

GDTECH engineering

Numerical modelling of the dynamic crushing of Composites C-channels using a mesoscale constitutive law

Lucas Márquez, Michael Bruyneel

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  - Context
  - GDTech constitutive models
    - Intra-laminar model for UD
    - Inter-laminar model
  - C-channels crushing benchmark
    - Model set-up
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  - Final remarks

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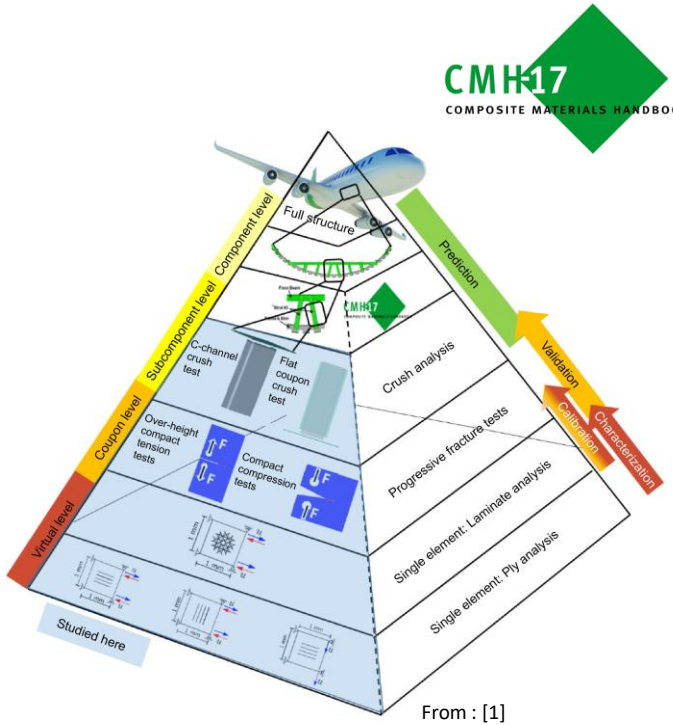
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Context

- Test correlation activities from CW group of CMH-17
  - **Progressive damage and failure** analysis of composite structures
  - **Building-block** approach

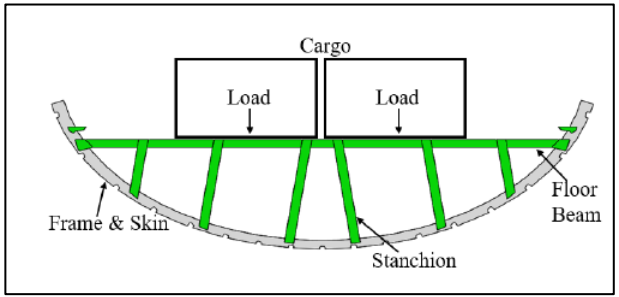


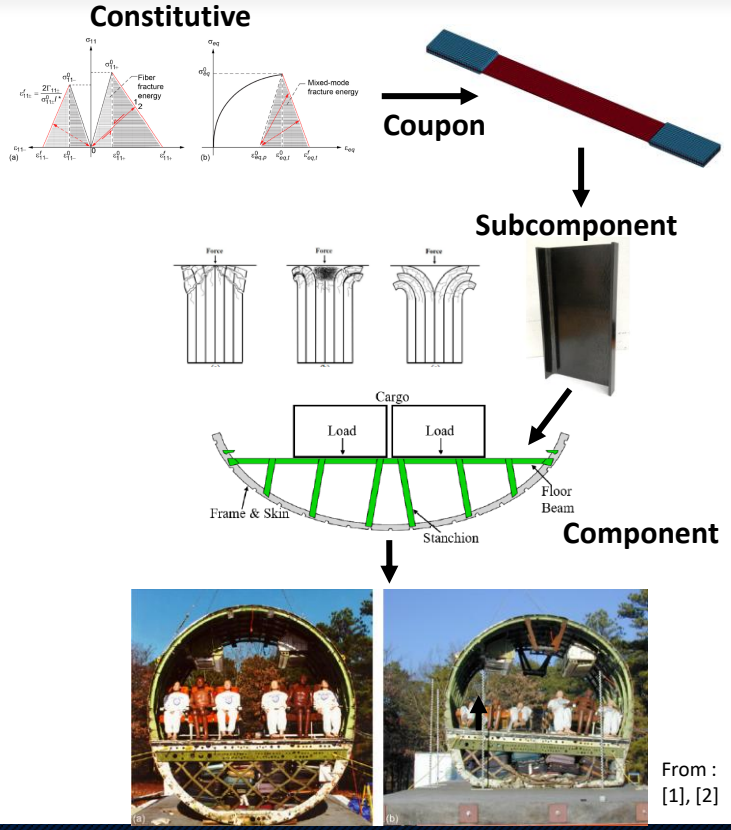
From : [1]

[1] (2025) Rassaian et al., Progressive damage and failure analysis methods applications for aircraft crashworthiness and impact energy management

Context

- Test correlation activities from CW group of CMH-17
  - **Progressive damage and failure** analysis of composite structures
  - **Building-block** approach





From : [1], [2]

