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Bristol Composites Institute

Modelling of damage in impact of composite structures using higher-order elements

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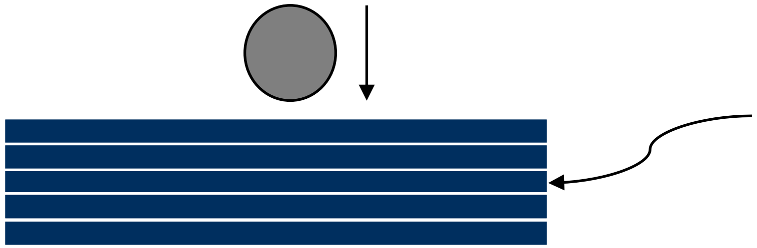
Overview

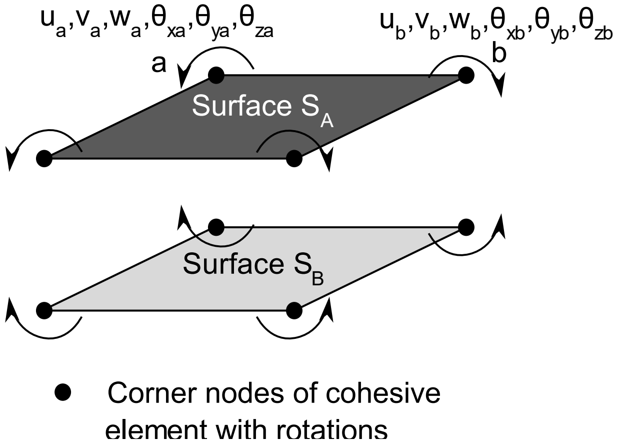
Impact modelling



In-plane damage modelling using continuum damage mechanics

Modelling of sublaminates with solid continuum elements C^1 continuity

Rotation enabled cohesive and continuum elements C^1 continuity



Implementation
Explicit time integration in LS-Dyna

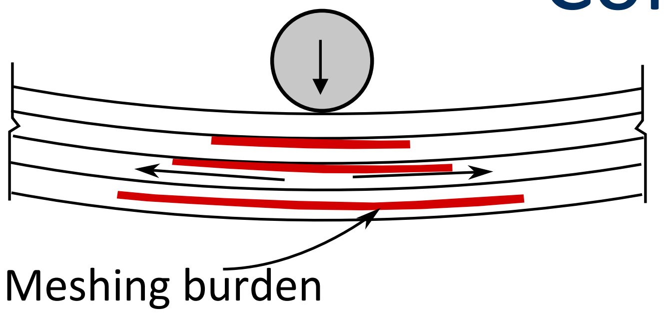
Verification examples
Rigid body impact

Adaptive initiation of cohesive elements between sublaminates

Higher order AMS [1]

[1] Jagan Selvaraj, Supratik Mukhopadhyay, Luiz F. Kawashita, Stephen R. Hallett, Modelling delaminations using adaptive cohesive segments with rotations in dynamic explicit analysis, Engineering Fracture Mechanics, Volume 245, 2021, 107571, ISSN 0013-7944, https://doi.org/10.1016/j.engfracmech.2021.107571.

Continuum and Cohesive element

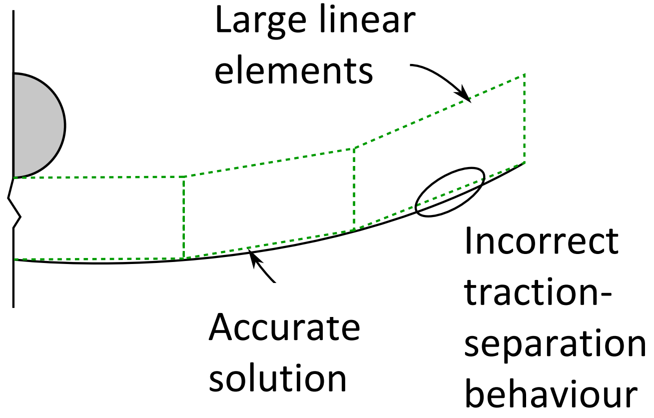


Continuum model + Cohesive zone modelling (CZM)

- Meshing Burden - Need to pre-define cohesive elements in a mesh.

→ Adaptive modelling of cracks

Adaptive Mesh Segmentation (AMS)



- CZM linear elements require fine mesh
- High computational cost
- Large linear meshes introduce discretisation errors

