Crashworthiness Prediction Of Composite Vehicle Structures

Xinran Xiao

Michigan State University

Outline

- Composite crashworthiness, what can we predict?
- Past experience
- Recent progress
- Conclusion and outlook

Crashworthiness Prediction of Composite Structures

Can we predict the crashworthiness performance of composite structures?

2014 Corvette C7

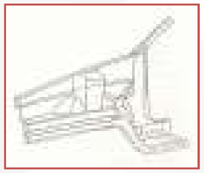
carbon-fiber: hood (inner and outer) and roof panel; SMC: quarters, doors, hatch; carbon nano-composite floor pan.

Al chassis

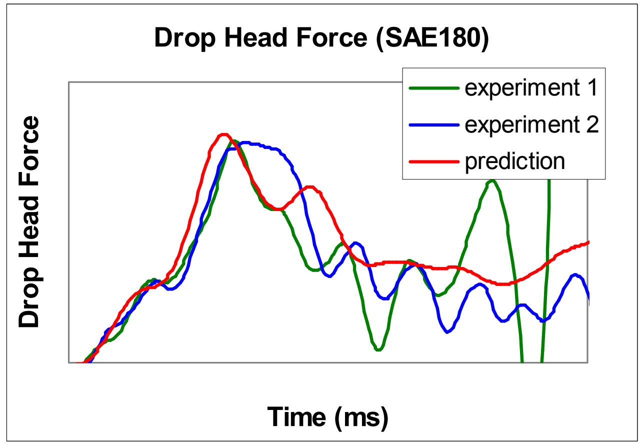
Crashworthiness Prediction of Composite Structures

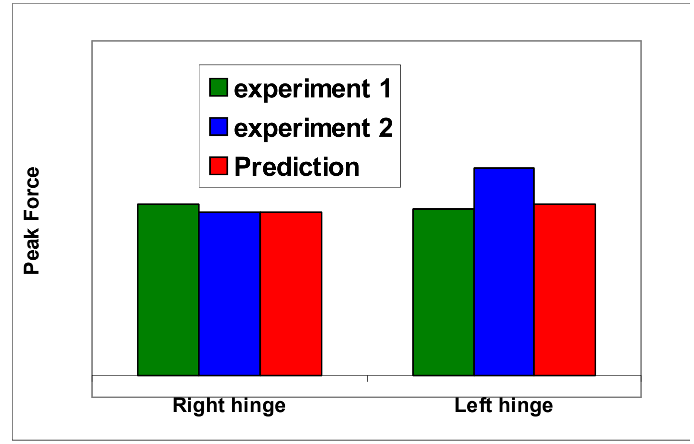
Body panels

Primary energy absorbing structures



Predictions Of Composite Body Panels





- The modeling method for composite hood was established in the design of a different vehicle.
- The design, iterations, and material selection were evaluated by FEA only.
- The predicted response agreed well with a test conducted later.
  - ➢ Existing composite models are sufficient to predict the body panels.

Collaboration with John Morley, 2004-05

Composite Crashworthiness, What Can We Predict?

- Body panels ✓
- Primary energy absorbing structures ?

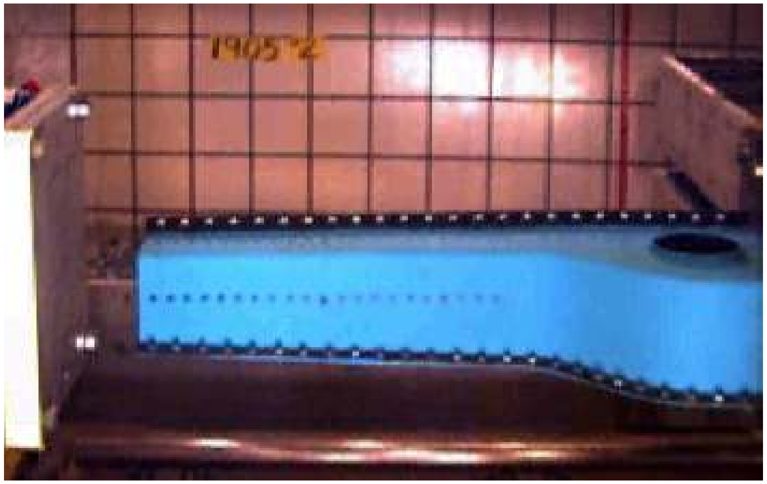
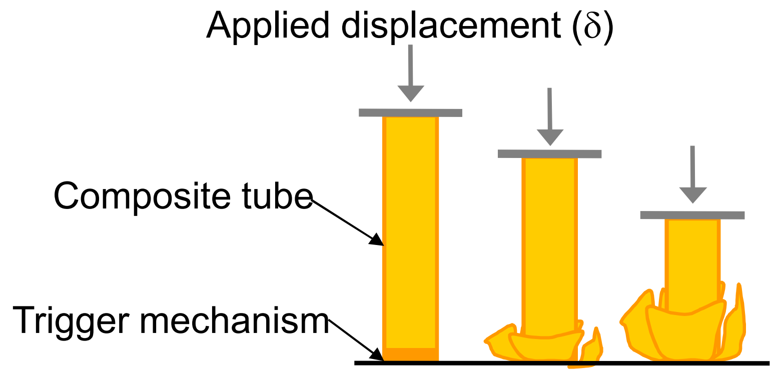


