Engineering and Physical Sciences Research Council

Application of second-order multi-scale modelling to composite components with delamination, fibre and matrix damage

Meng yi Song, Aewis K.W. Hii*, Bassam El Said*, Stephen R. Hallett**

*Bristol Composites Institute

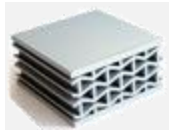
ECCM21 Nantes 3 July 2024

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

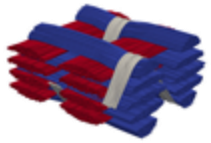
Challenges

Analytical / empirical shell material models do not exist in the following scenarios:

Materials with internal architecture

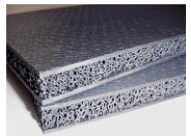


Exotic panels

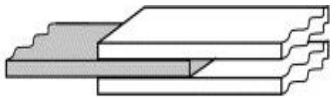


Textile composites

Porous materials

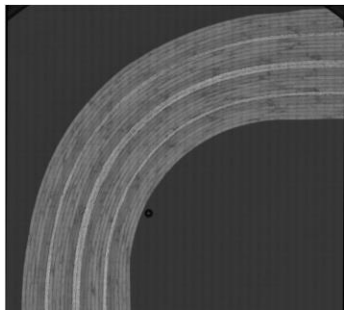


CMCs

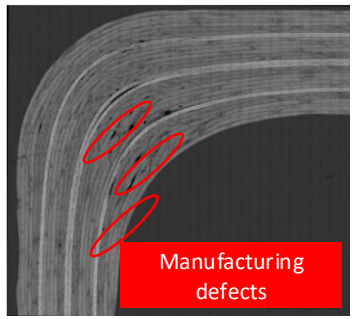


Joints

Manufacturing defects

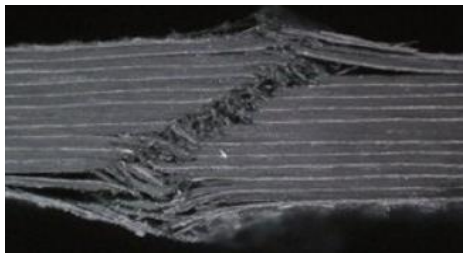


Ideal component



As-manufactured part

Complex failure modes



3D interactions of fibre breakage, matrix cracking, delamination etc.

Engineering and Physical Sciences Research Council

Goal

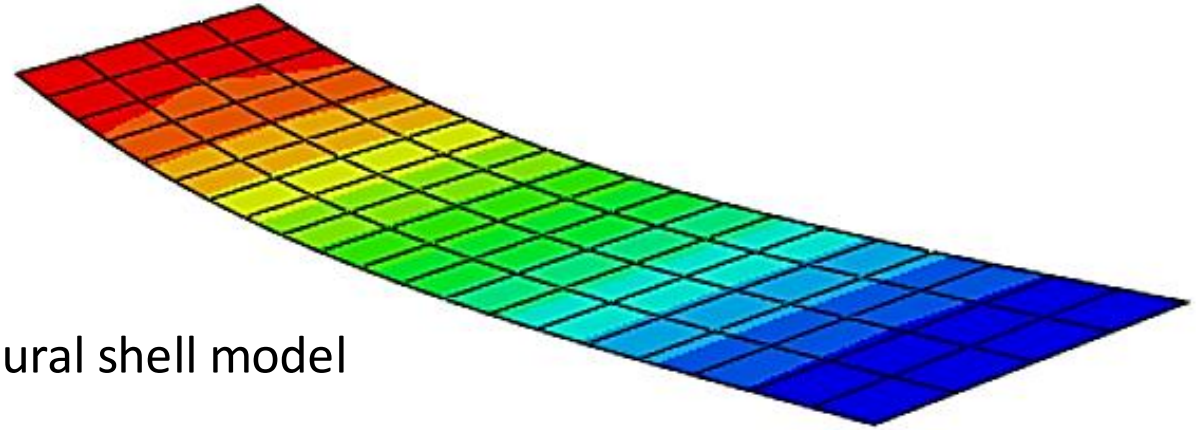
"Create a framework to model *complex materials and manufacturing defects* with shell elements"

- Direct plug-in to existing shell models in commercial software
- *e.g.* shell elements that can model delamination, wrinkles, 3D woven materials …

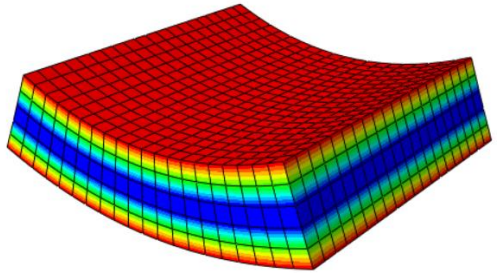
University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

Multi-scale



Structural shell model



Sub-structural solid model (RVE)

"FE^2"

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

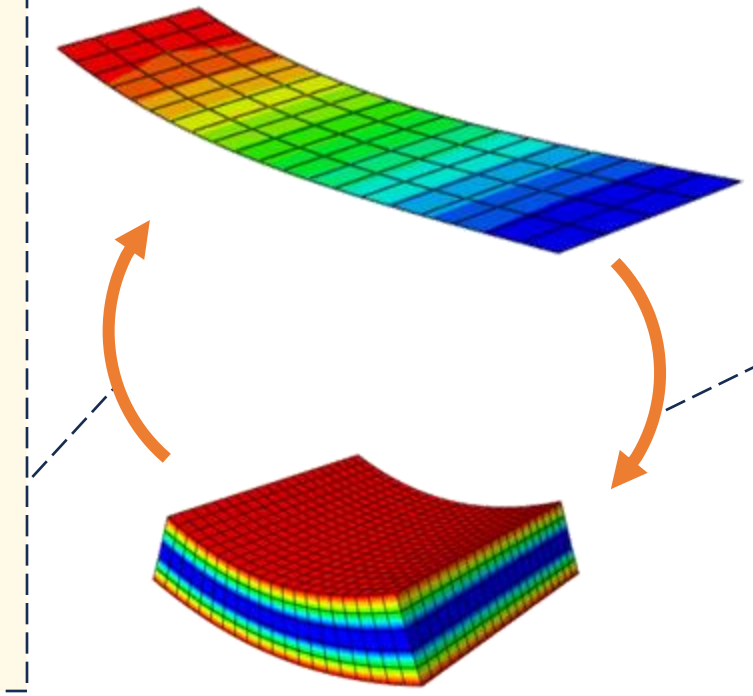
Mathematical background

Principle of energy equivalence:

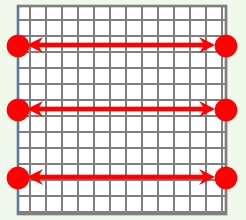
Sub-scale energy
=
Macro-scale energy

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\begin{array}{ccc|ccc} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \hline B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{array}\right] \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \hline K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

Homogenised quantities: resultants and ABD(K) matrices

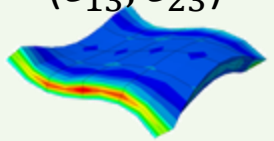


Principle of orthogonality and kinematic equivalence:

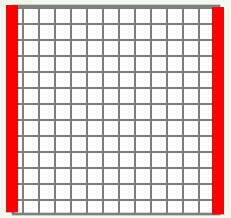


Nodes

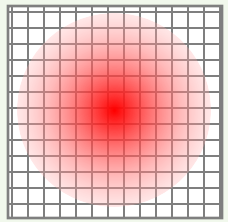
$(\epsilon_{13}, \epsilon_{23})$



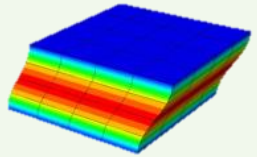
Classical shell homogenisation



Surfaces



Volume



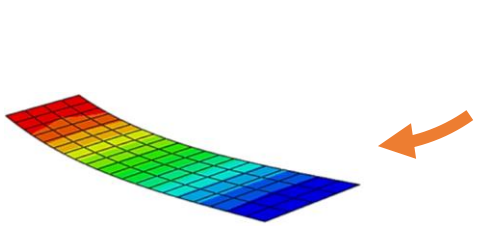
Realistic transverse shear deformation

Aewis K.W. Hii, Bassam El Said. "A kinematically consistent second-order computational homogenisation framework for thick shell models." *Computer Methods in Applied Mechanics and Engineering*, 398, 2022.

Engineering and Physical Sciences Research Council

Second Order

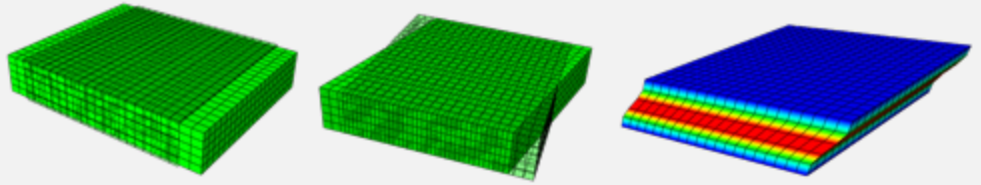
Fine scale deformation = *1st order deformation* + *2nd order deformation* + *Fluctuation field* $\vec{w}$



$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\begin{array}{ccc|ccc} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \hline B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{array}\right] \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \hline K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

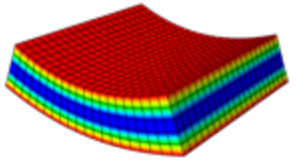
Second-order homogenisation

First-order homogenisation



'Strains': $\epsilon_{11}, \epsilon_{22}, \epsilon_{33}, \gamma_{12}, \gamma_{23}, \gamma_{13}$