→ Higher order cohesive segments

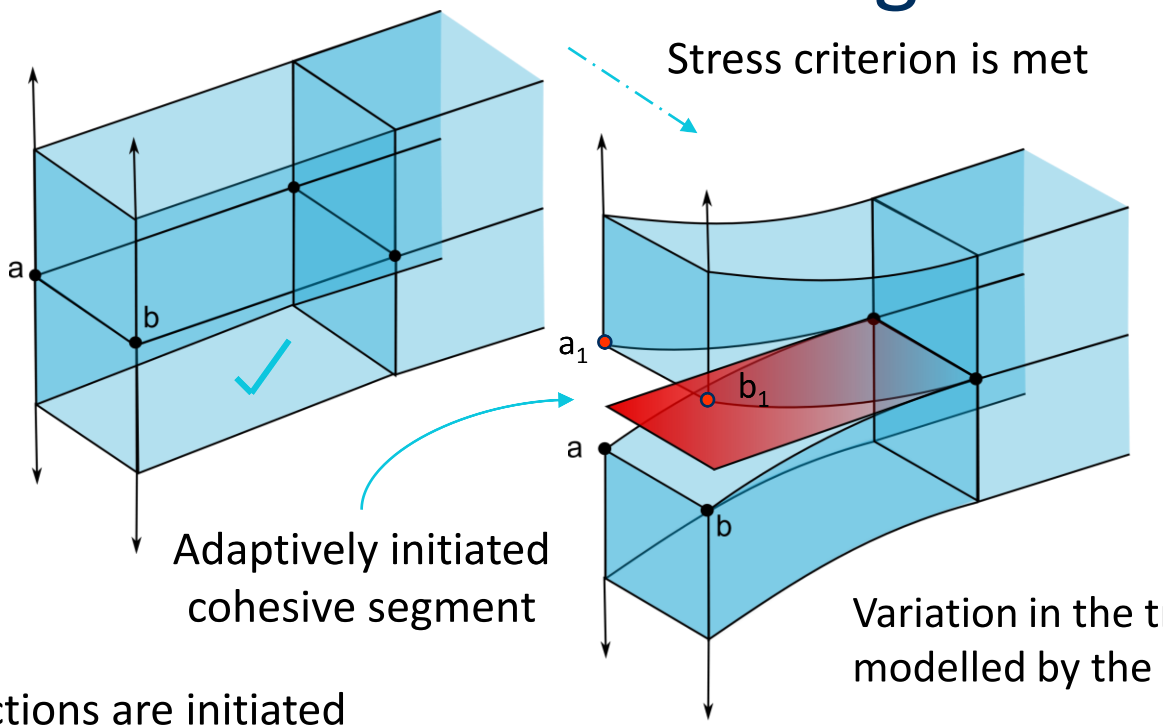
Higher order AMS

An integrated approach to solve problems in damage modelling

- Demonstrated with impact modelling cases

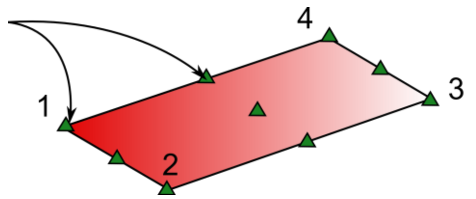
Higher order AMS

Stress criterion is met



Adaptively initiated cohesive segment

Tractions are initiated with the balance of nodal forces



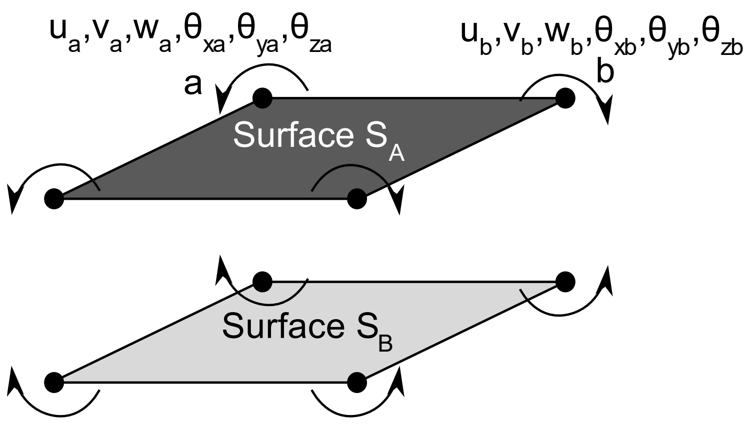
▲ Integration points

Variation in the traction field is modelled by the cohesive segment

- New nodes - a_1,b_1
- Existing nodes - a,b

Loss in rotational continuity is modelled using a Moment-Damage relationship.

Discretisation using coarser meshes



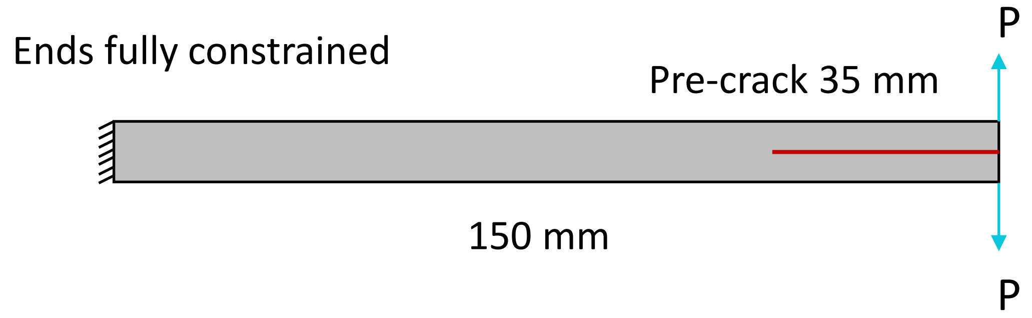
● Corner nodes of cohesive element with rotations

Rotation enriched cohesive elements

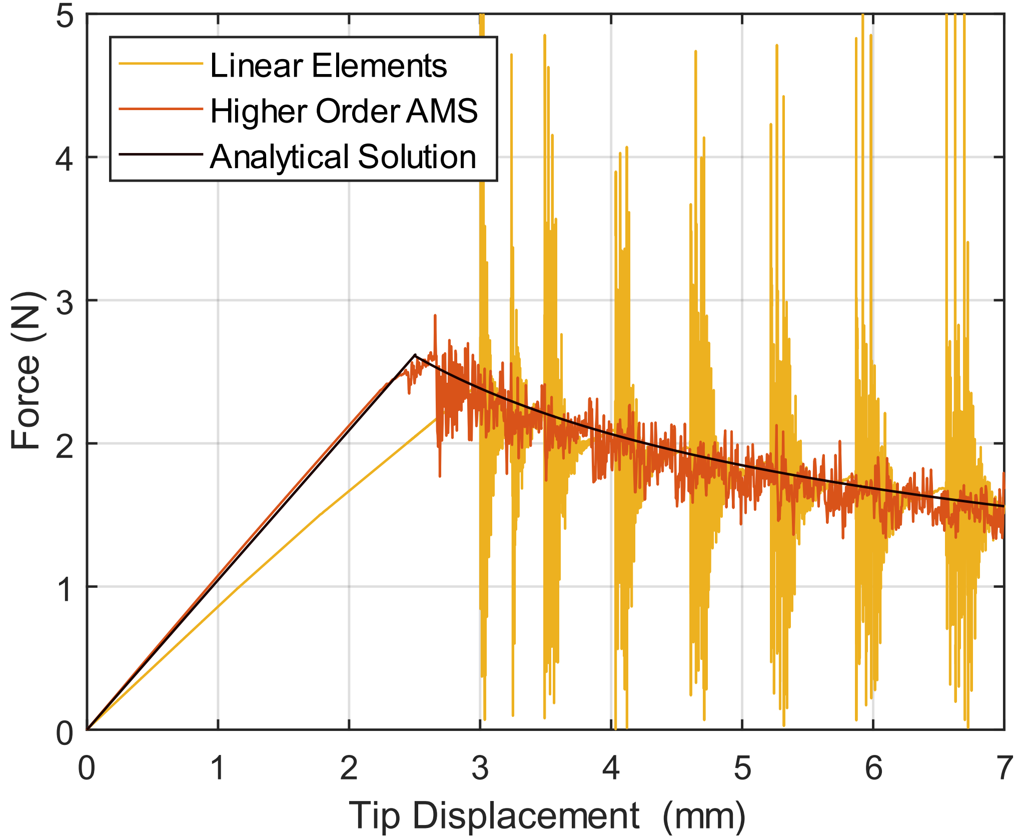
Higher order

Jagan Selvaraj, Luiz F. Kawashita, Mehdi Yasaee, Gordon Kalwak, Stephen R. Hallett, Soft body impact on composites: Delamination experiments and advanced numerical modelling, Composites Science and Technology, Volume 208, 2021, 108777, ISSN 0266-3538, https://doi.org/10.1016/j.compscitech.2021.108777.