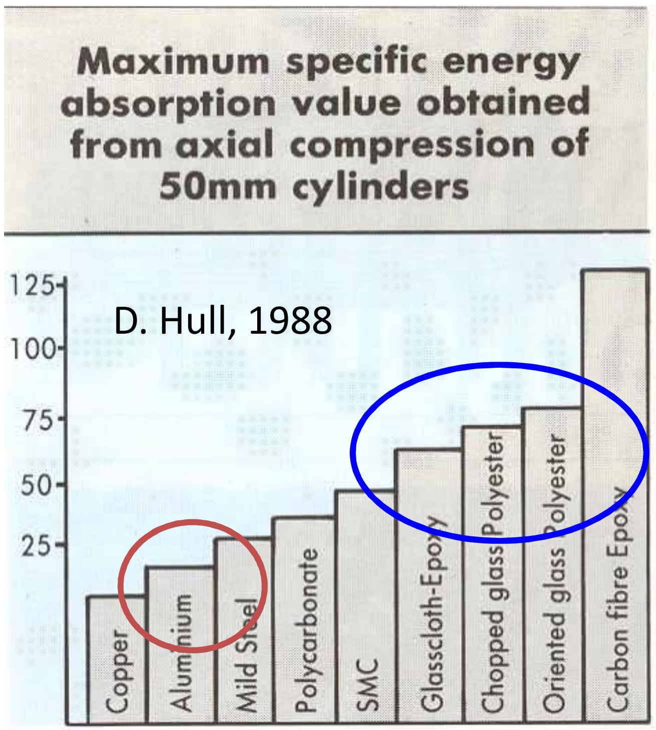
Photo courtesy: ENGENUITY

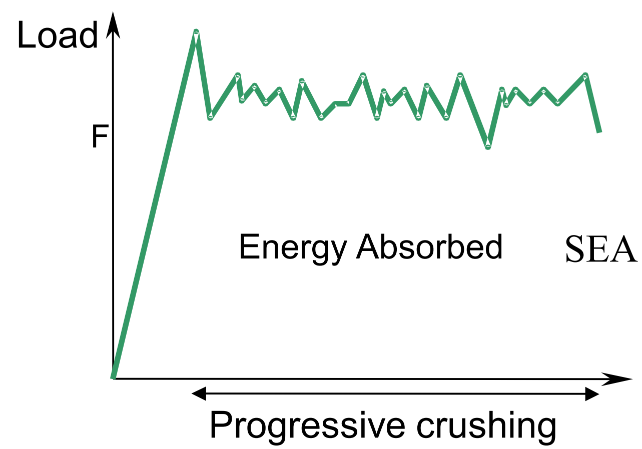

D1046
4280-2-4
10 29 01

Axial Crush of Tubes

- A measure of the specific energy absorption (SEA) of a material
- A benchmark problem to gauge the capability to model primary energy absorbing structures





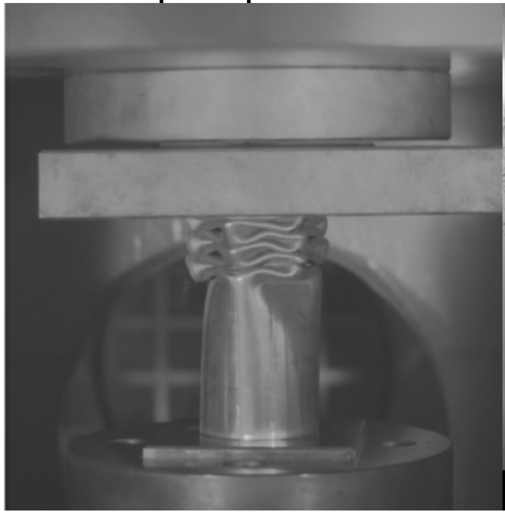


$$SEA = \frac{\int_0^{\delta} F dx}{\rho\, \delta A}$$

McGregor et al, Comp A, 2008

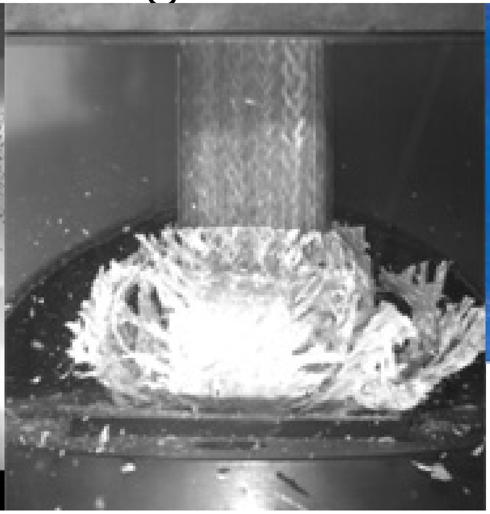
Challenge In Modeling Composite Primary Energy Absorbing Structures

- Extensive failure, resin pulverize, fiber rupture, delamination…
- Require to model the behavior much beyond the failure criterion
- Require experimental techniques to characterize the properties of composites with damage



DP steel tube

PW carbon composite



Braided carbon composite

Kevlar composite

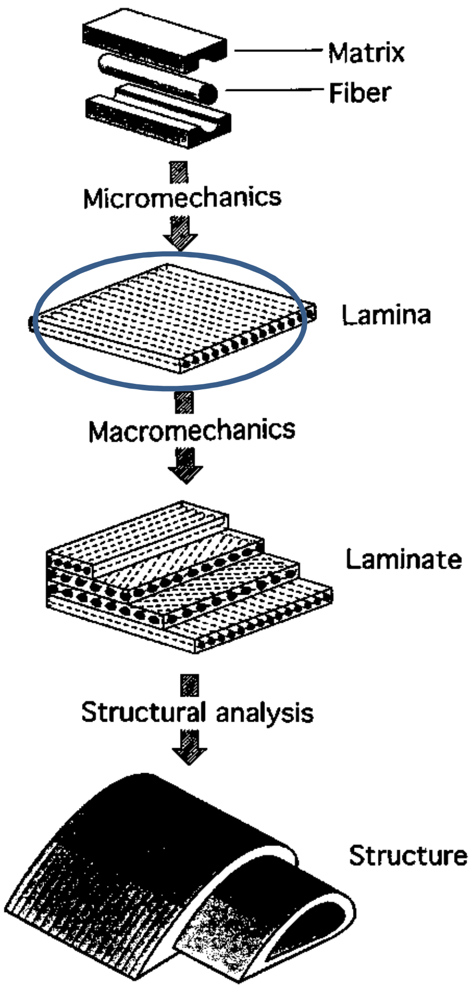
Photo courtesy: A. Browne

Photo courtesy: M.Starbuck

Outline

- Composite crashworthiness, what can we predict?
- Past experience
- Recent progress
- Conclusion and outlook