'Strain-gradients': $\kappa_{11}, \kappa_{22}, \kappa_{12}, \ldots$



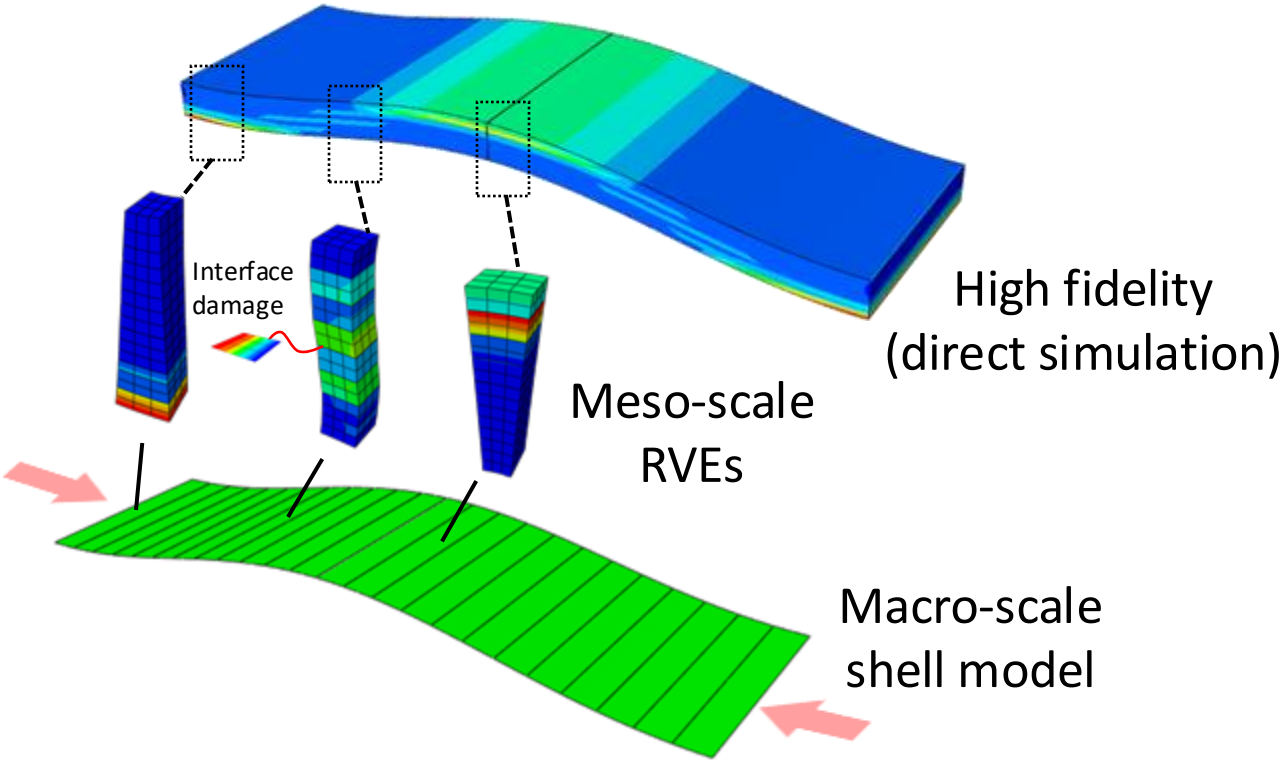
Curvature/bending

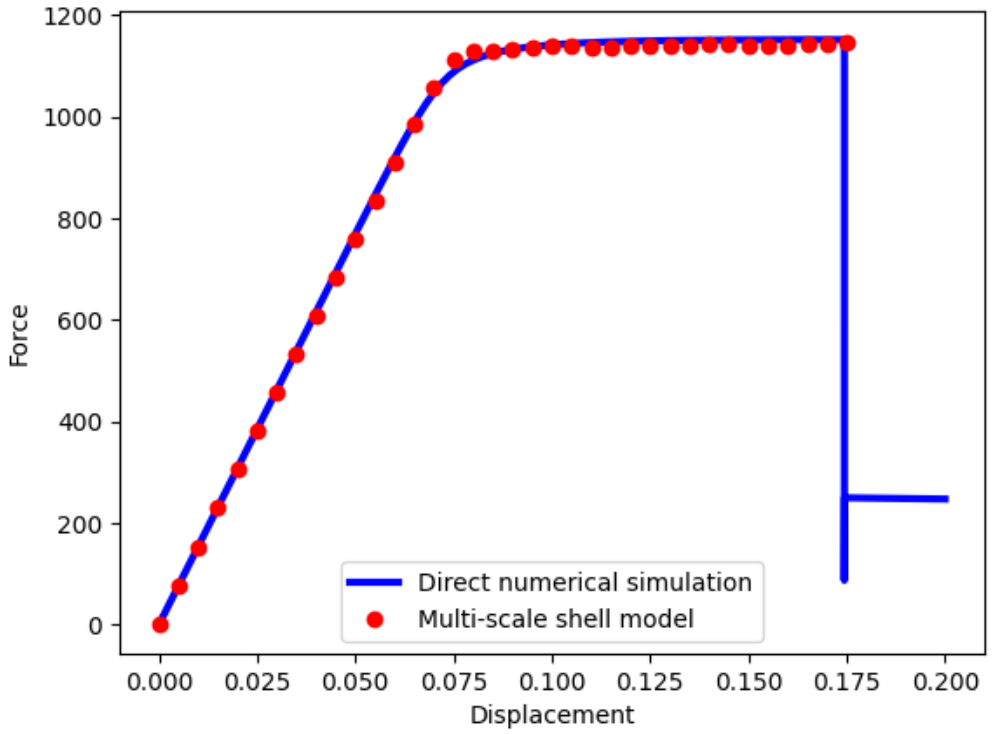
Twist

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

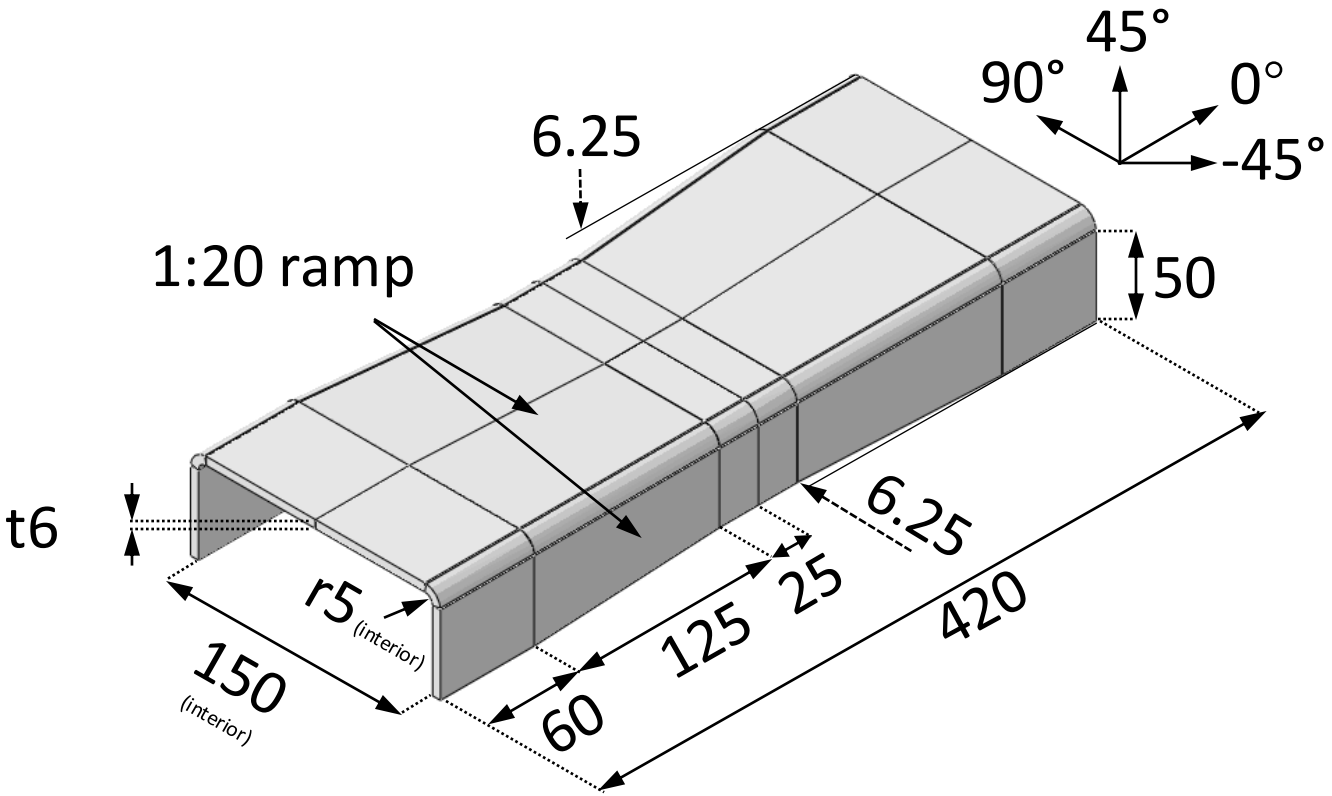
Verification example





University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

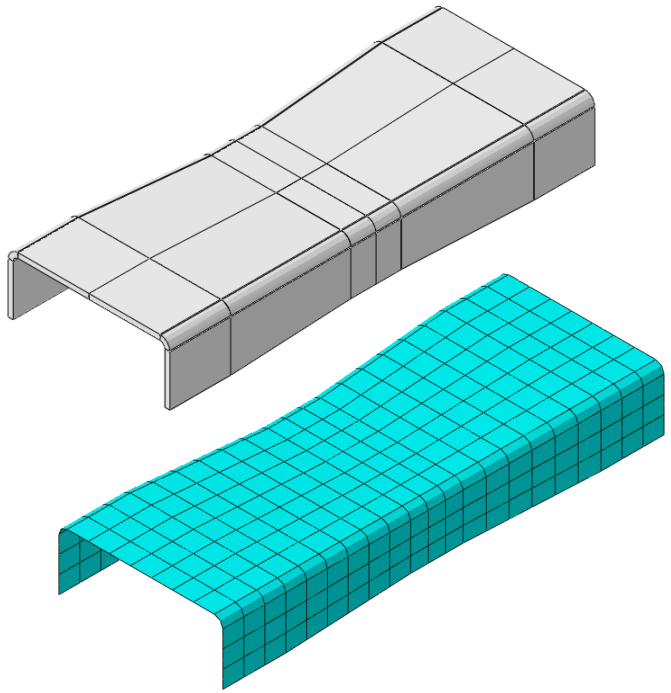
Demonstrator part: The c-spar

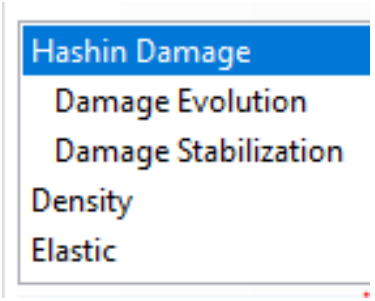


$$[(+45_2/-45_2/90_2/0_2)_3]_S$$

Lay-up from the interior surface

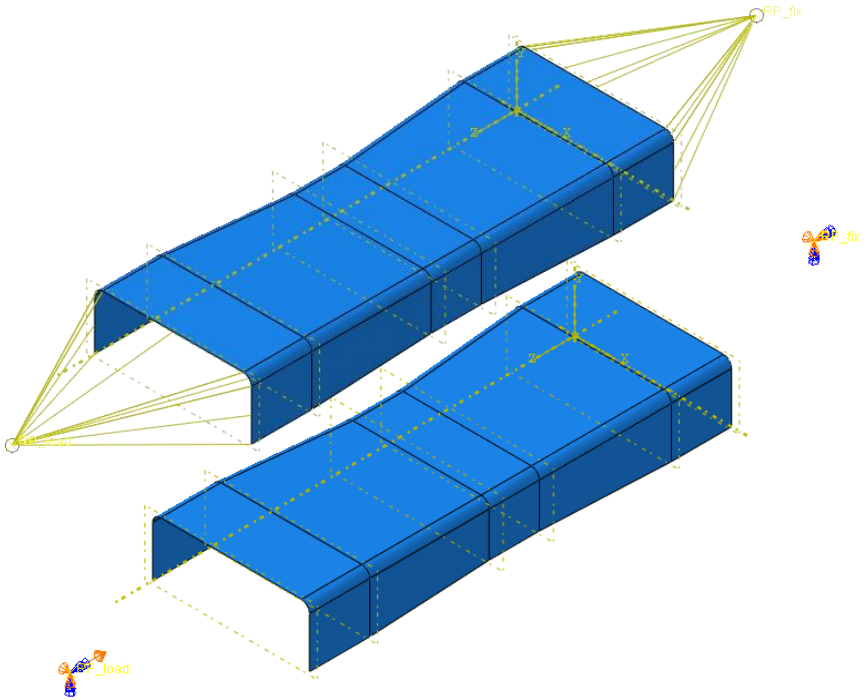
Demonstrator part: Simple shell model creation