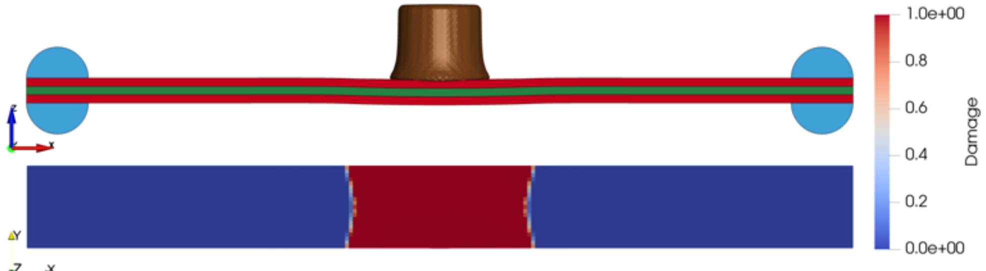
Double Cantilever Beam



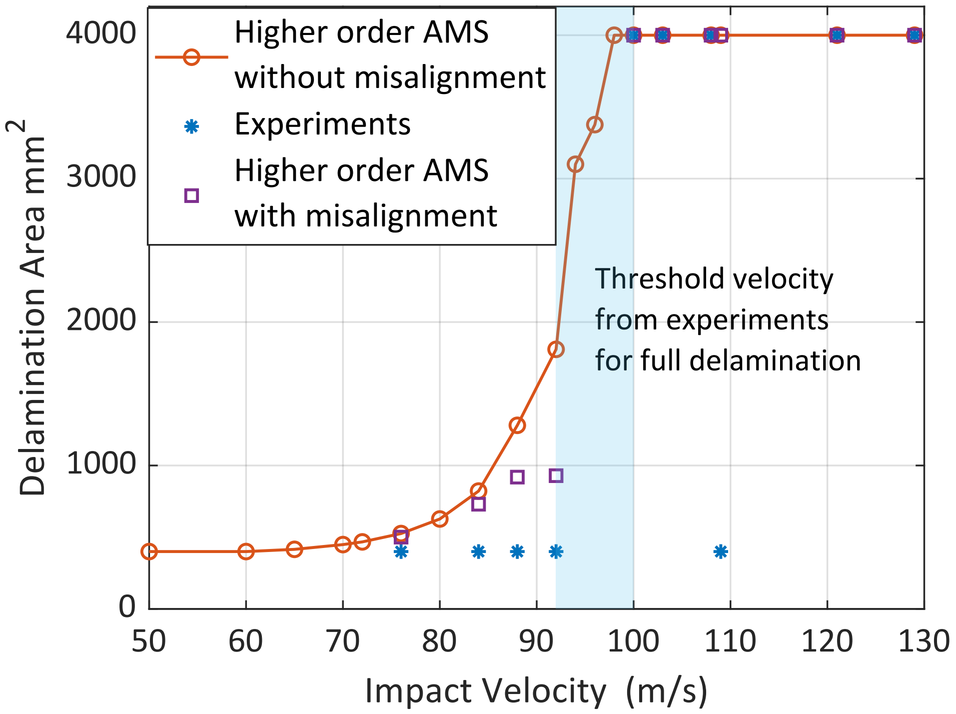
- Ability to add multiple integration points within cohesive segments.
- Numerically accurate modelling with Higher Order AMS using 1 mm mesh.
- Discretisation using larger meshes – Linear elements require 0.25 mm mesh.
- 50% less CPU time for similar accuracy when compared to linear elements with same implementation.

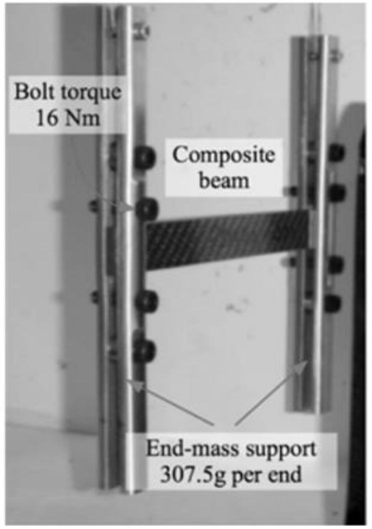


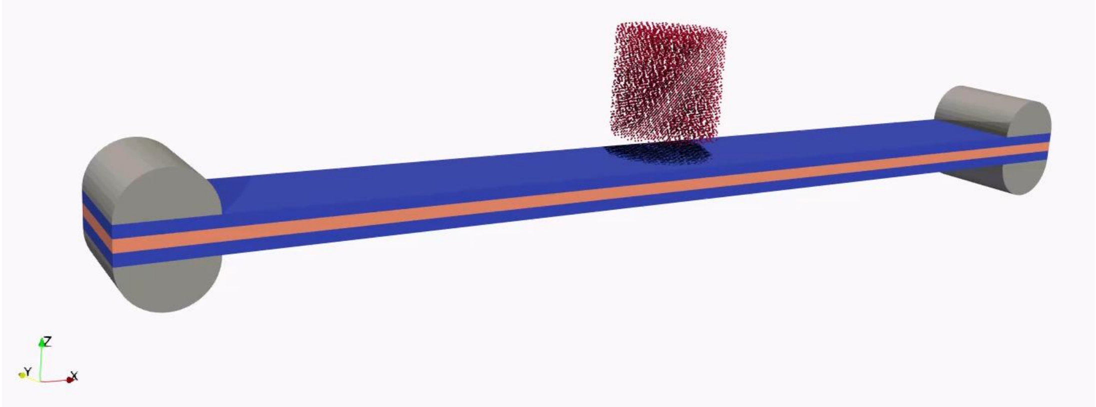
Soft Body Beam Bending Impact



b) Time = 0.06 ms







65 % less CPU time than linear elements

	Mesh Size x	y	z	No. of elements	No. of degrees of freedom
Linear elements	0.5	0.5	1.0	96,000	288,000
Higher order AMS	1.5	1.5	1.0	10,374	62,444

4.5 times fewer degrees of freedom than linear elements

Jagan Selvaraj, Luiz F. Kawashita, Mehdi Yasaee, Gordon Kalwak, Stephen R. Hallett, Comp. Sci. Tech. https://doi.org/10.1016/j.compscitech.2021.108777.

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Ply-scale semi-discrete crack modelling

Damage Initiation

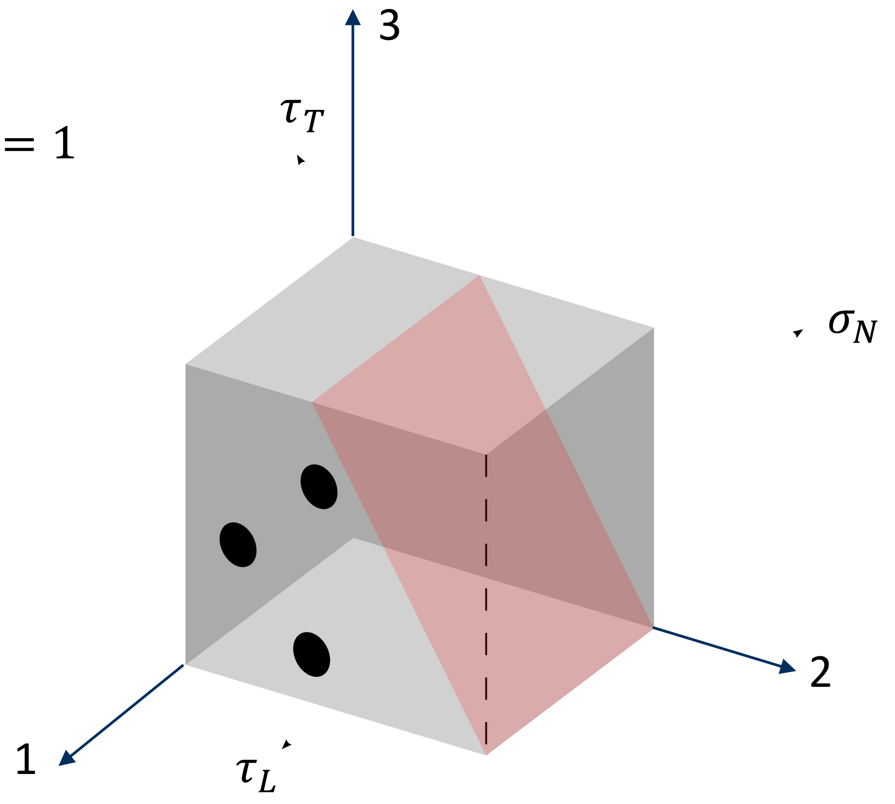
Matrix in Compression

Based on Mohr-Coulomb theory

$$\left(\frac{\tau_L}{S_L - \mu_L \sigma_N}\right)^2 + \left(\frac{\tau_T}{S_T - \mu_T \sigma_N}\right)^2 = 1$$

S_L - Longitudinal shear strength; S_T - Transverse shear strength
μ_L , μ_T - longitudinal and transverse friction coefficients
τ_L , τ_T - longitudinal and transverse shear stress

$$S_T = \frac{Y_c}{2\tan\varphi_0} \qquad \mu_T = -\frac{Y_c}{\tan 2\varphi_0} \qquad \mu_L = S_L \frac{\mu_T}{S_T}$$



1-2-3 Material Frame

Matrix in Tension

$$\left(\frac{\sigma_N}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 + \lambda\left(\frac{\sigma_N}{S_T}\right)\left(\frac{\tau_L}{S_L}\right) + \kappa\left(\frac{\sigma_N}{S_T}\right) = 1$$

Y_T - Transverse tensile strength; Y_C - Transverse compressive strength
λ and κ are based on in-situ tensile strength and longitudinal friction co-efficient