Composite Material Models In Commercial Codes

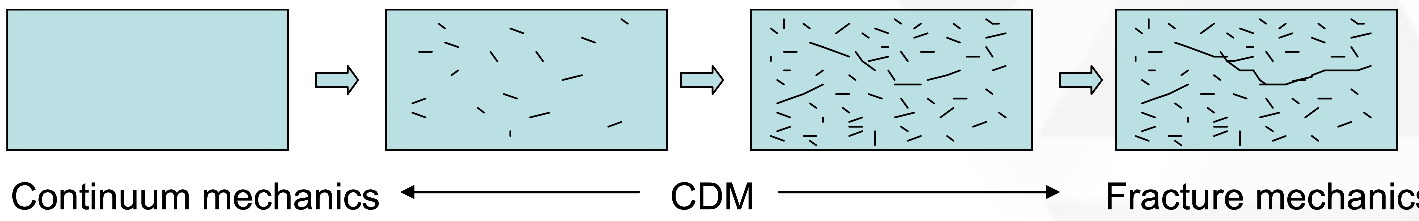


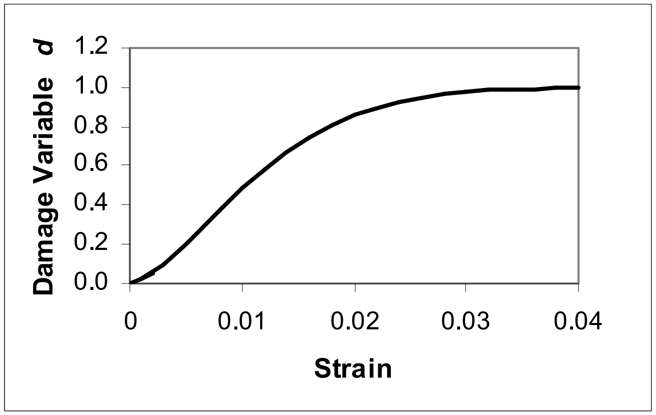
Daniel and Ishai,
Engineering Mechanics of
Composite Materials, 1994.

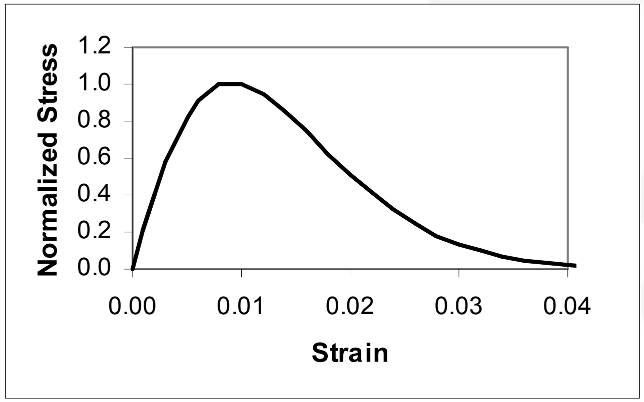
Phenomenological models with homogenized properties

- Orthotropic solid
  - Brick (solid) element
    E1, E2, E3, G12, G23, G31, ν12, ν23, ν31
  - Shell (plate) E1, E2, G12, ν12
- Failure criteria
- Property degradation beyond failure
  - ➢ Progressive failure models
  - ➢ Damage mechanics models

Continuum Damage Mechanics (CDM) Model



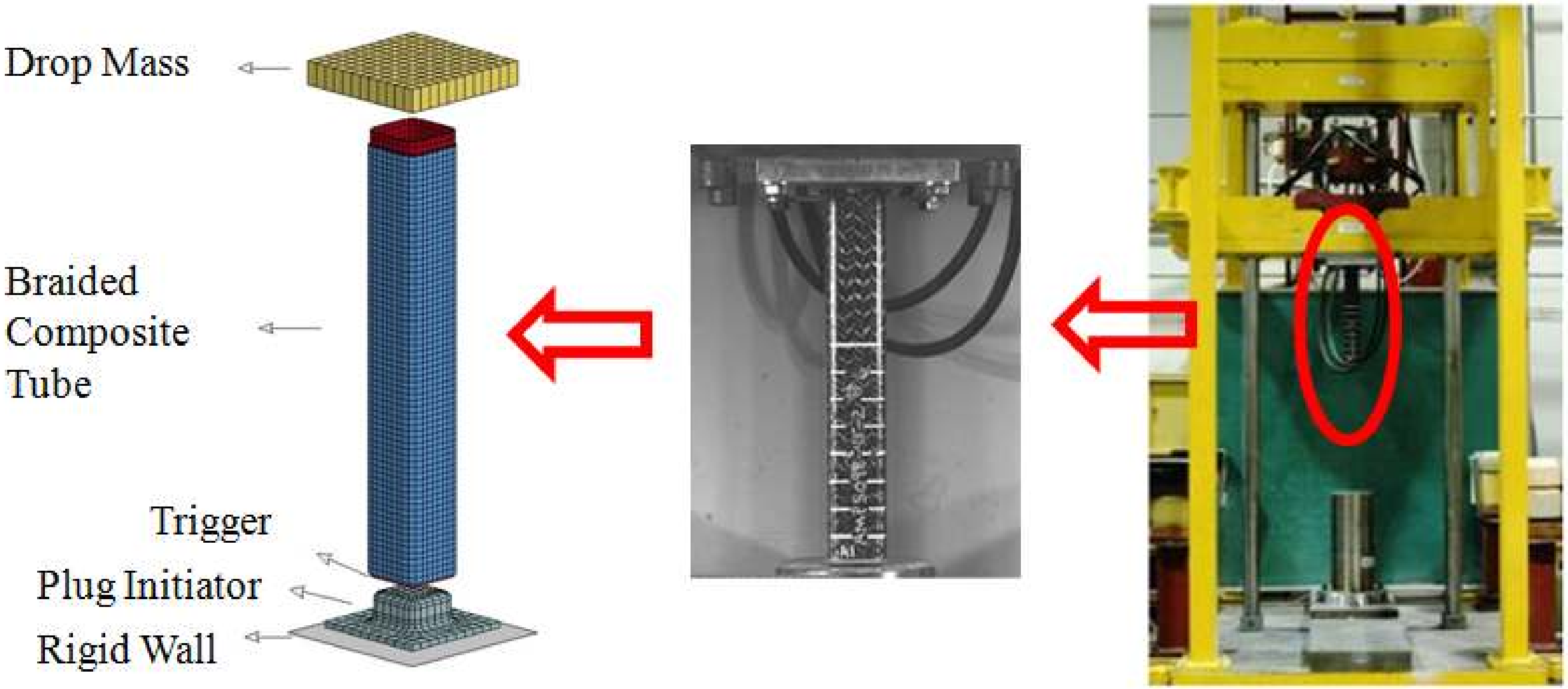




$$d = 1 - \exp\left(-\frac{1}{me}\left(\frac{\varepsilon}{\varepsilon_f}\right)^m \right)$$