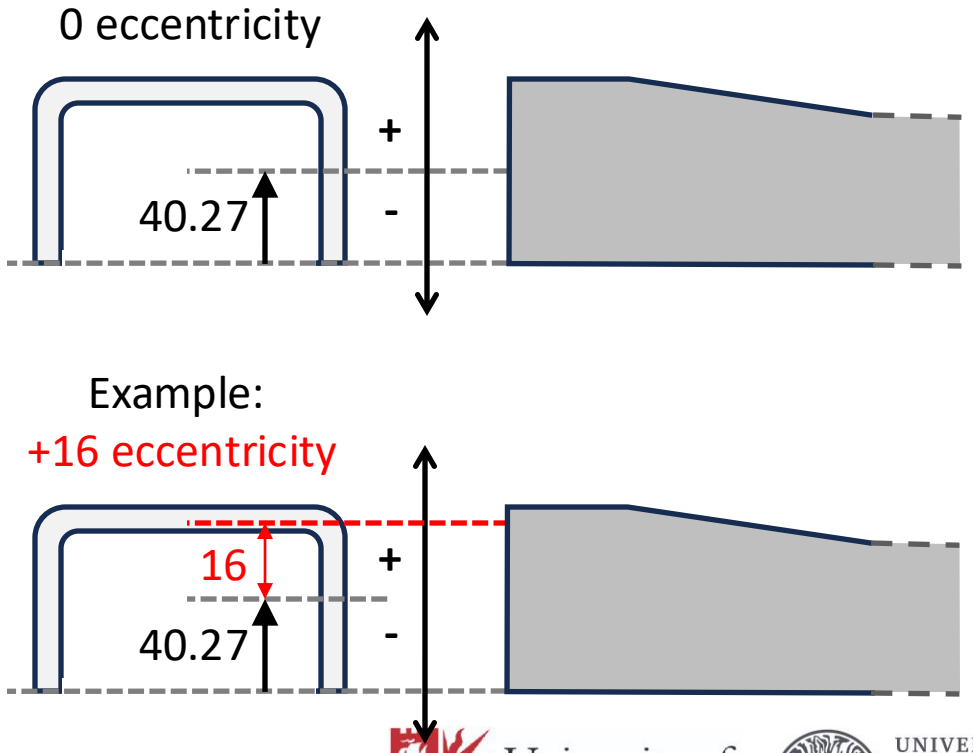


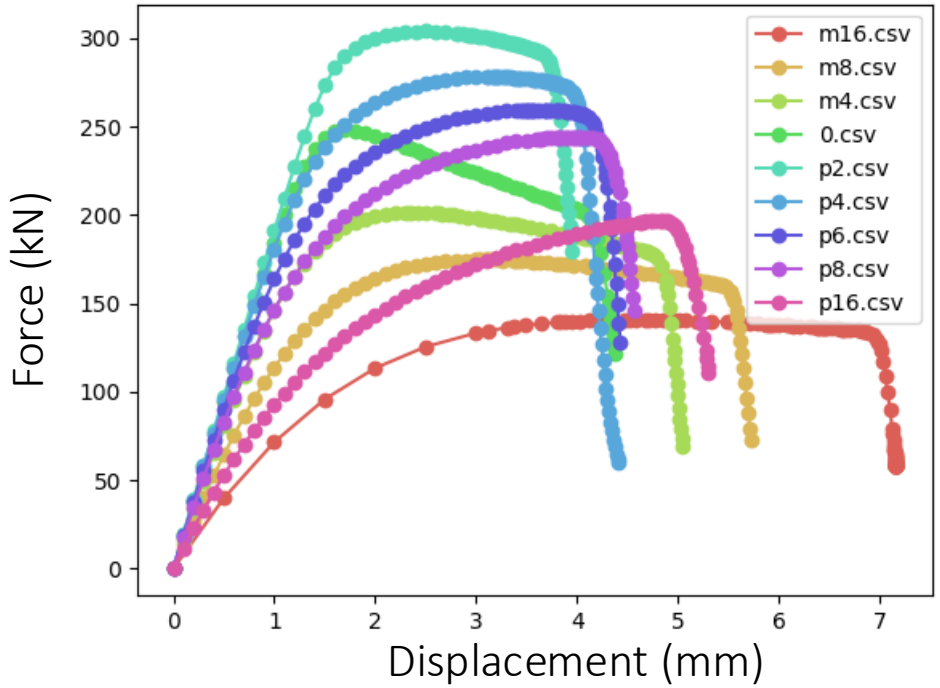
Make calculated sections symmetric

		Ply Name	Region	Thickness	Rotation Angle	Integration Points
1	✔	Ply-1	set_face_web_flat	0.25	45	5
2	✔	Ply-2	set_face_web_flat	0.25	-45	5
3	✔	Ply-3	set_face_web_flat	0.25	90	5
4	✔	Ply-4	set_face_web_flat	0.25	0	5
5	✔	Ply-5	set_face_web_flat	0.25	45	5
6	✔	Ply-6	set_face_web_flat	0.25	-45	5
7	✔	Ply-7	set_face_web_flat	0.25	90	5
8	✔	Ply-8	set_face_web_flat	0.25	0	5
9	✔	Ply-9	set_face_web_flat	0.25	45	5
10	✔	Ply-10	set_face_web_flat	0.25	-45	5
11	✔	Ply-11	set_face_web_flat	0.25	90	5
12	✔	Ply-12	set_face_web_flat	0.25	0	5