Damage Evolution

Using a equivalent mixed-mode driving stress from a quadratic stress calculation

$$\sigma_m = \sqrt{\sigma_N^2 + \tau_T^2 + \tau_L^2}$$

Similarly, driving strain ε_m can be calculated

Damage variable $$d_m = \frac{\varepsilon_m^f(\varepsilon_m - \varepsilon_m^0)}{\varepsilon_m(\varepsilon_m^f - \varepsilon_m^0)}$$

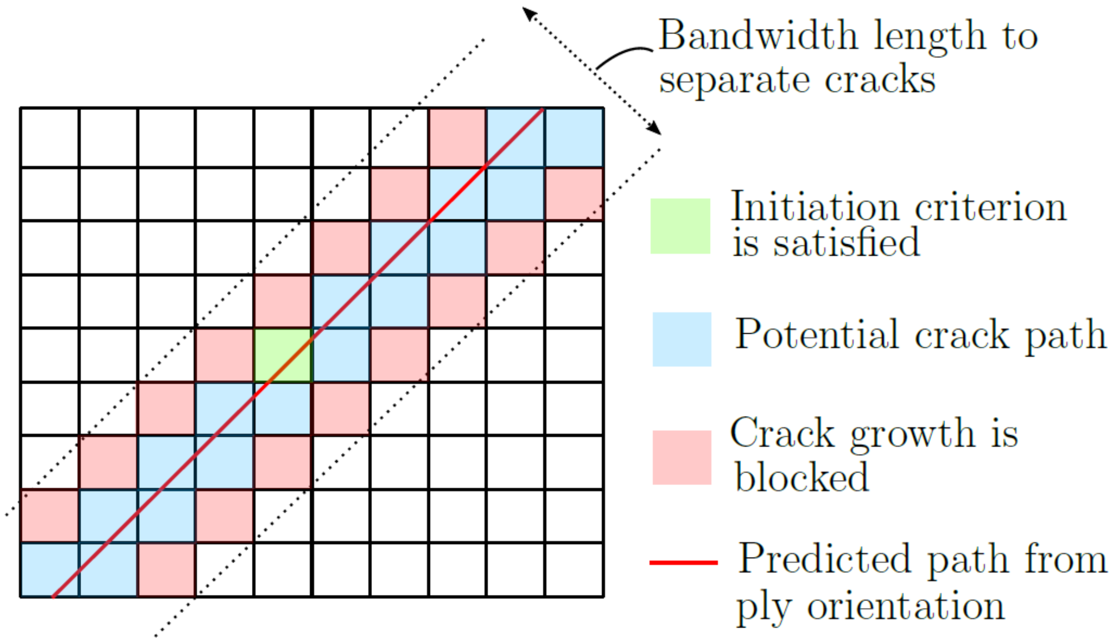
ε_m^f - strain at failure; ε_m^0 - strain at initiation