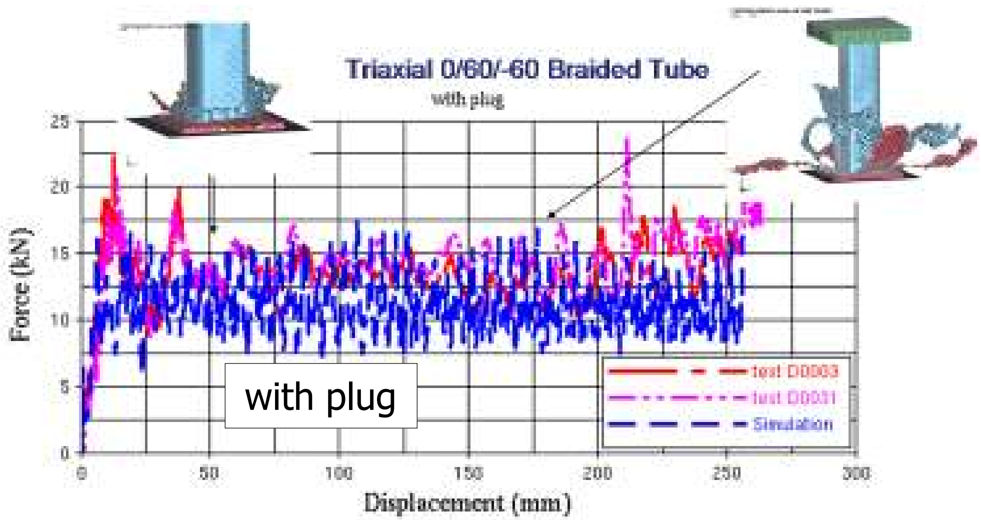
$$\sigma = \varepsilon E = \varepsilon E_0 (1 - d)$$

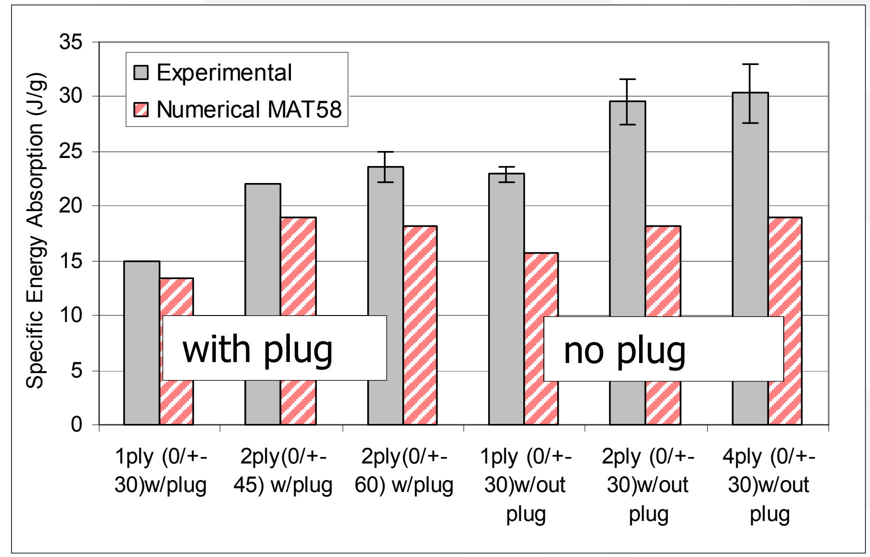
Axial Crush Of Braided Carbon Composite Tubes

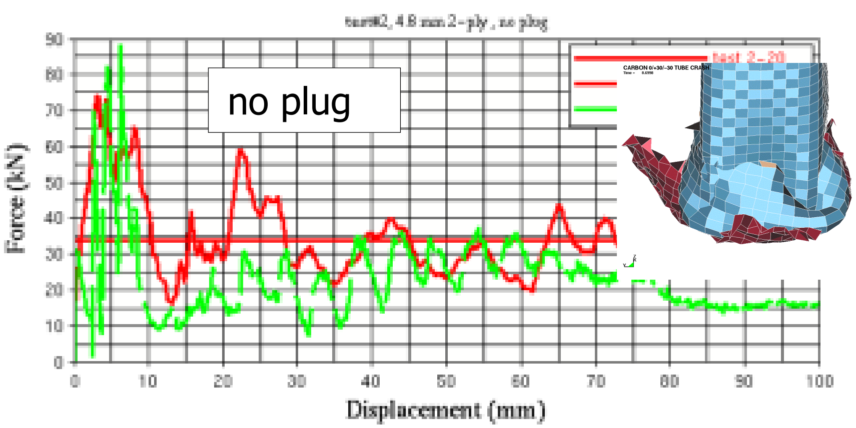


- Triaxial braided composite tubes, 0/±30, 0/±45, 0/±60, 1-ply, 2-ply, 4-ply
- The tube front edge with 45°chamfer
- Tested with or without a plug initiator
- Simulation with LS-DYNA, each ply was modeled with one layer of shell with MAT58. Delamination was modeled with contact tiebreak

Simulation Of Axial Crush Of Braided Carbon Composite Tubes With MAT58 (MLT model[1]) in LS-DYNA







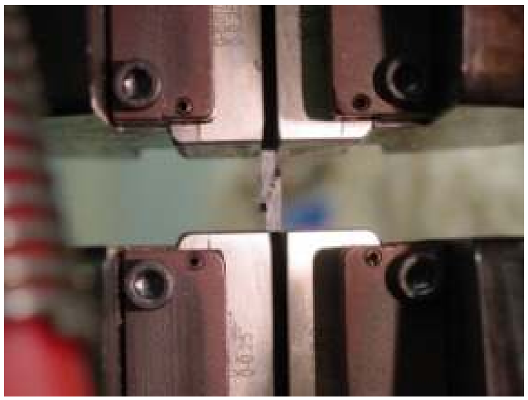
- With plug, underestimate SEA ~20%
- No plug, underestimate SEA~40%, instability