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[1] (2025) Rassaian et al., Progressive damage and failure analysis methods applications for aircraft crashworthiness and impact energy management
[2] (2021) Ostler, D., Characterization of Carbon/epoxy C-Channels for Crashworthiness applications

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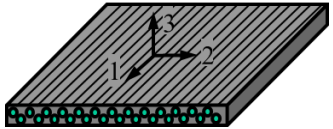
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GDTech constitutive models

Model overview

- Constitutive model of the **UD ply (intra-laminar)**
  - Extended version of model proposed by **Ladeveze [3]**
  - Formulated at the **mesoscale level** (i.e., ply level)
  - 3D orthotropic **elasto-plastic damage** model
  - **Main features**
    - **Progressive damage through CDM**
      - Effective stresses
    - **Post-peak regularization based on the smeared crack approach**
      - Direction-dependent fracture energies
    - **In-situ strengths in 12 and 22**
      - Based on methodology proposed by Camanho[4] and Furtado[5]

3D orthotropic



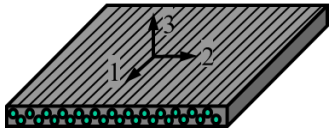
[3] (1992) Ladeveze P, et al., Damage modelling of the elementary ply for laminated composites
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Model overview

3D orthotropic



Effective stresses

$$\begin{Bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ \tilde{\sigma}_{33} \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{13} \end{Bmatrix} = \begin{Bmatrix} \frac{\sigma_{11}}{1-d_{11}} \\ \frac{\langle \sigma_{22} \rangle}{1-d_{22}} + \langle -\sigma_{22} \rangle \\ \frac{\langle \sigma_{33} \rangle}{1-d_{22}} + \langle -\sigma_{33} \rangle \\ \frac{\sigma_{12}}{1-d_{12}} \\ \frac{\sigma_{23}}{1-d_{22}} \\ \frac{\sigma_{13}}{1-d_{12}} \end{Bmatrix}$$

Damage/plasticity coupling

$$F = \sqrt{\tilde{\sigma}_{12}{}^2 + \tilde{\sigma}_{13}{}^2 + \tilde{\sigma}_{23}{}^2 + a^2[\tilde{\sigma}_{22}{}^2 + \tilde{\sigma}_{33}{}^2]}$$

[3] (1992) Ladeveze P, et al., Damage modelling of the elementary ply for laminated composites
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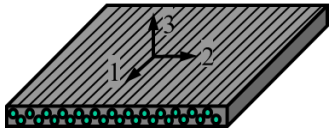
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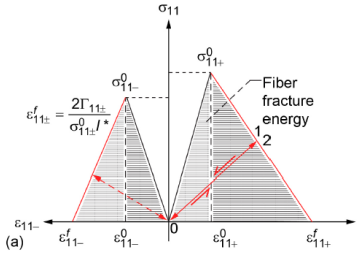
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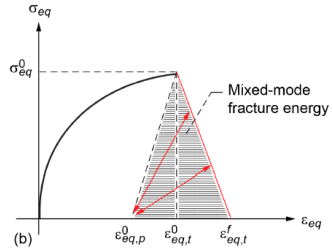
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Failure: Fiber-dominated



Failure: Matrix-dominated



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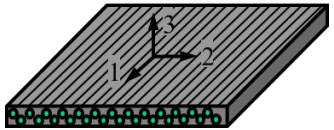
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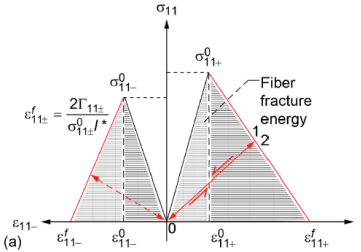
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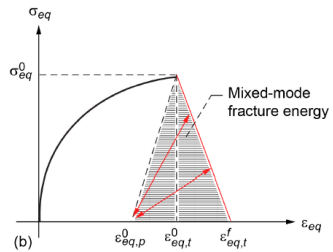
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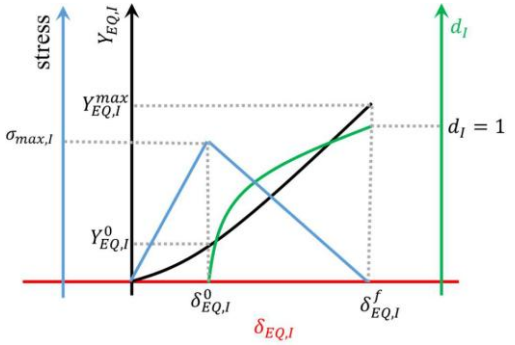
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GDTech constitutive models

- Constitutive model of the **interface (inter-laminar)**
  - Based on the model proposed by **Allix and Ladeveze [6]**
  - Formulated as a **cohesive constitutive law**
  - **Bilinear interface law** with mode mixity

Model overview



Force-opening relationship

$$\begin{Bmatrix} \sigma_{NN} \\ \sigma_{NL} \\ \sigma_{NT} \end{Bmatrix} = \begin{bmatrix} C_N & 0 & 0 \\ 0 & C_L & 0 \\ 0 & 0 & C_T \end{bmatrix} \begin{Bmatrix} \langle \delta_{NN} \rangle (1 - d_I) + \langle - \delta_{NN} \rangle \\ \delta_{NL} (1 - d_I) \\ \delta_{NT} (1 - d_I) \end{Bmatrix}$$