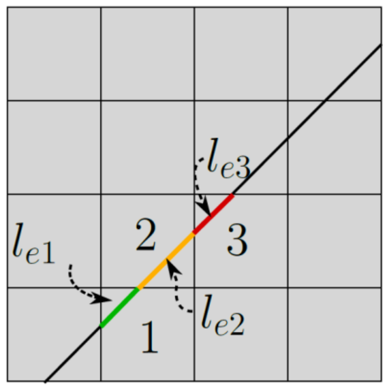
G_c - mixed mode fracture energy

$$\varepsilon_m^f = \frac{2\,G_c}{\sigma_m^0 l_e}$$

l_e - characteristic length; taken as cubic root of the volume

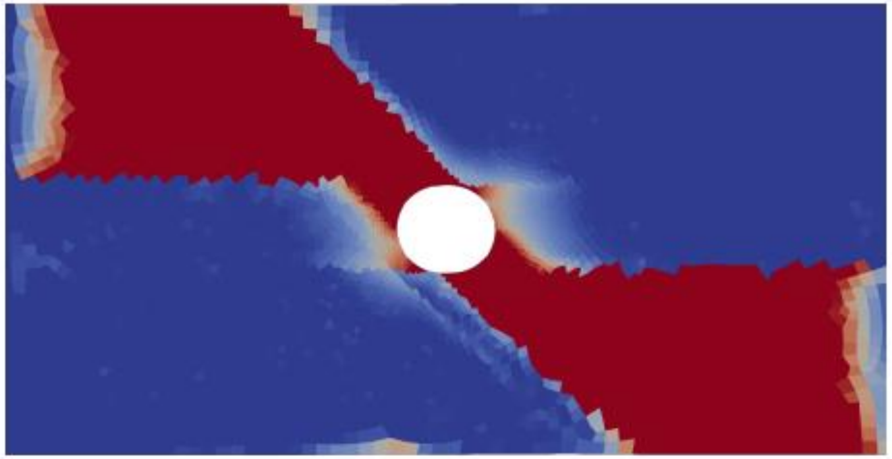
In directed CDM exact length is used



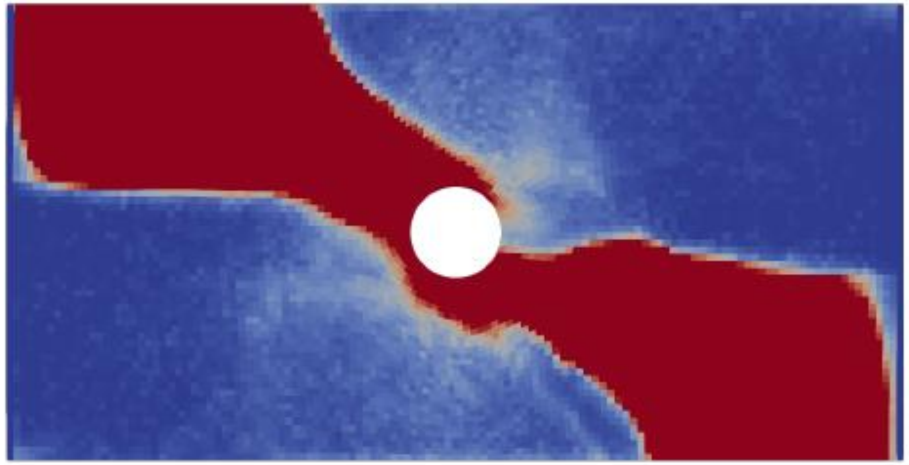


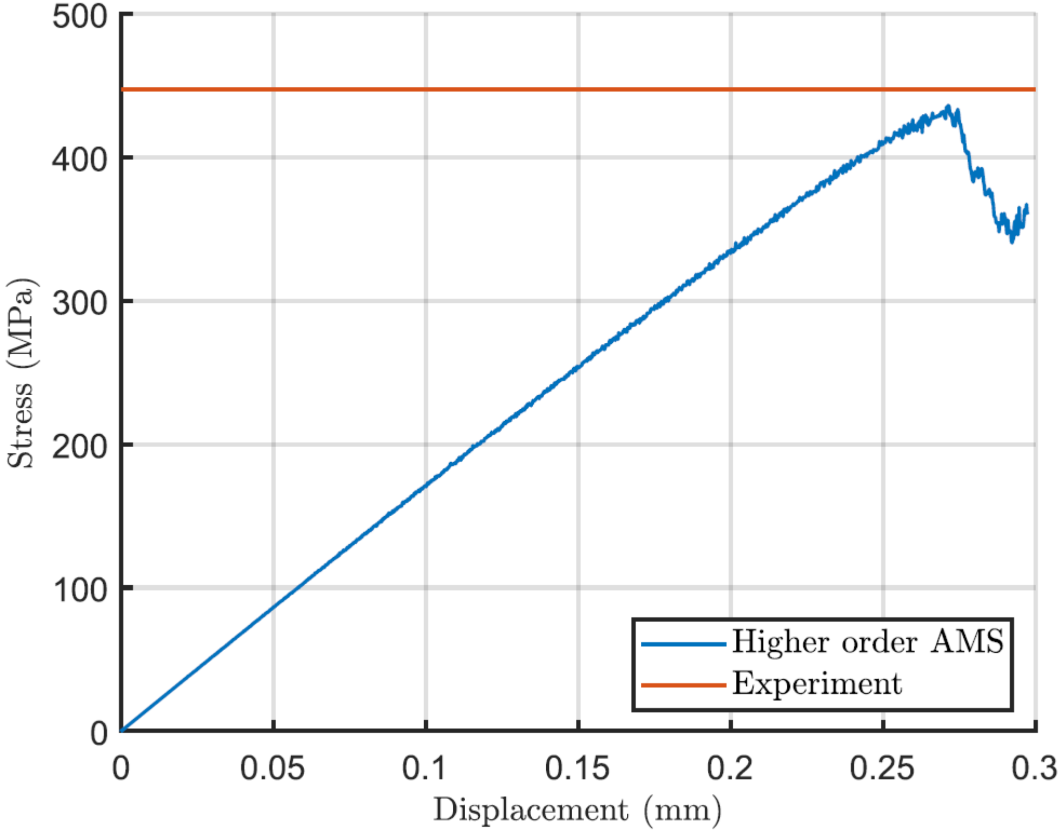
Open-hole tensile test

Ply-scale discrete crack modelling [1]



Ply-scale semi-discrete crack modelling





[1] Jagan Selvaraj, Luiz F. Kawashita, Stephen R. Hallett, Mesh independent modelling of tensile failure in laminates using mixed-time integration in explicit analysis, Engineering Fracture Mechanics, Volume 259, 2022, 108113, ISSN 0013-7944

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Sublaminate scale semi-discrete crack modelling

Sublaminate Modelling

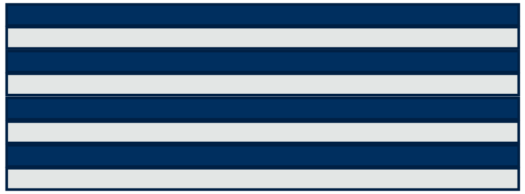
Continuum damage mechanics (CDM)

To calculate in-plane damage in plies and model the equivalent damage in sublaminates

Cohesive Zone Modelling (CZM)

To model the delamination between the sublaminates

Mesolevel



Modelling of Plies

To model equivalent in-plane damage

Macrolevel

Modelling of sublaminates

- Eliminates the ply-level discretisation requirement.
- Aimed at modelling global damage behaviour.
- Performed without directed CDM

Damage variable

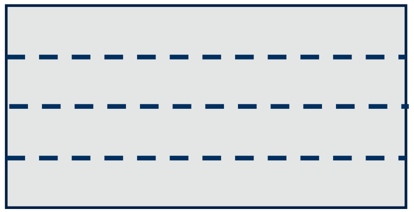
- Strain in the plies of the sublaminate are assumed to be same.

$$\text{Strain in global frame of the sublaminate} \xrightarrow[\text{tensor}]{\text{Rotation}} \text{Strain in material frame of the ply}$$

Sublaminate modelled by a continuum element

- Check for damage initiation and application of damage evolution with a damage variable.

$$\left.\begin{aligned} \sigma_{22} &\leftarrow (1-\mathrm{D})\,\sigma_{22} \\ \sigma_{12} &\leftarrow (1-\mathrm{D})\,\sigma_{12} \\ \sigma_{23} &\leftarrow (1-\mathrm{D})\,\sigma_{23} \end{aligned}\right\} \text{Ply-level stress}$$

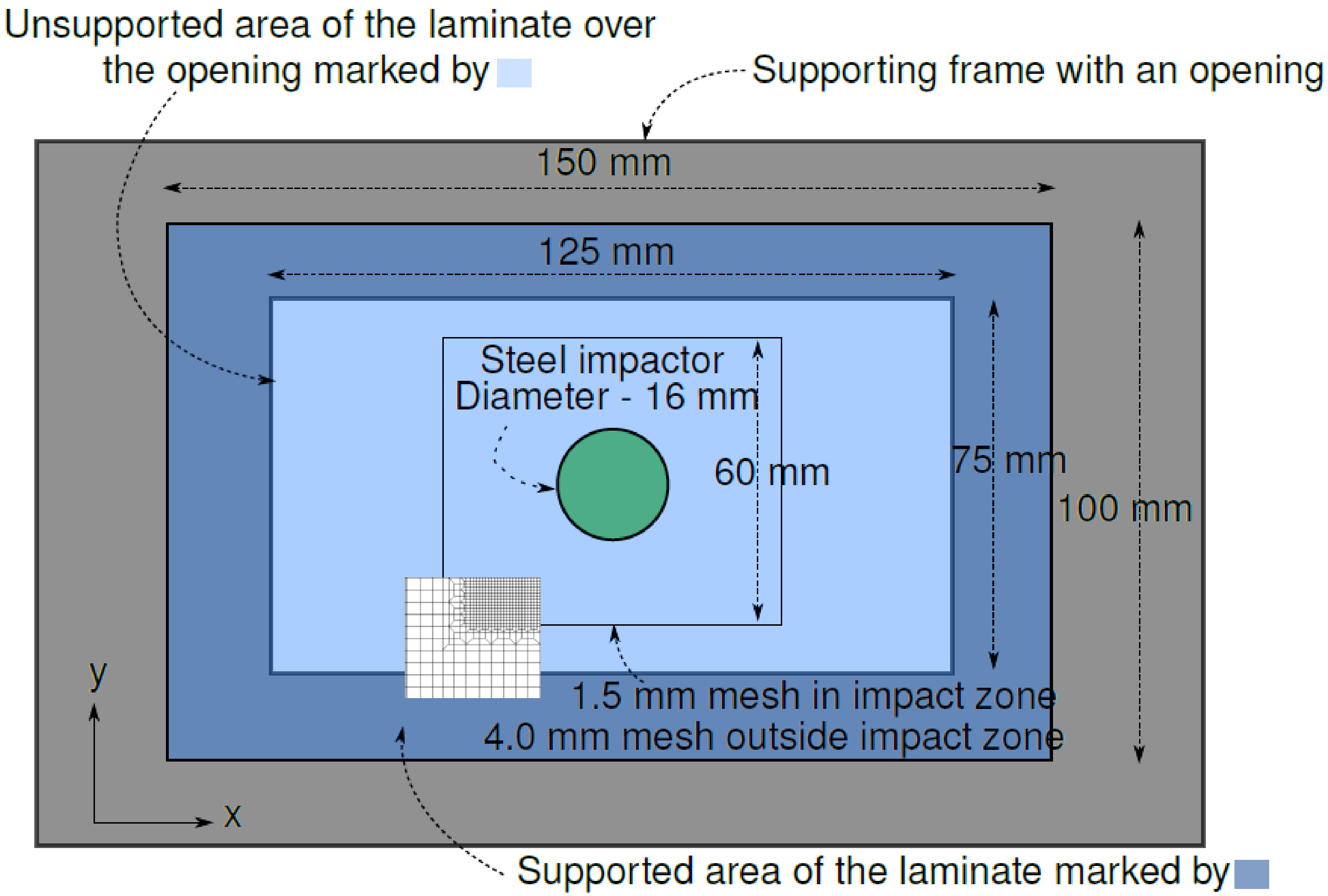


Distribution of plies within a sublaminate

Damage is calculated for each ply

- Stress in the sublaminate is calculated with a weighted average of ply-level stress

Low velocity BVID test



X.C. Sun, S.R. Hallett, Barely visible impact damage in scaled composite laminates: Experiments and numerical simulations, International Journal of Impact Engineering, Volume 109, 2017, Pages 178-195.

