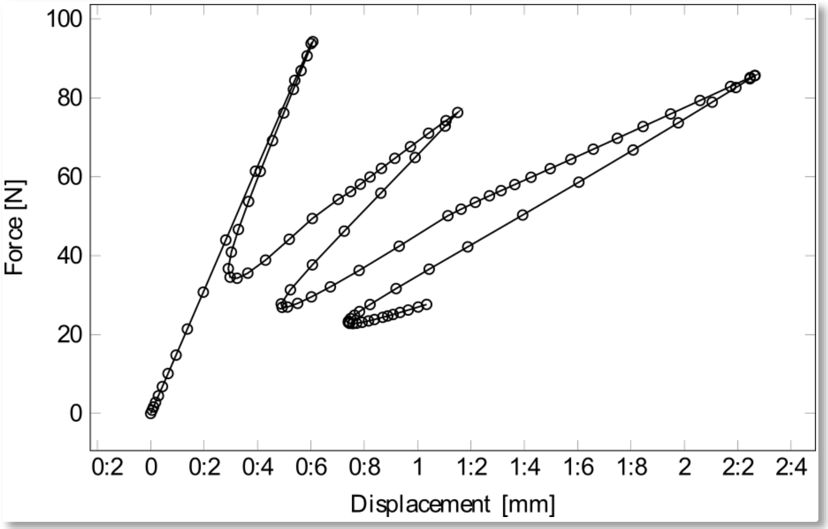
$\mathbf{R_i}$ = 5 mm, $\mathbf{L_{leg}}$ = 25.4 mm, **t** = 6.61mm

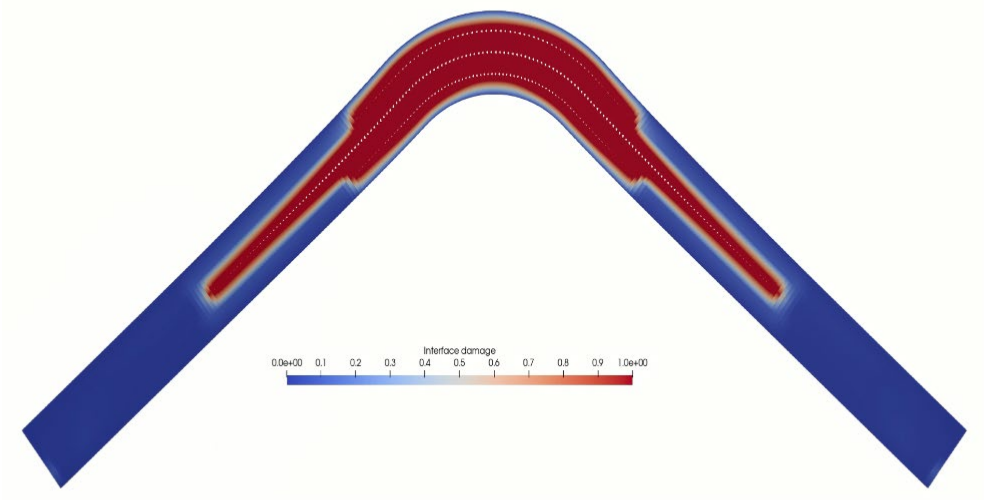
Material properties:

E_1	141 GPa	G_{12}	5.8 GPa	ν_{12}	0.3
E_2	11 GPa	G_{13}	5.8 GPa	ν_{13}	0.3
E_3	11 GPa	G_{23}	3.9 GPa	ν_{23}	0.4

Example - “NASA specimen”

Elias Börjesson, Joris Remmers and MF: *Computational Mechanics 2022*





Thank you!

PhD students and post-docs:

- Goran Ljustina
- Salar Mostofizadeh
- Erik Svenning
- **Johannes Främby**
- Carolyn Oddy
- **Pierre Daniel**
- **Elias Börjesson**
- Ehsan Ghane
- **Jim Brouzoulis**
- Hana Zrida
- Mohsen Mirkhalaf

Co-supervisors and research collaborators:

- Ragnar Larsson
- Frans van der Meer
- Bert Sluys
- Fredrik Larsson
- Magnus Ekh
- Leif Asp
- Robin Olsson
- Renaud Gutkin
- Camiel Adams
- **Pere Maimí**
- **Joris Remmers**
- Kristian Samuelsson
- Eric Hamrin Senorski

Other co-authors:

Jesus Mediavilla, Elias Blomstrand, Daniel Johansson, Niklas Karlsson, Nicklas Olofsson, Petra SteenJohn McVeagh, Matz Brown, Christian Finnsgård, Martin Granlund, Gustav Gräsberg, Andreas Karlsson, Tomas Ekermann, Stefan Hallström, Fredrik Stig, Eva Eggels, Tom van Beurden, David Ekström, Max Forkman, Adam Persson, Lars Larsson, Michael Stadler, Brina Blinzler, Max Salminen, John Borenius, Henrik Edman, Albin Lindmark, Marcus Pålsson, Thomas Abrahamsson, Jesper Karlsson, Ershad Pourbahaaddini, Philip Simonsson, Tom van Westendorp, Brian Castricum

- Supporting organisations and funding agencies

UNIVERSITY OF GOTHENBURG
VOLVO
VOLVO
Gestamp
DYNA MORE NORDIC
FS DYNAMICS
BITEAM
Exstream ENGINEERING
RI. SE
TU/e
MSC Software
escenda
Altair
KTH VETENSKAP OCH KONST
Autoliv
NEVS
BETA SIMULATION SOLUTIONS
GKN AEROSPACE
btech Barcelona Technical Center
UdG
SIEMENS
TUDelft
LIGHTer
Swedish Research Council
CHALMERS UNIVERSITY OF TECHNOLOGY Area of Advance MATERIALS SCIENCE
Swedish Energy Agency
M2i materials innovation institute
SEVENTH FRAMEWORK PROGRAMME
VINNOVA