[6] (1992) Allix, O. and Ladeveze, P., Interlaminar interface modelling for the prediction of delamination

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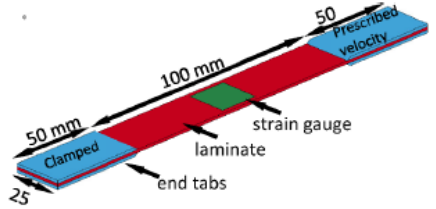
GDTech constitutive models

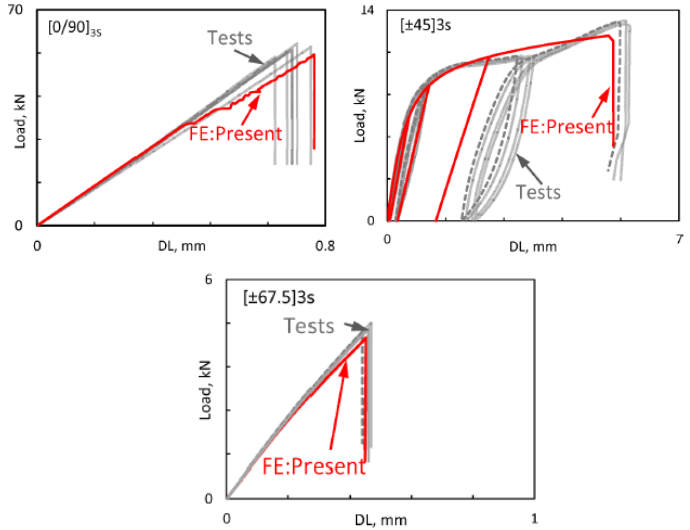
Intra-laminar Identification

- All parameters are **identifiable**

  - **Tension**
    - Monotonic [0/90] → Elastic and strength in +11
    - Monotonic and cyclic [±45] → Elastic, plst., dmg. and strength in 12
    - Monotonic and cyclic [±67.5] → Elastic and strength in 22 ¦ coupling 12-22
  - **Compression**
    - Monotonic [0/90] → Elastic and strength in -11
  - **Fracture energies**
    - Compact tension/ Compression → Fiber dominant fracture energies
    - DCB/ ENF → Matrix dominant fracture energies
  - **Out-of-plane normal/shear***
    - Through-thickness tension
    - Out-of-plane shear

Standard tests





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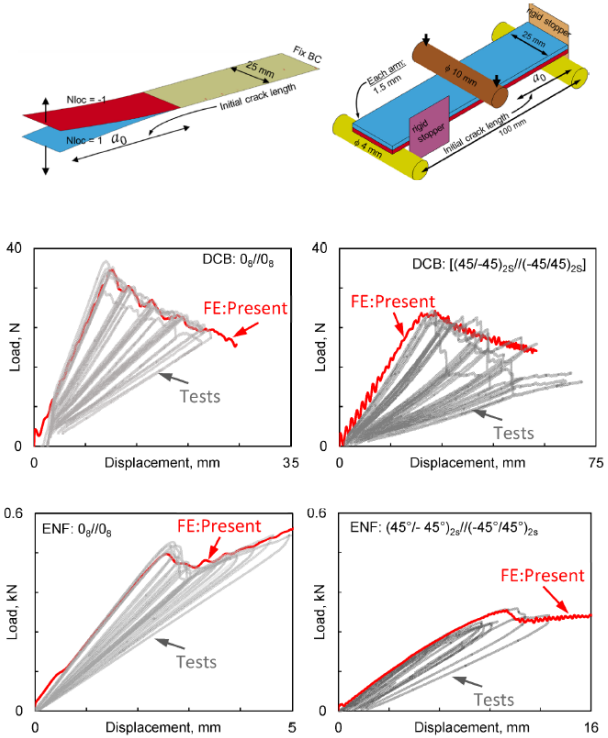
GDTech constitutive models

Inter-laminar Identification

- All parameters are **identifiable**
  - **Mode I**
    - Double Cantilever Beam → Stiffness, strength and fracture
  - **Mode II**
    - End-Notch Flexure → Stiffness, strength and fracture
  - **Mode mixity***
    - Mixed-mode bending → Mode mixity coefficient

$$Y_{EQ,\,I} = \left[Y_N^{\alpha_I} + \left(\frac{G_{IC}}{G_{IIC}} Y_L \right)^{\alpha_I} + \left(\frac{G_{IC}}{G_{IIIC}} Y_T \right)^{\alpha_I} \right]^{1/\alpha_I}$$