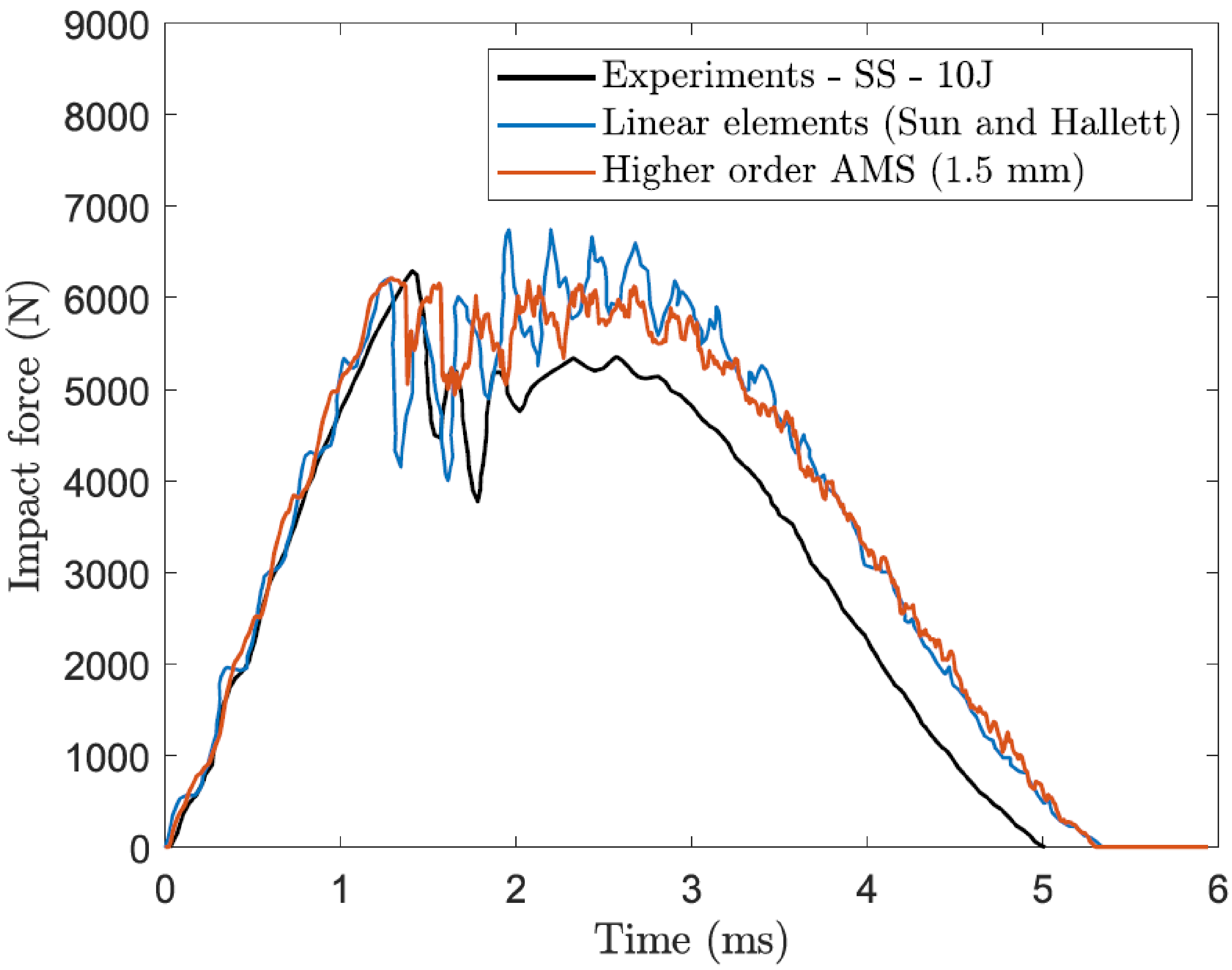
Low velocity BVID test

Reference – Sun & Hallett

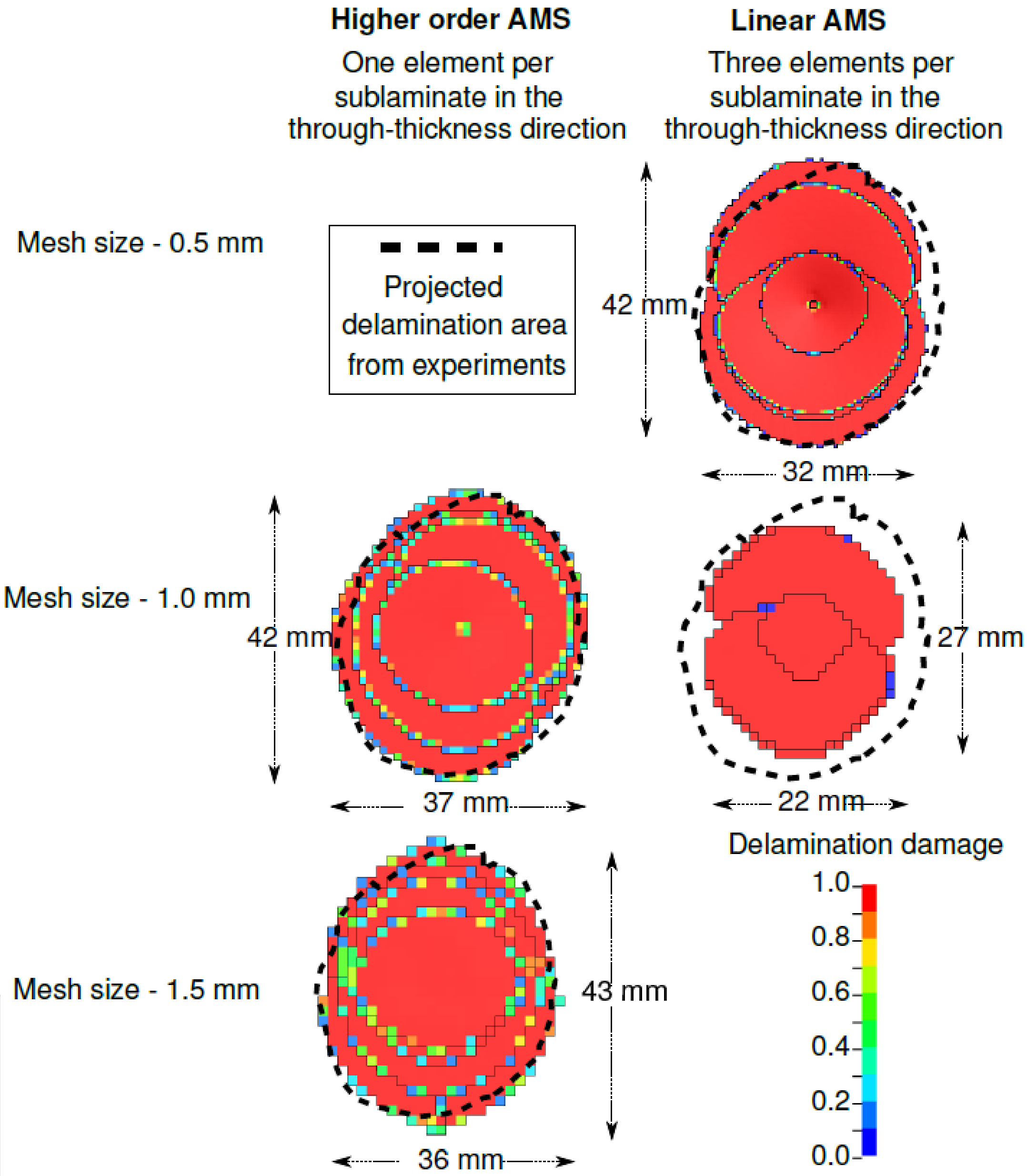
- Ply level model; 32 individual plies are modelled
- Linear solid elements - 290,480 elements
- Cohesive elements (Delamination + embedded matrix cracks) - 2,907,624 elements