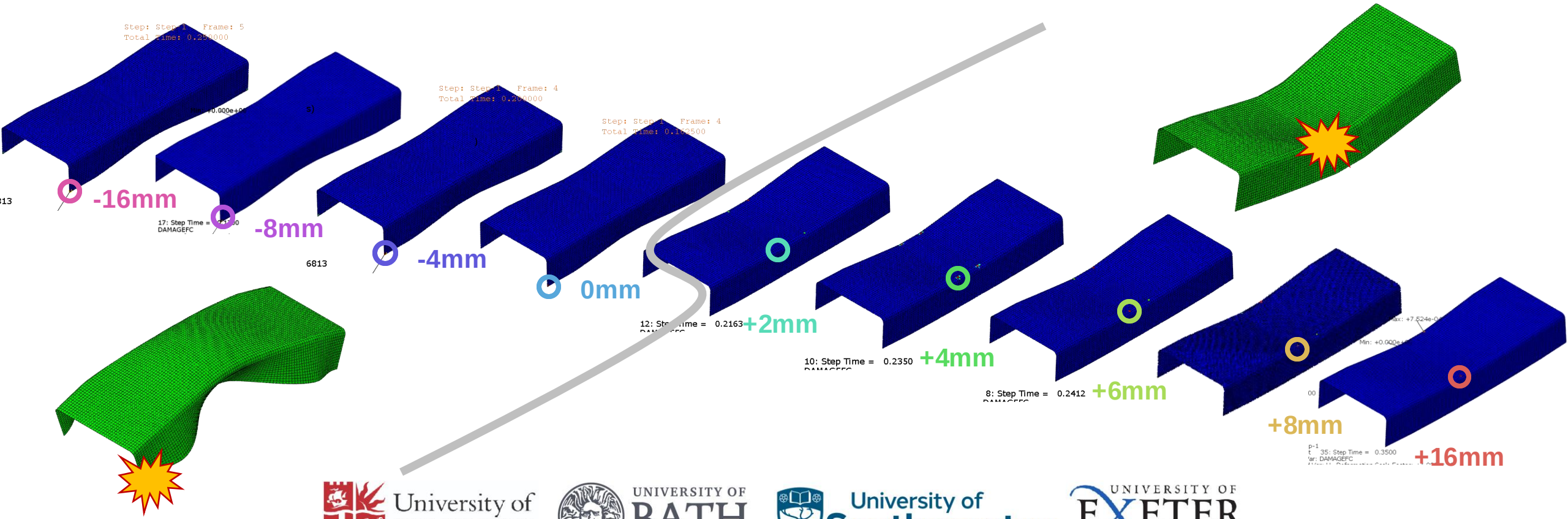


Simple shell model: Eccentricity (1/2)



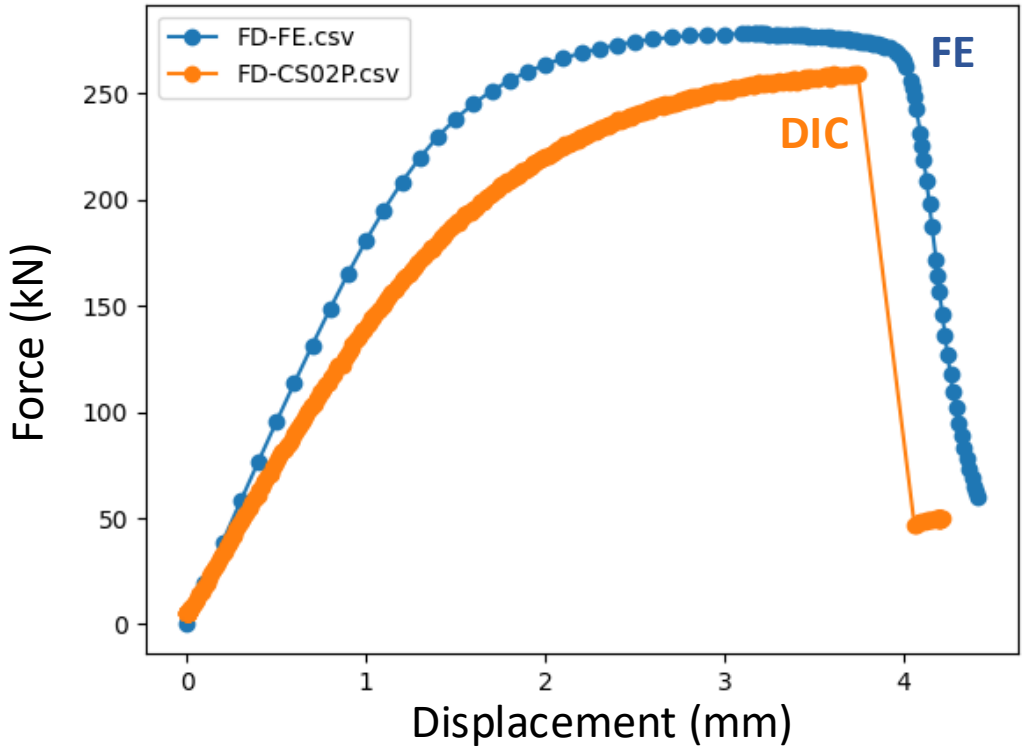


Simple shell model: Eccentricity (2/2)



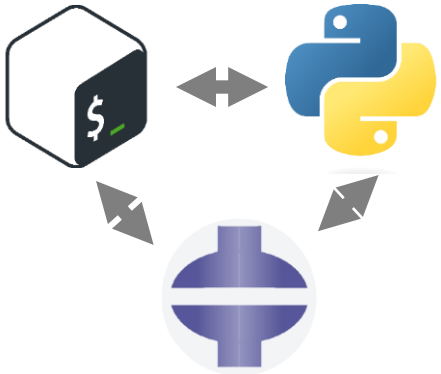
Engineering and Physical Sciences Research Council

Simple shell model vs experiment



University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council



As an input to FE^2

Commercial shell model

*Assembly
*Instance
*Node
*Element
*Nset
*Elset

*Surface
*Shell Section
*Coupling
*Step
*Boundary
*Material (ply-level)

User specify in input script

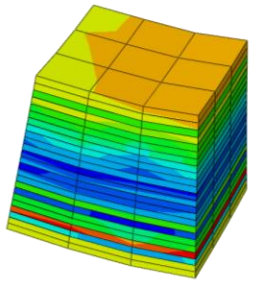
Additional material properties:

CDM (damage) of fibre & matrix: *Volume fraction, density, modulus, Poisson ratio, strength, energy*

CZM (cohesive): *Energy, strength, penalty stiffness*

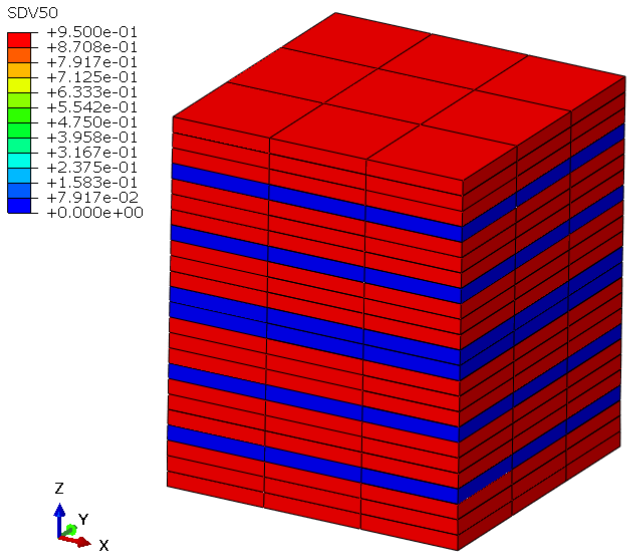
RVE:

Dimension, number of voxels, cohesive layers, artificial delamination

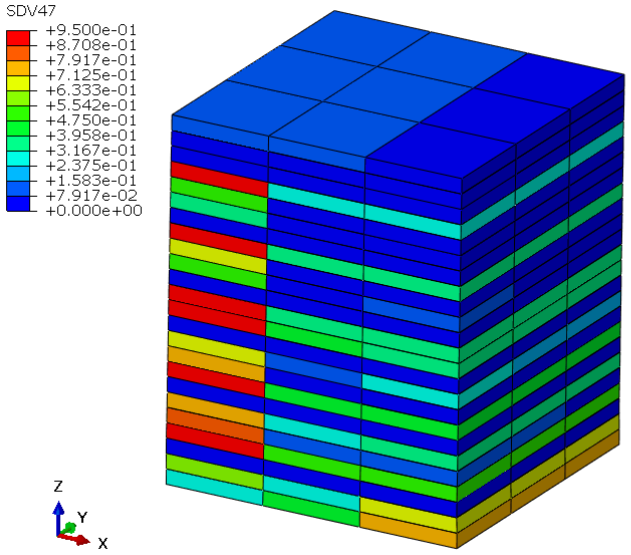


University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

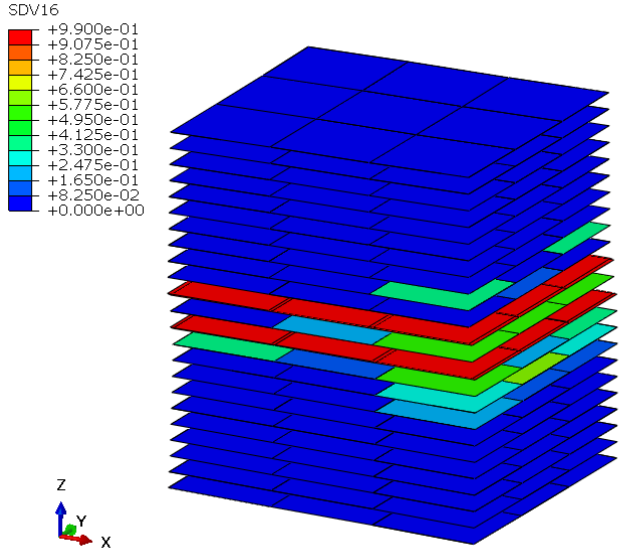
RVE Damage



Matrix damage



Fibre damage



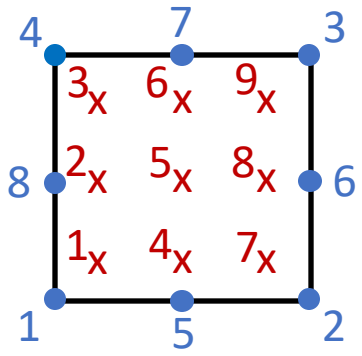
Interface damage - delamination

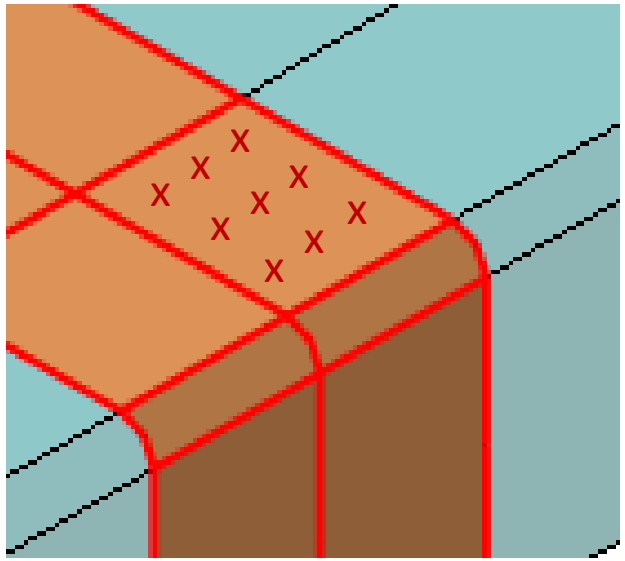
Implicit continuum damage material model: Ioannis Topalidis, Bristol Composites Institute

Cohesive zone material model: Aewis K.W. Hii, Bristol Composites Institute

Shell element formulation

- User element: U-type
- 8-noded shell
- 9 integration points

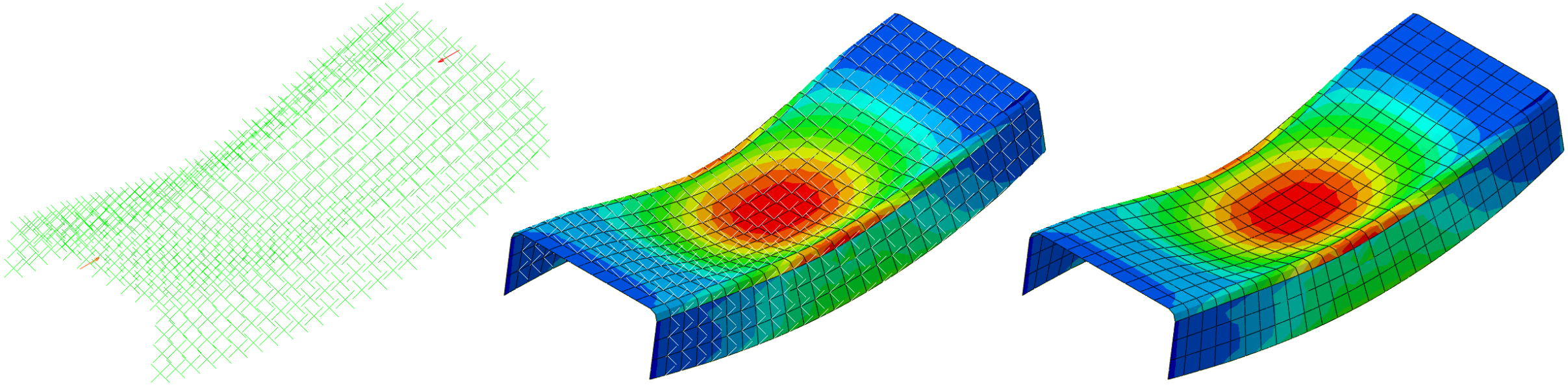




Each element will have 9 meso-scale solid models

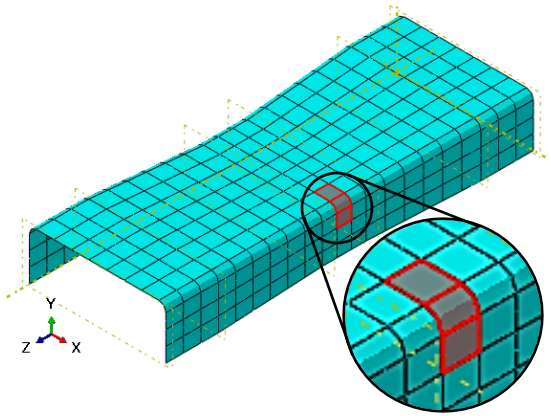
Engineering and Physical Sciences Research Council