Standard tests



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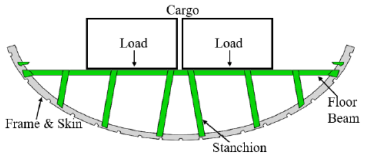
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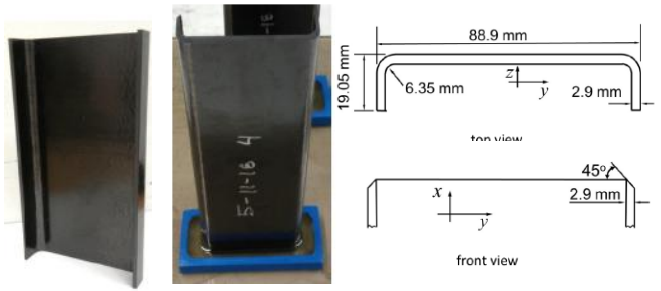
C-Channels crushing benchmark

C-Channels crushing benchmark

- Benchmark consists of **drop-weight and sled crash tests**
  - **Material**
    - IM7/8552 (prepreg UD tape)
  - **Trigger mechanism**
    - Bevel
  - **Two (2) velocities studied**
    - 3.8 and 7.6 m/s
  - **Two (2) stacking sequences studied**
    - **HL1:** $[90/+45/\mathbf{0_2}/90/-45/\mathbf{0_2}]_s$
    - **HL2:** $[90_2/\mathbf{0_2}/\pm45/\mathbf{0_2}]s$

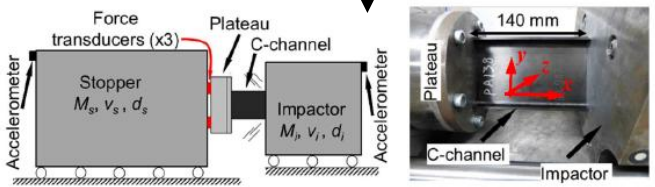


C-channel geometry



From : [2], [7]

Sled crash test



[2] (2021) Ostler, D., Characterization of Carbon/epoxy C-Channels for Crashworthiness applications
[7] (2024) Rajaneesh, A. et al, Finite element simulation of axial crushing of flat and C-channer composite coupons using a modified mesomodel

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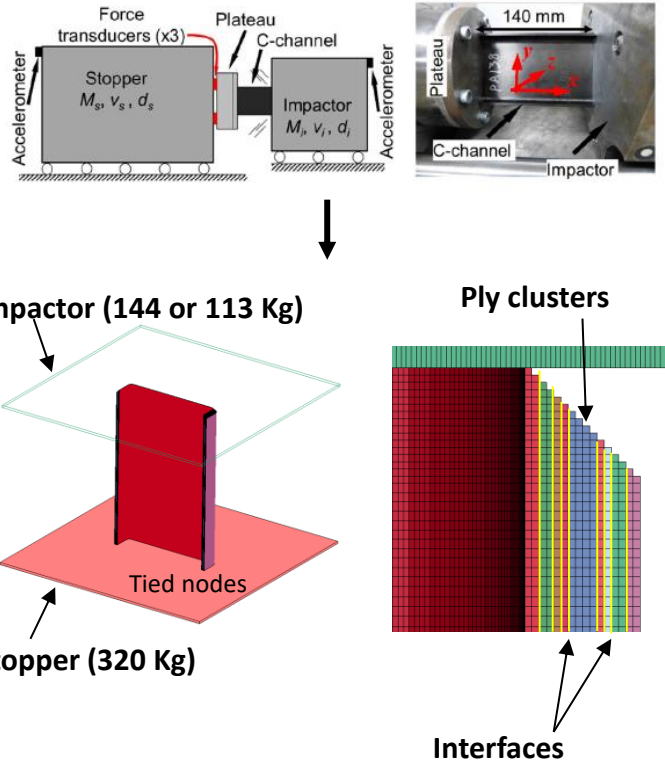
C-Channels crushing benchmark

C-Channels crushing benchmark

Main features

- Regular mesh of 0.2 mm (after mesh sensitivity in [7])
- Stepped trigger
- Cohesive elements in between ply clusters
- FI 8-point hexahedrons
- Element erosion when any damage metric > 0.999