Higher order AMS

- Sublaminate model; 8 sublaminates (one element per sublaminate)
- Rotation enabled elements - 120,000 elements (~ 60 % less)
- Delamination - Cohesive elements ‘on-the-fly’
- Matrix cracks – Sublaminate damage modelling



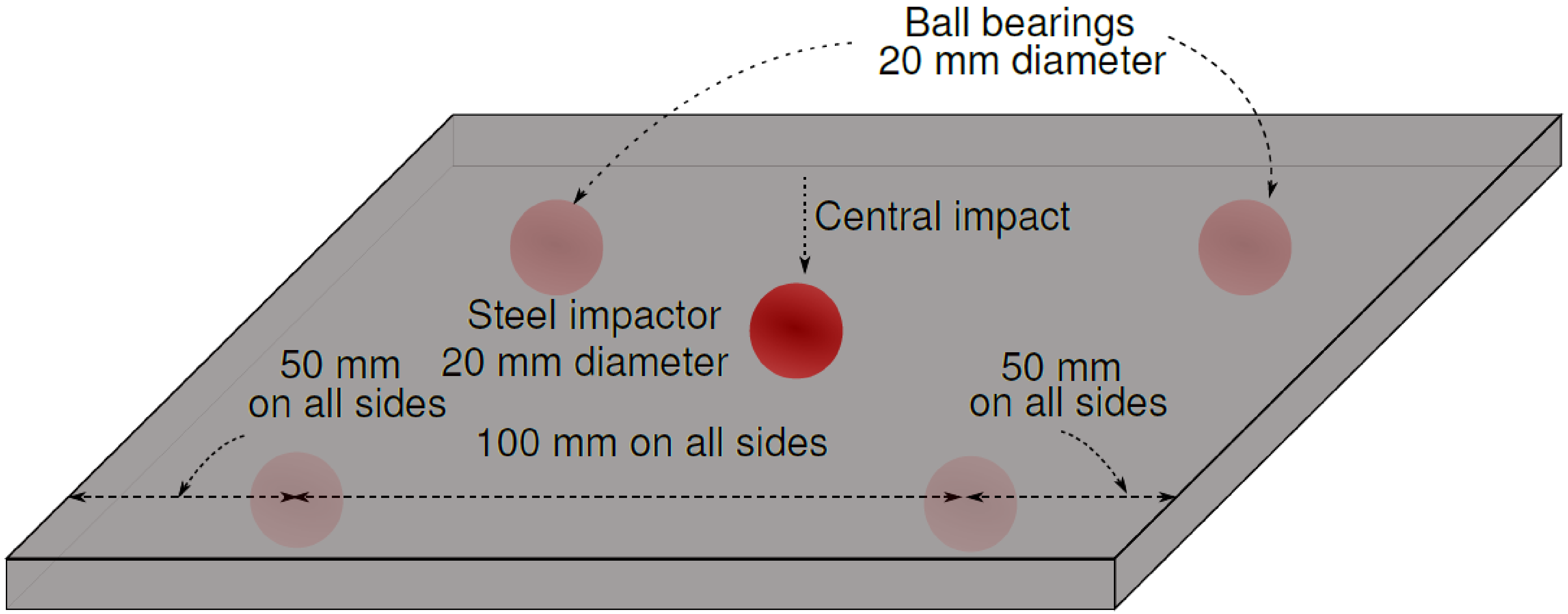
Low velocity BVID test



Low velocity BVID test

	In-plane mesh size (mm)	No. of elements per sublaminate through the thickness	Delamination diameter (mm)	No. of DOFs	Time step (s)	Run-time (hours)
Linear formulation (Reduced integration)	0.5	3	37.0	3,773,173	1.21×10^{-5}	54
	1.0	3	24.0	1,143,875	1.21×10^{-5}	35
Linear formulation (Full integration)	0.5	3	36.0	3,773,173	1.21×10^{-5}	151
	1.0	3	25.0	1,143,875	1.21×10^{-5}	94
Higher-order AMS	1.0	1	41.0	326,238	3.05×10^{-5}	20
	1.5	1	41.0	169,830	3.05×10^{-5}	15

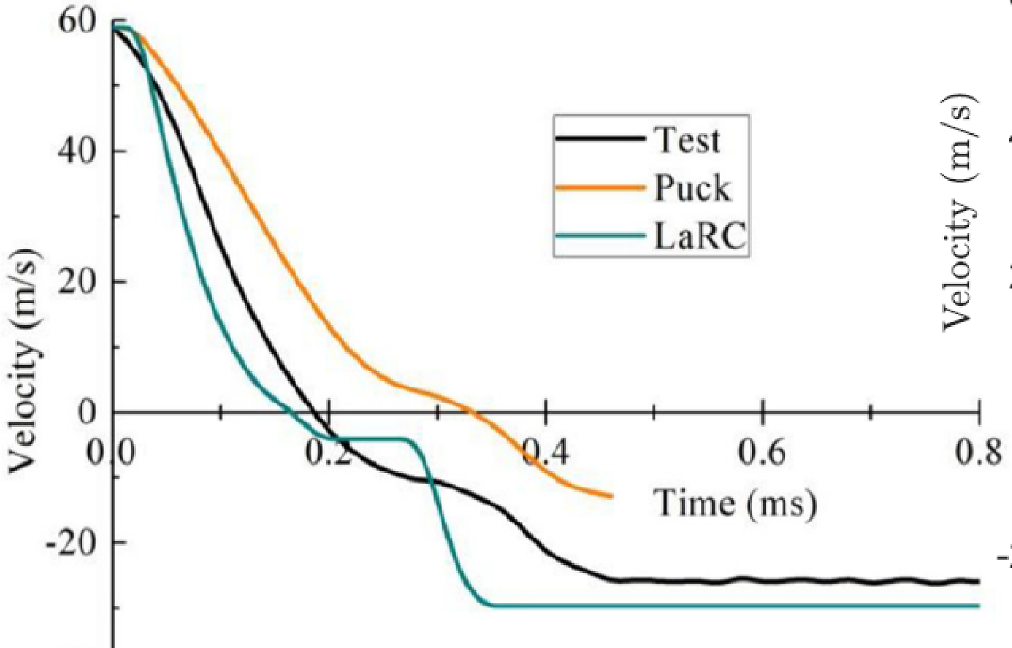
High velocity impact



Hao Cui, Daniel Thomson, Sina Eskandari, Nik Petrinic, A critical study on impact damage simulation of IM7/8552 composite laminate plate, International Journal of Impact Engineering, Volume 127, 2019, Pages 100-109.