Dummy elements (1/2)

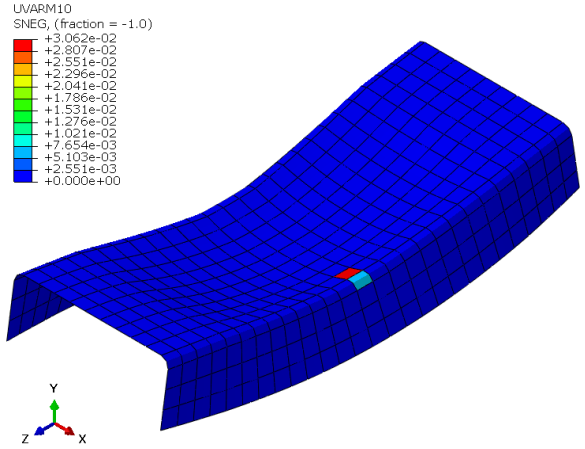


University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

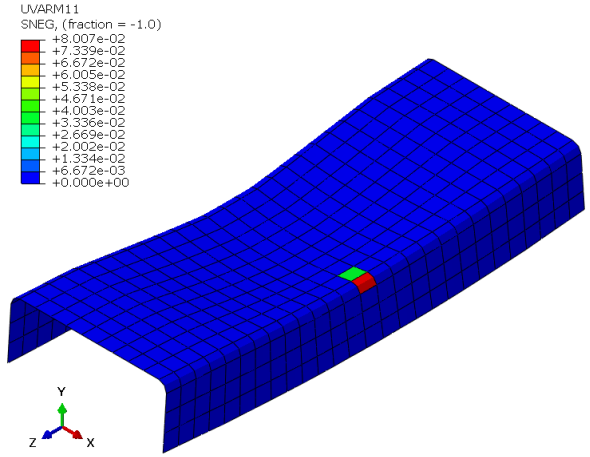
Dummy elements (2/2)