Predictive modelling → Capture damage modes with fully identifiable models

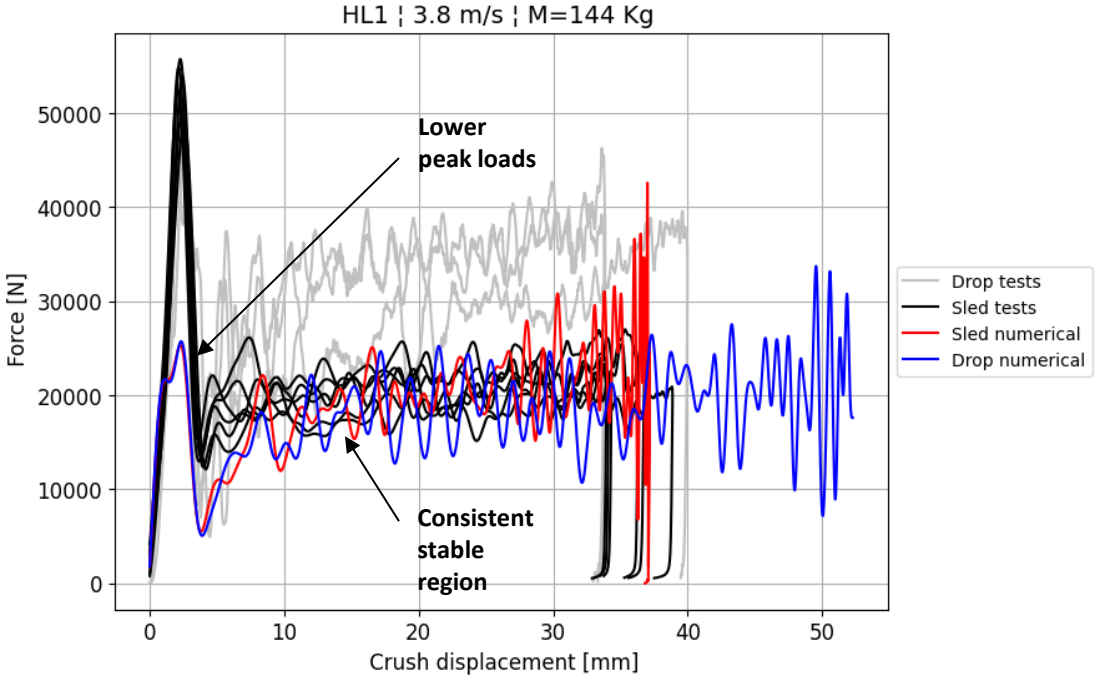


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C-Channels crushing benchmark

- HL1 Laminate : $[90/+45/0_2/90/-45/0_2]_s$



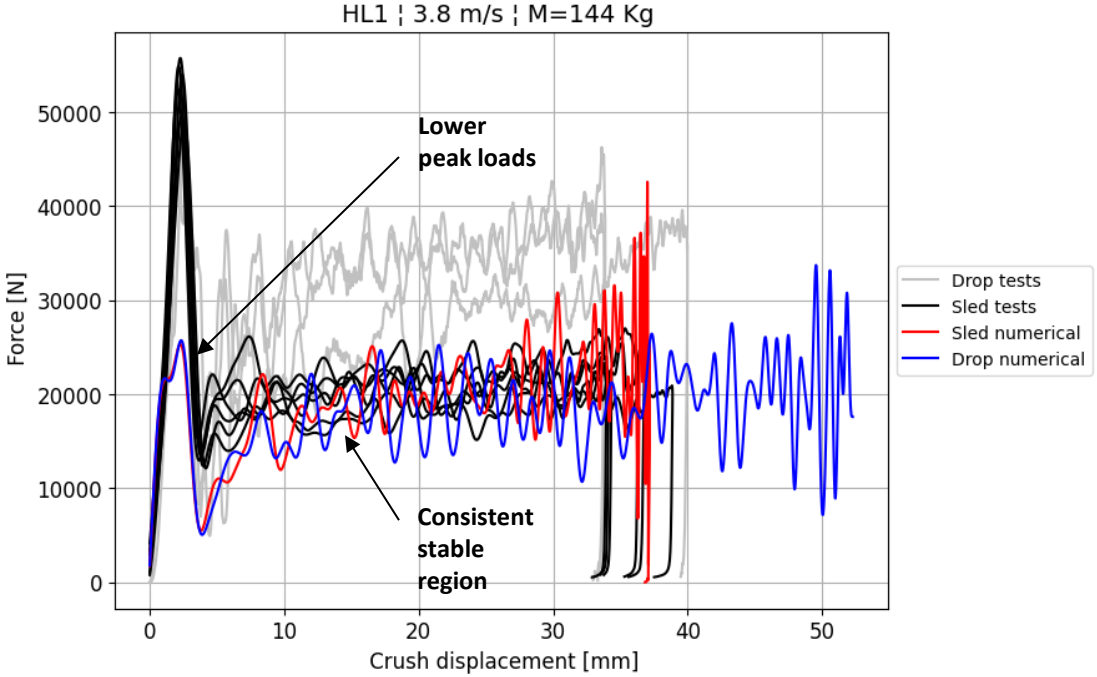
***Experimental curves as per filtered data provided by each laboratory**

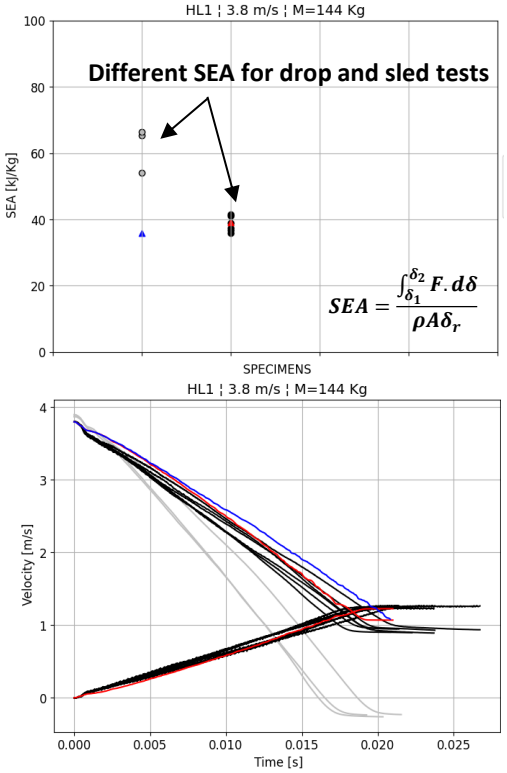
**** Numerical curves filtered using a 4th-order BW filter with a cutoff frequency of 2000 Hz**