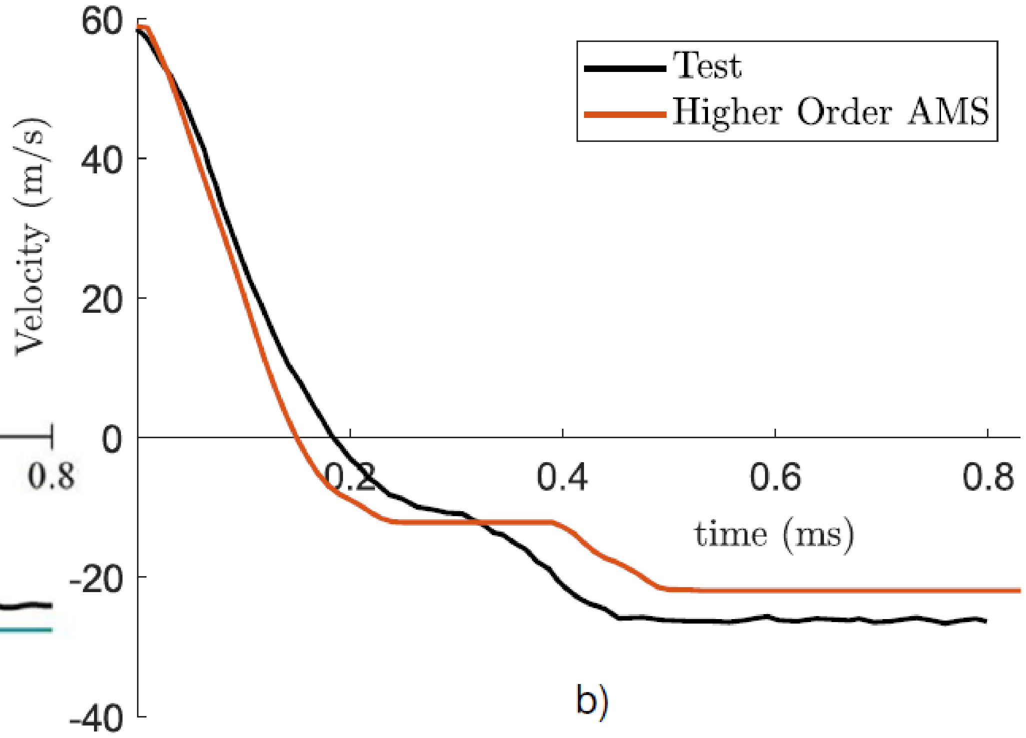
High velocity impact – 59 m/s

Ply-level damage modelling using CDM for intra and interlaminar damage



a)

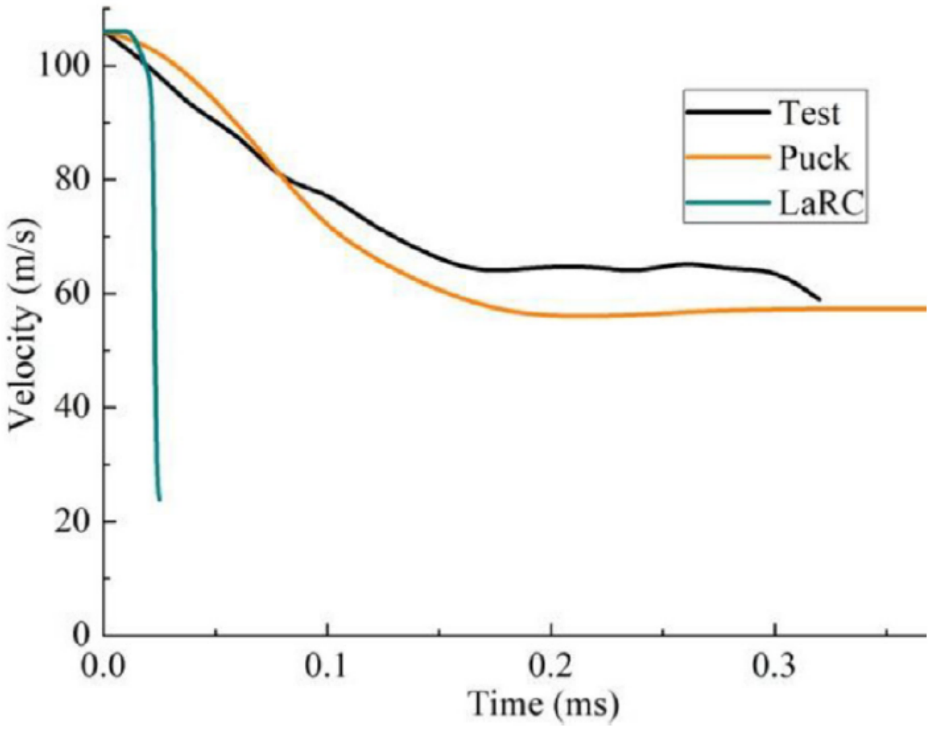
Sublaminate-scale damage modelling using CDM for intralaminar damage and adaptively initiated cohesive elements for delamination

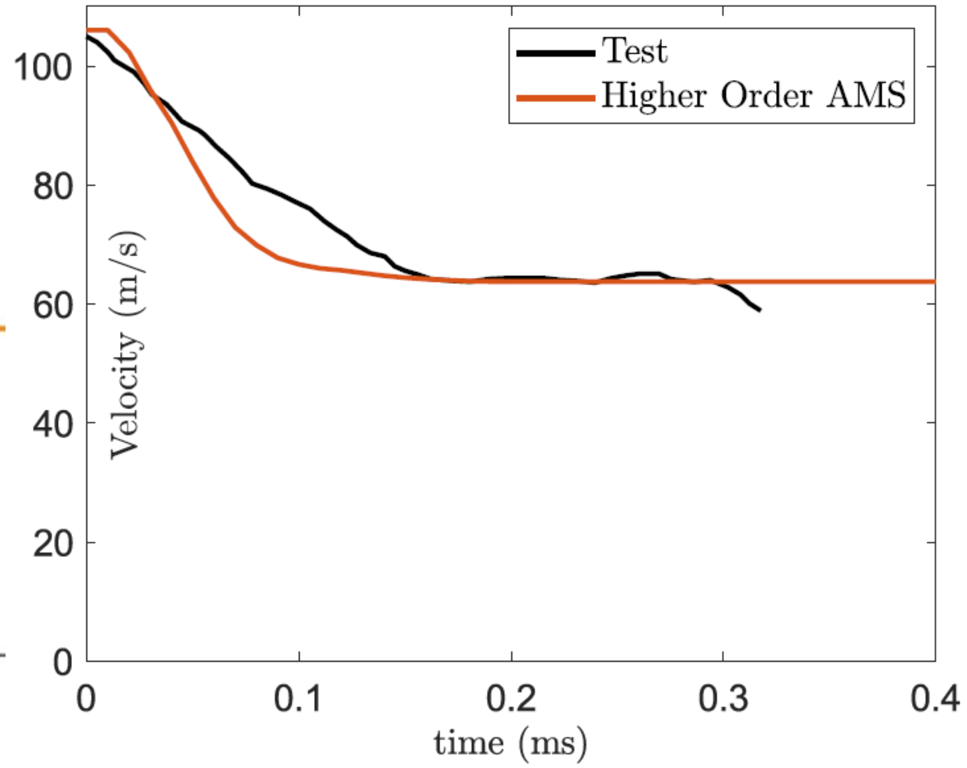


b)

High velocity impact – 106 m/s

Impact modelling with projectile penetration





High velocity impact

- Accurate modelling of stiffness and the residual velocity is obtained with the proposed method.
- Ability to model at sublaminate-scale is essential in modelling large structures.
- Higher-order elements are therefore beneficial at larger length scales and mesh sizes

	No. of DOFs	Thickness direction mesh (mm)	In-plane mesh (mm)
Ply-level modelling	4,848,120	0.125	1.0
Sublaminate-scale Higher Order AMS	1,185,096	1.0	1.5

Summary

- An adaptive damage modelling method using higher order continuum and cohesive elements are introduced.
- This method is semi-discrete; delamination is modelled using cohesive elements and in-plane damage using continuum damage mechanics.
- Verification of the method is performed using impact modelling examples.
- The method successfully models global damage behaviour and is computationally efficient.

Acknowledgements

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Thank you

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