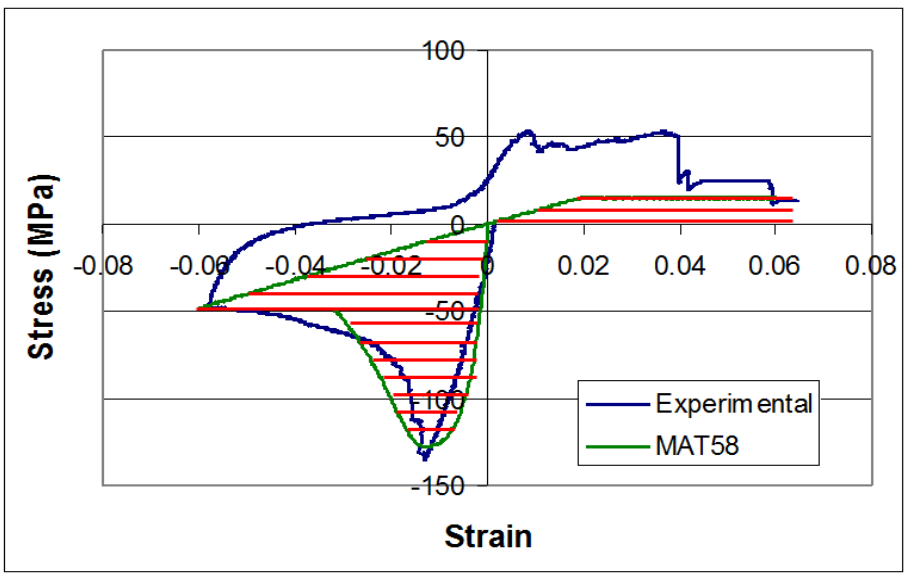
Xiao et al, ACC TR EM03-02, 2003

1-Matzenmiller, Lubliner, Taylor, Mech Mat. 1995

Limitations of Continuum Damage Mechanics Models in Composite Crash Simulations

DeTerasa's compression experiment, 2001





Xiao et al, Thin-walled Struc, 2009

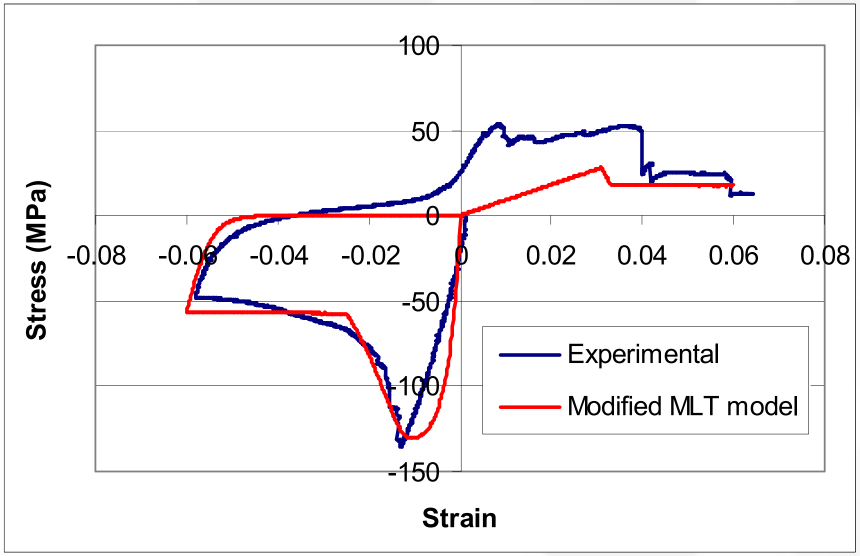
- CDM model cannot represent the unloading response of substantially damaged composites
  - ➢ Underestimate the total energy absorption
- The stiffness of the damaged composite modeled by CDM is much lower than experimental value
  - ➢ Tendency to instability

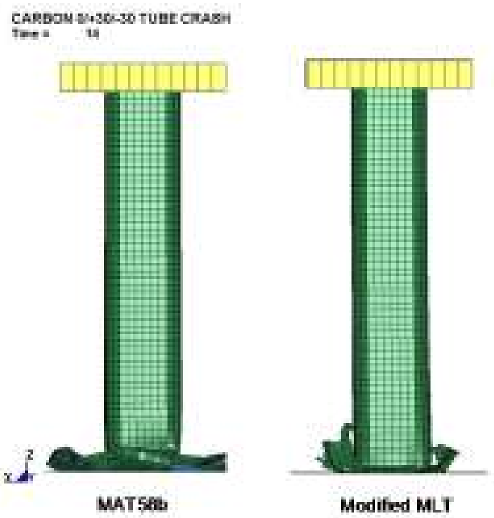
AUTOMOTIVE COMPOSITES CONSORTIUM

Modification of MLT model (2007)

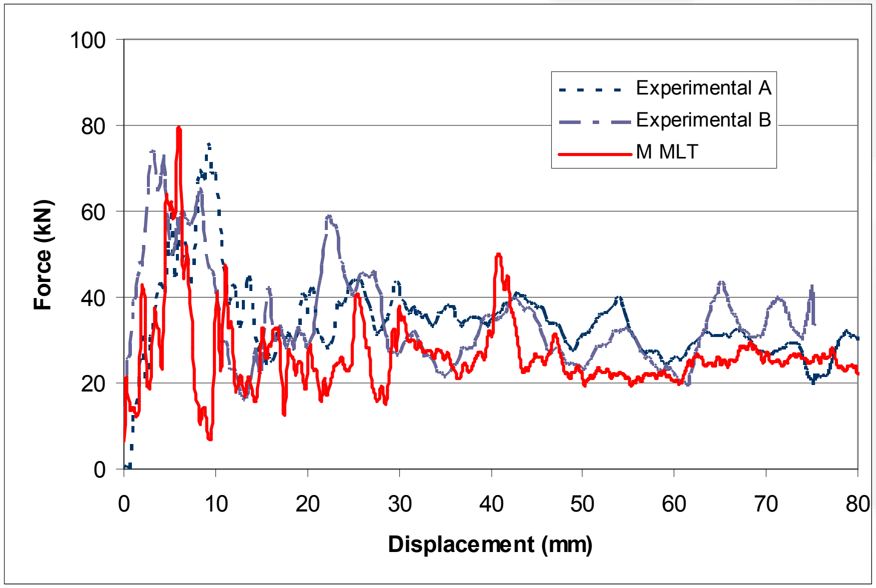
$$\varepsilon_p = \frac{\sigma_{\max}}{E_u}$$

$$\sigma_u = \frac{\sigma_{\max}}{\exp\left(-\dfrac{\varepsilon - \varepsilon_p}{\varepsilon_{\max} - \varepsilon_p}\right)}$$





Xiao, J Composite Materials, 2009.