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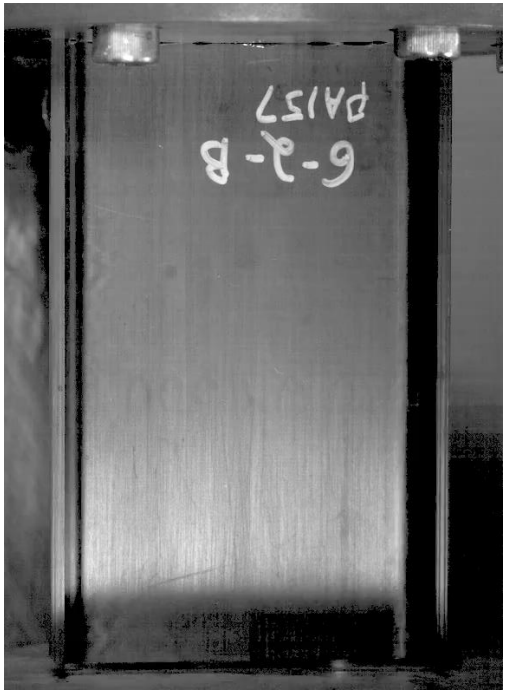




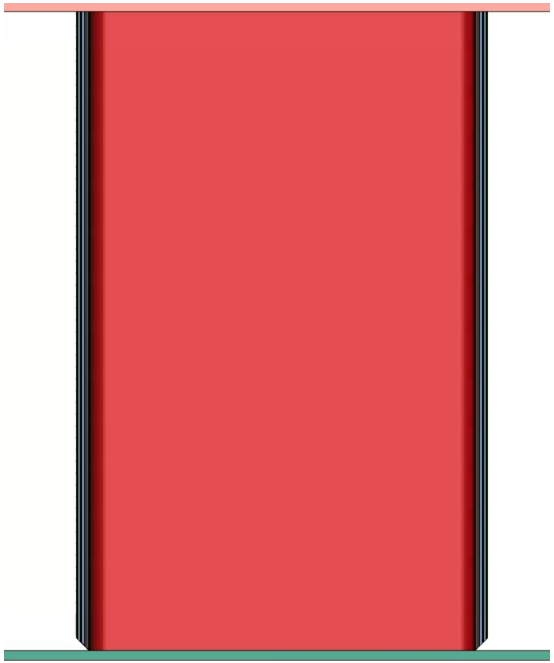
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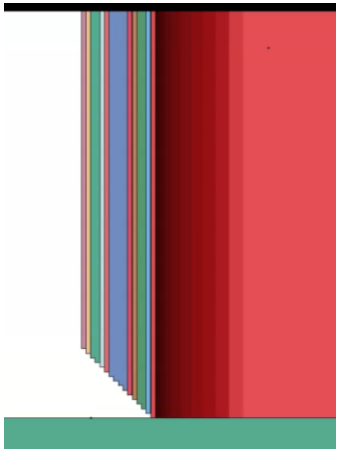
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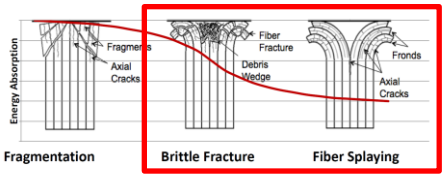