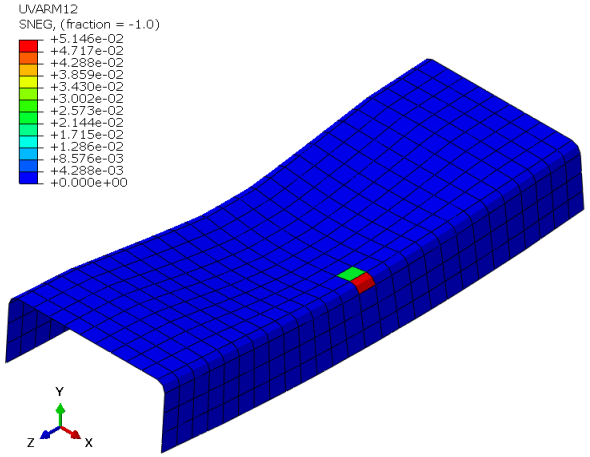
FE2 element location



Delamination

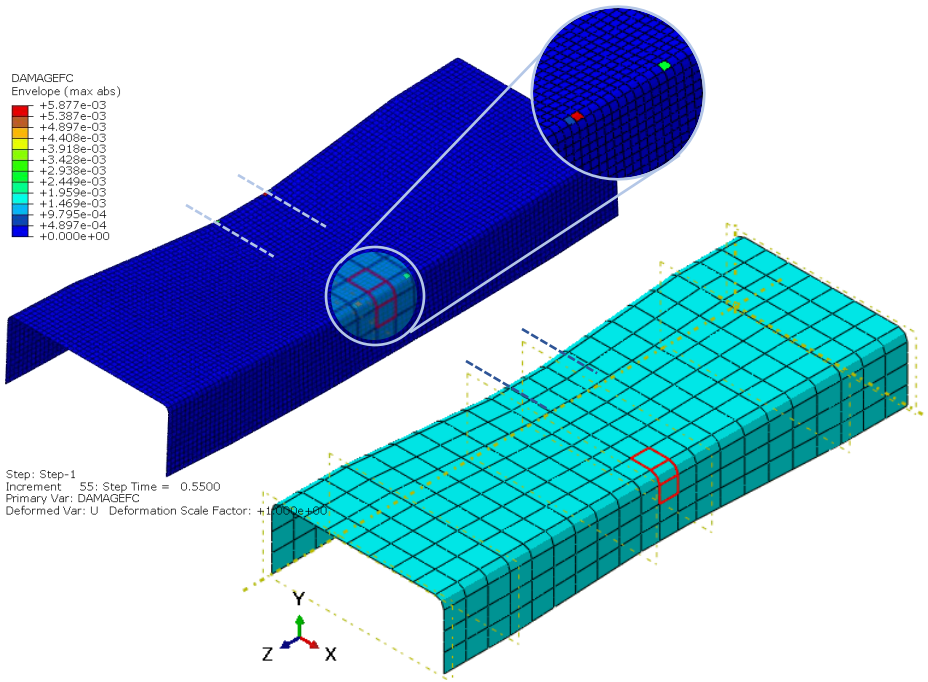


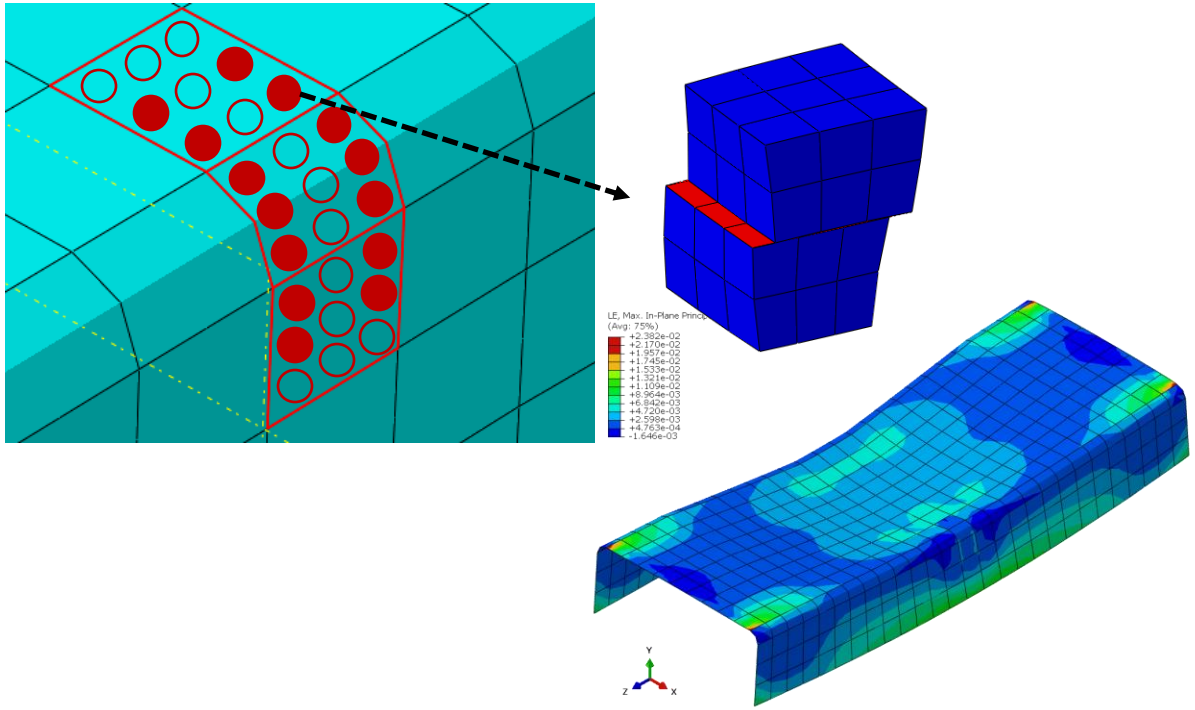
Matrix damage



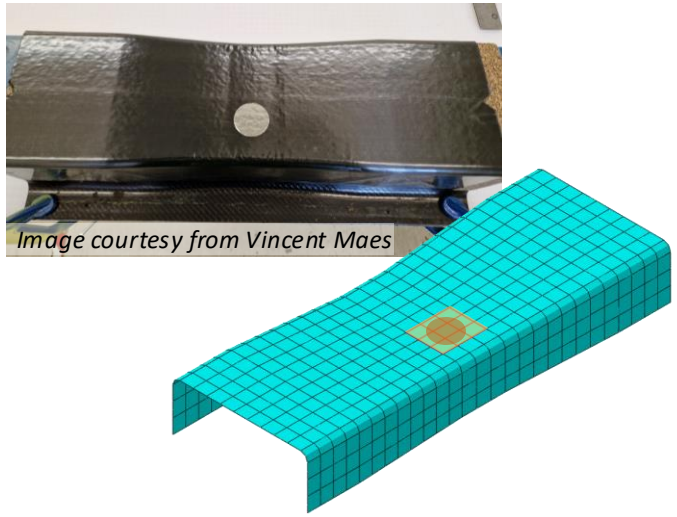
Fibre damage

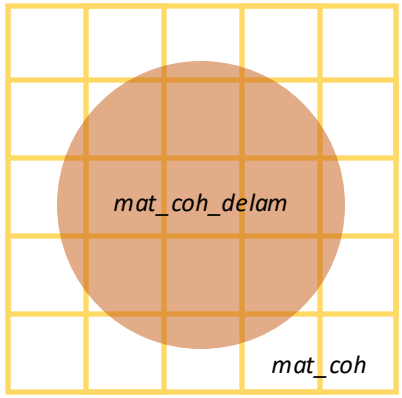
0/90 Example

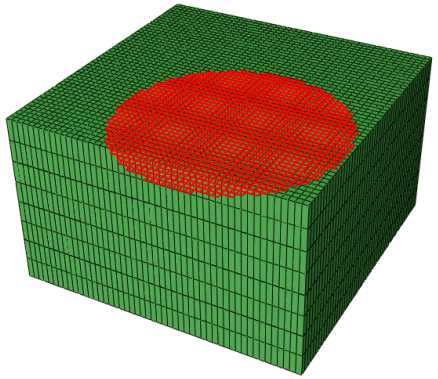

DAMAGEFC
Envelope (max abs)
+5.877e-03
+5.387e-03
+4.897e-03
+4.408e-03
+3.918e-03
+3.428e-03
+2.938e-03
+2.449e-03
+1.959e-03
+1.469e-03
+9.795e-04
+4.897e-04
+0.000e+00
Step: Step-1
Increment 55: Step Time = 0.5500
Primary Var: DAMAGEFC
Deformed Var: U Deformation Scale Factor: +1.000e+00
Y
Z
X

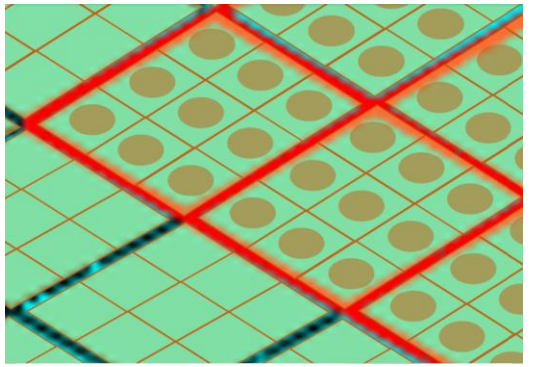

LE, Max. In-Plane Princ
(Avg: 75%)
+2.382e-02
+2.170e-02
+1.957e-02
+1.745e-02
+1.533e-02
+1.321e-02
+1.109e-02
+8.964e-03
+6.842e-03
+4.720e-03
+2.598e-03
+4.763e-04
-1.646e-03

Artificial delamination







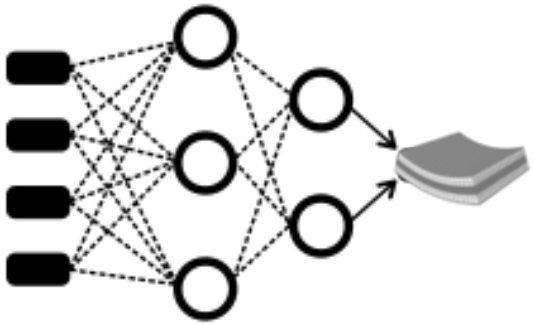


upscale.py

- Very slow - RVE compute at each integration point and at every increment
- New functionality - machine learning model ...

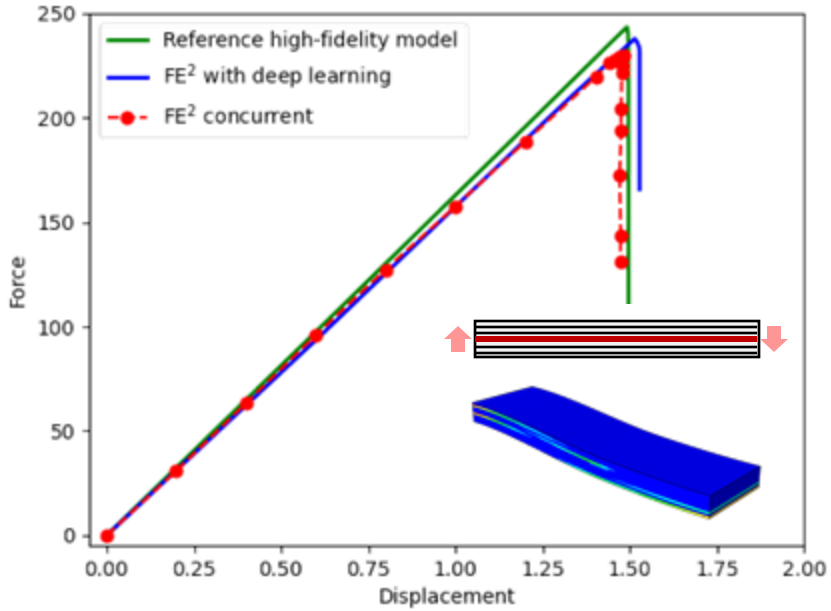
Engineering and Physical Sciences Research Council

Deep learning as a surrogate



Deep Learning with neural network

Using TensorFlow Library within Abaqus



Example: Modelling shear delamination with shell elements

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Thank you!

Meng yi Song
mengyi.song@bristol.ac.uk
+447429204766
composites-certest.com
bristol.ac.uk/composites/