Coupled CDM-plasticity model and its implementation in LS-DYNA

MLT model

loading surface - Hashin failure criteria with damage evolution

$$f_1 = \left[\frac{\sigma_{11}}{(1-\omega_{11t,c})X_{t,c}}\right]^2 - r_1 = 0$$

$$f_2 = \left[\frac{\sigma_{22}}{(1-\omega_{22t,c})Y_{t,c}}\right]^2 + \left[\frac{\sigma_{12}}{(1-\omega_{12})S_c}\right]^2 - r_2 = 0$$

loading surfaces in strain space

$$g_1 = \varepsilon^T G_1 \varepsilon - r_1 = 0$$

$$g_2 = \varepsilon^T G_2 \varepsilon - r_2 = 0$$

$$G_1 = \left(\frac{E_1}{DX_{t,c}}\right)^2 \begin{bmatrix} 1 & (1-\omega_{22})\nu_{12} & 0 \\ (1-\omega_{22})\nu_{12} & (1-\omega_{22})^2 {\nu_{12}}^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$G_2 = \left(\frac{E_2}{DY_{t,c}}\right)^2 \begin{bmatrix} (1-\omega_{11})^2 {\nu_{21}}^2 & (1-\omega_{11})\nu_{21} & 0 \\ (1-\omega_{11})\nu_{21} & 1 & 0 \\ 0 & 0 & \left(\frac{DY_{t,c}}{E_2}\frac{G}{S_c}\right)^2 \end{bmatrix}$$

Matzenmiller et al, *Mech Materials, 1995*

Coupled model

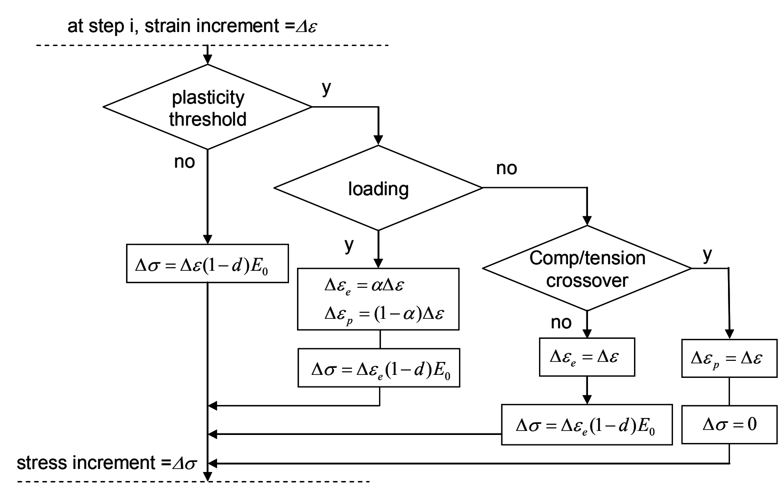
Plasticity onset at threshold strain

$$\varepsilon \le \varepsilon_{0i,} \Delta\varepsilon_i = \Delta\varepsilon_{ei}$$

$$\varepsilon > \varepsilon_{0i,} \Delta\varepsilon = \Delta\varepsilon_{ei} + \Delta\varepsilon_{pi}$$

Stress increment

$$\Delta\sigma = \Delta\varepsilon_e(1-d)E_0 = \alpha\Delta\varepsilon(1-d)E_0$$

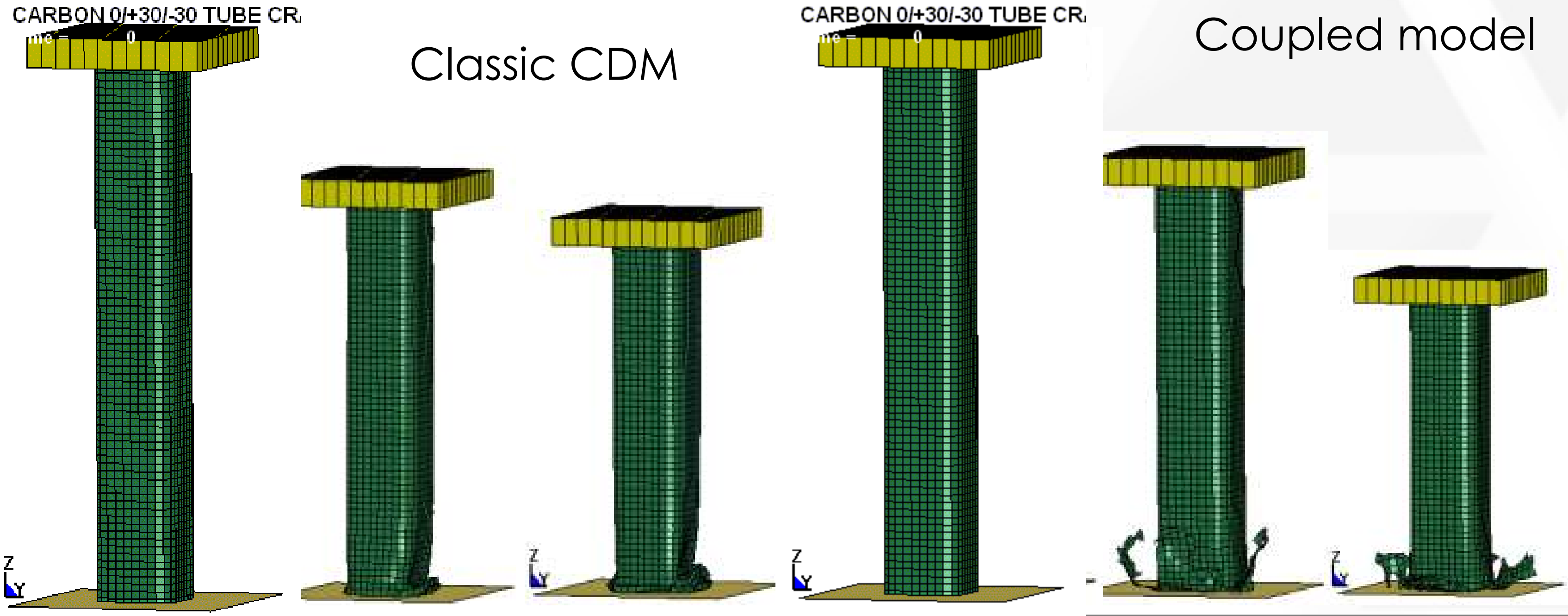


Xiao, *Int J Damage Mechanics, 2010.*

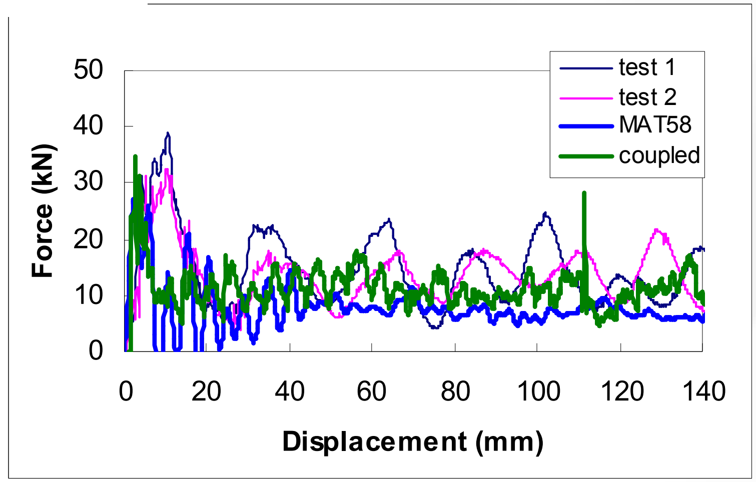
A Coupled Damage-Plasticity Model for Composite Crash Simulations