Tests performed by NASA Glenn research center







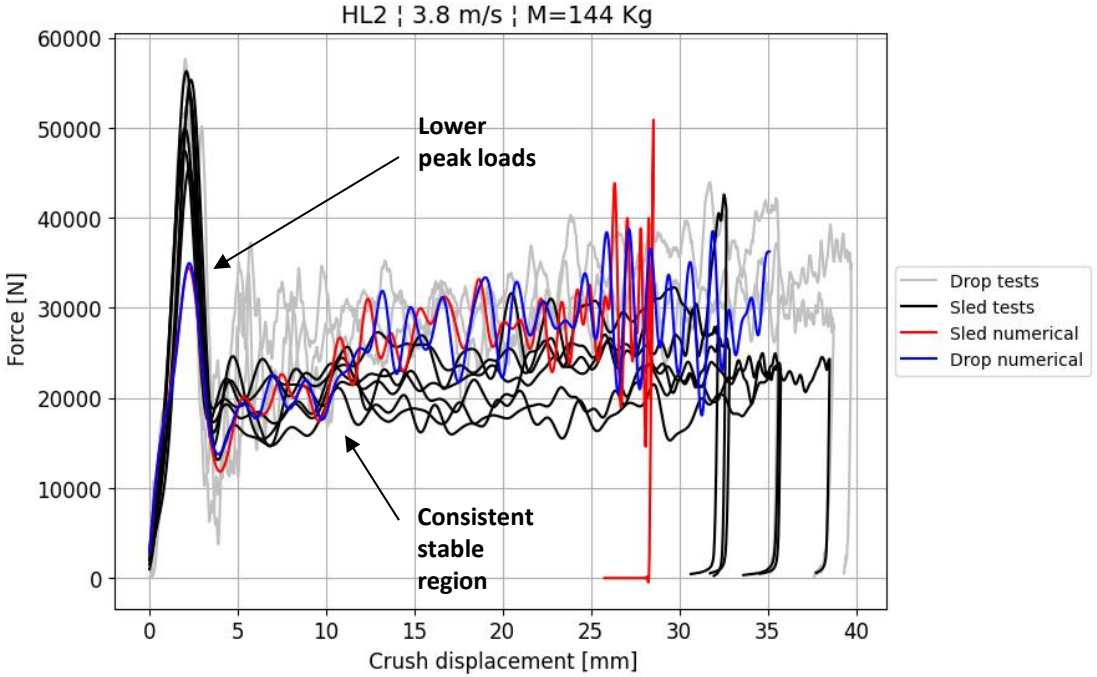


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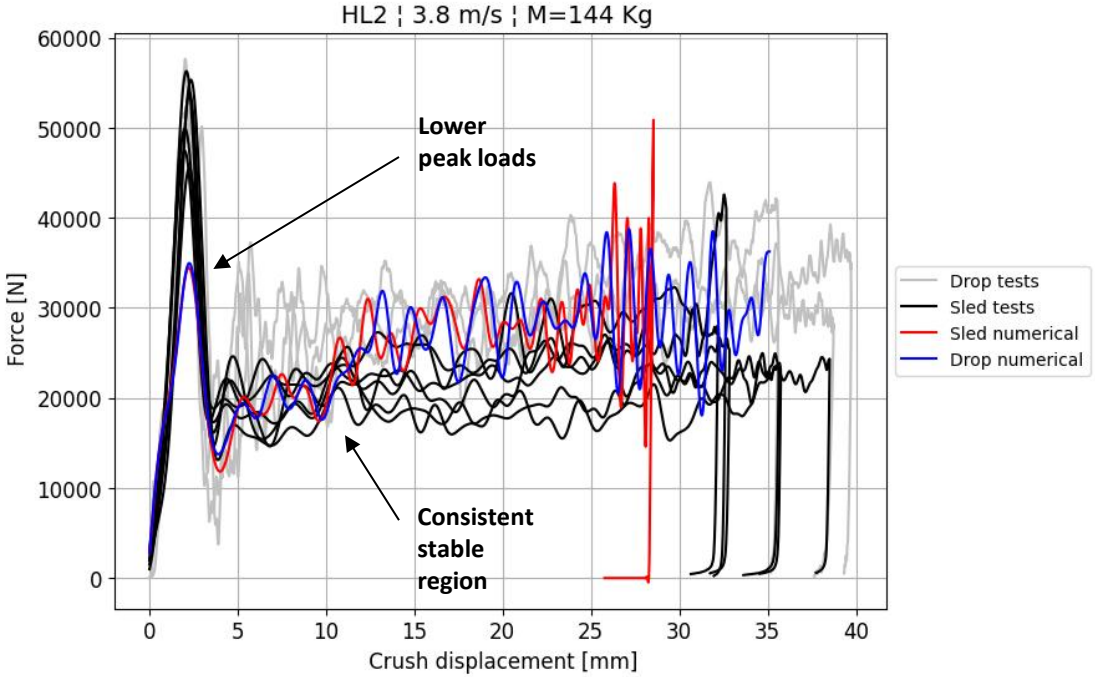
- HL2 Laminate : $[90_2/0_2/\pm45/0_2]_s$

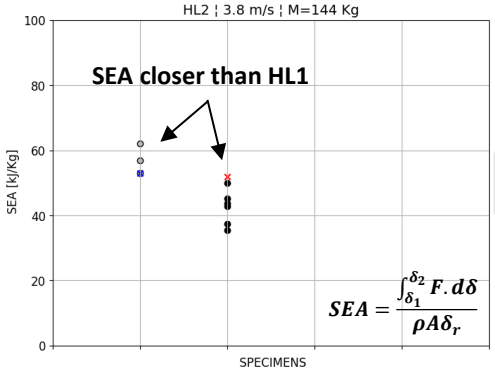


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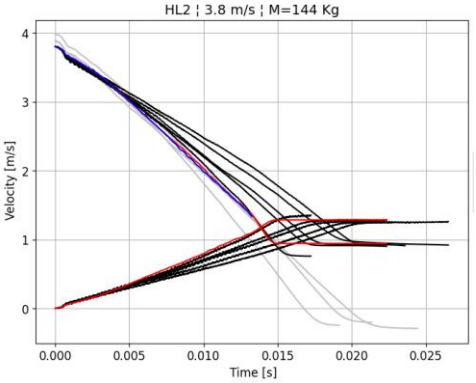
C-Channels crushing benchmark