Classic CDM

Coupled model



Case 1 1-ply triaxially braided tube under axial impact

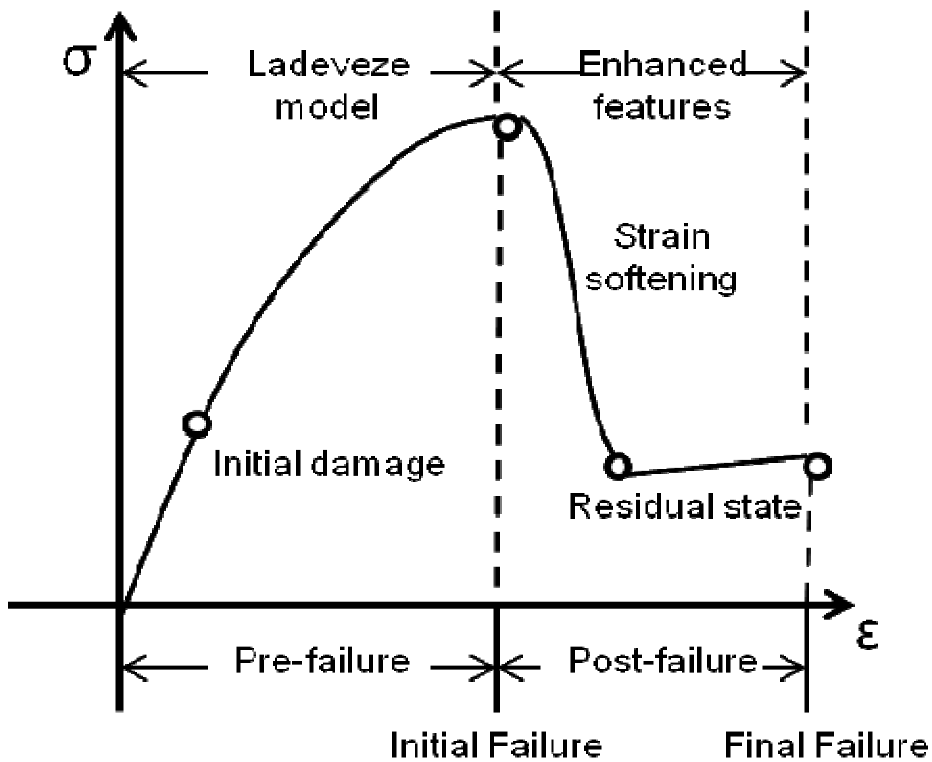


Xiao, Int J Damage Mechanics, 2010.

Outline

- Composite crashworthiness, what can we predict?
- Past experience
- Recent progress
- Conclusion and outlook

Enhanced Continuum Damage Mechanics Model

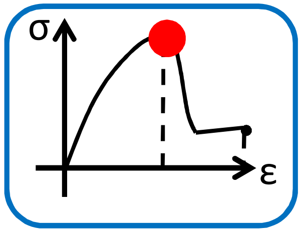


Danghe Shi, PhD thesis, Dec 2015.

- The pre-failure and post-failure regions are described by two separate sub-models.
- A residual state is defined by either a residual stiffness or a residual strength.
- Implemented as LS-DYNA user material model

Enhanced Continuum Damage Mechanics Model

- Failure criteria

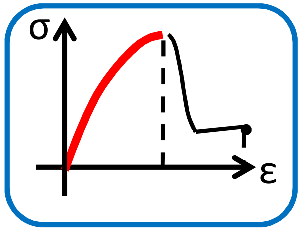


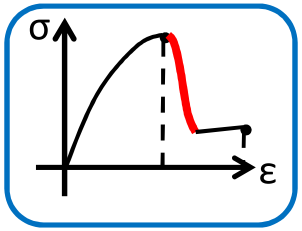
Axial direction: $$\left(\frac{\sigma_{11}}{X_{t,c}}\right)^2 - 1 \begin{cases} \geq 0 & \text{failure} \\ \leq 0 & \end{cases}$$

Transverse direction:

$$\left(\frac{\sigma_{22}}{Y_{t,c}}\right)^2 + \left(\frac{\sigma_{12}}{S}\right)^2 - 1 \begin{cases} \geq 0 & \text{failure} \\ \leq 0 & \end{cases}$$

- The pre-failure and post-failure regions are described by two separate sub-models.





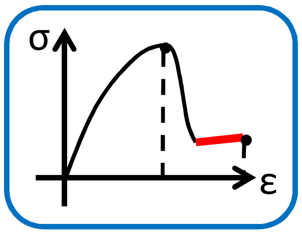
$$d = 1 + (d_f - 1)e^{\frac{1}{m}\left(1-\left(\frac{\varepsilon}{\varepsilon_f}\right)^m\right)}$$

$d \in (0, d_f)$ before initial failure

$d \in (d_f, 1)$ after initial failure

Enhanced Continuum Damage Mechanics Model

- Residual property

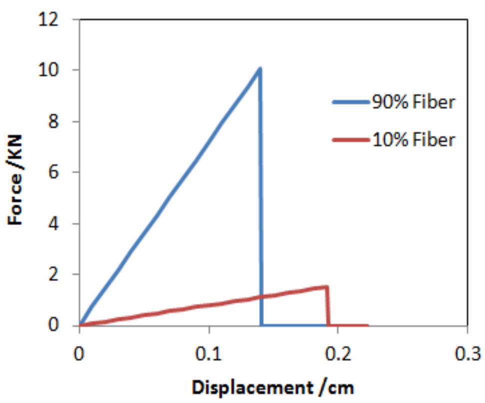


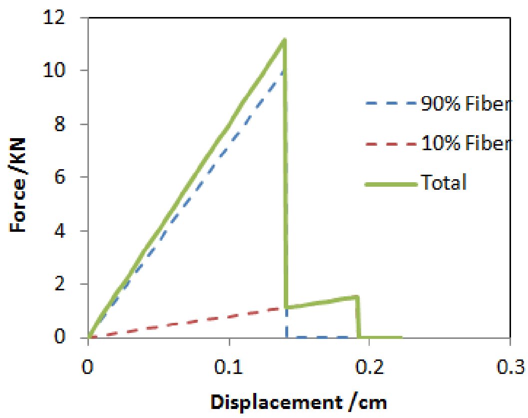
Constant strength:

$$d = \min\left(1 - \frac{\sigma_{residual}}{E \times \varepsilon_{\varepsilon}}, 1 + (d_f - 1)e^{\frac{1}{m}\left(1 - \left(\frac{\varepsilon}{\varepsilon_f}\right)^m\right)}\right)$$