- HL2 Laminate : $[90_2/0_2/\pm45/0_2]_s$





$\delta_1 = 10\ mm$
$\delta_2 = \delta_{max}$



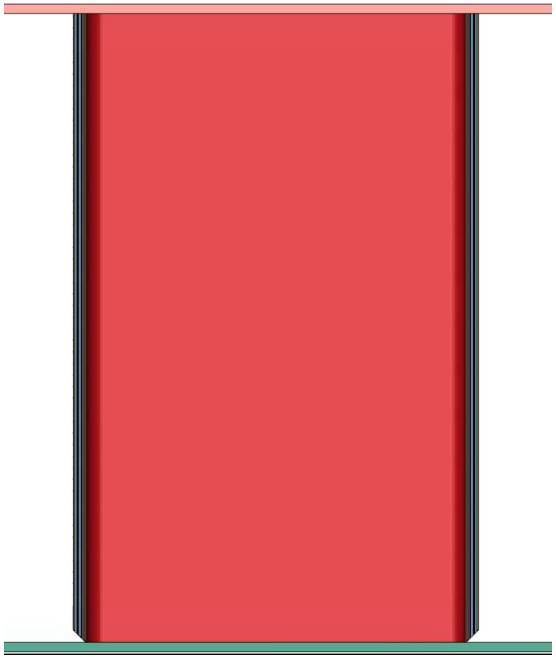
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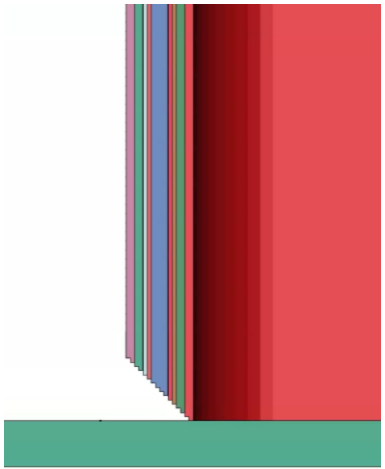
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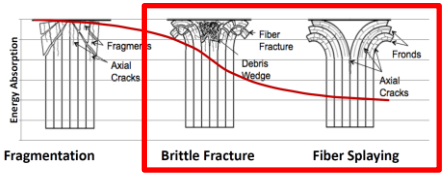


Tests performed by NASA Glenn research center









From : [2]

[2] (2021) Ostler, D., Characterization of Carbon/epoxy C-Channels for Crashworthiness applications

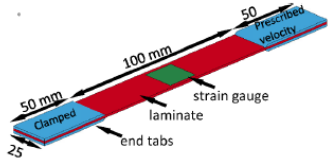
Table of contents

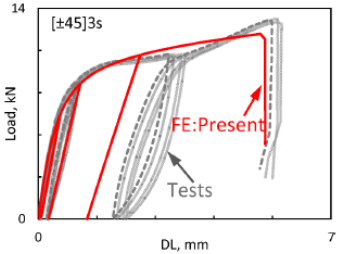
- Overview
  - Context
  - GDTech constitutive models
    - Intra-laminar model for UD
    - Inter-laminar model
  - C-channels crushing benchmark
    - Model set-up
    - Results
  - Final remarks

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Final remarks

- **Constitutive modelling**
  - Fully identifiable constitutive models proposed
    - Coupling between damage and plasticity is accounted for
    - Mesh regularized using smeared crack approach
    - Validated in quasi-static and dynamic scenarios (standard coupons, OHT,LVI, CAI, HVI)

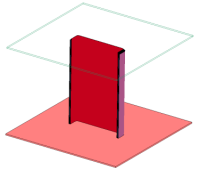


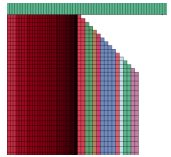


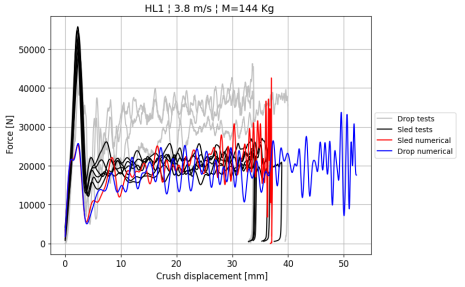
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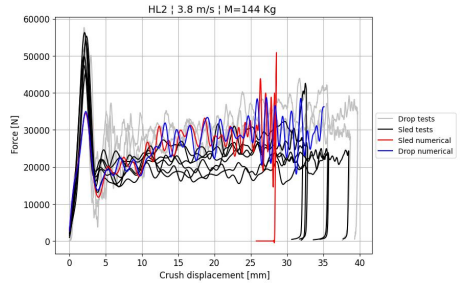
Final remarks

- **Constitutive modelling**
  - Fully identifiable constitutive models proposed
    - Coupling between damage and plasticity is accounted for
    - Mesh regularized using smeared crack approach
    - Validated in quasi-static and dynamic scenarios (standard coupons, OHT,LVI and CAI, HVI)
- **C-channel crushing benchmark**
  - Detailed modeling to capture damage modes with emphasis on predictability
  - Crushing stable region correctly captured in both laminates
    - Sled tests ➞ stable crushing force $[90_2/0_2/\pm45/0_2]_s$ > $[90/+45/0_2/90/-45/0_2]_s$
  - Numerical peak load lower in both laminates
    - Non-negligible influence of erosion and contact formulation parameters (i.e., penalty factors)
    - Currently under study
  - Strain rate effects on laminates under higher velocities to be studied









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Acknowledgements

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