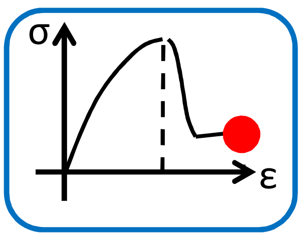
Constant stiffness:

$$d = \max\left(d_{residual}, 1 + (d_f - 1)e^{\frac{1}{m}\left(1 - \left(\frac{\varepsilon}{\varepsilon_f}\right)^m\right)}\right)$$



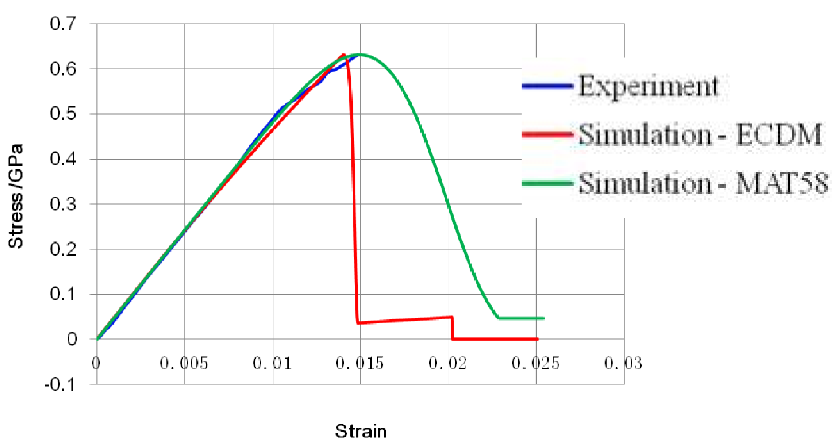
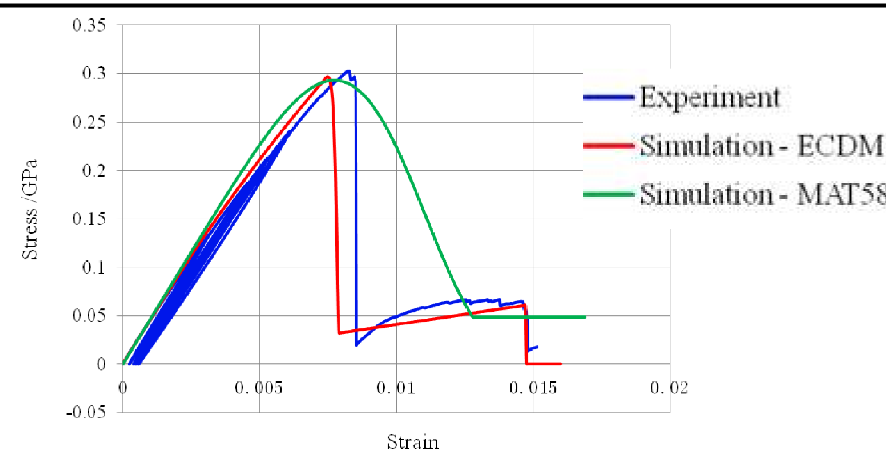
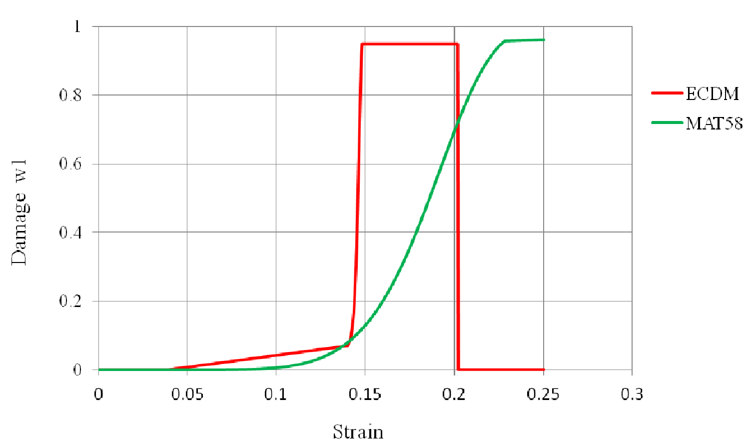
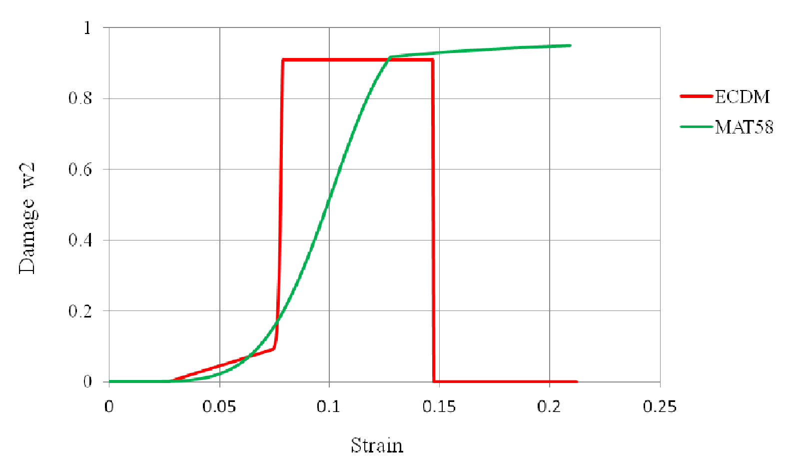


- Element deletion



ECDM vs. MAT58

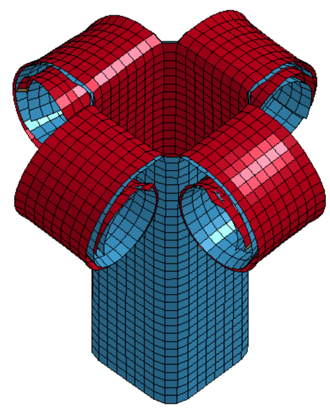
Quasi-static coupon testing of a braided composite

	Axial response	Transverse response
Stress-strain response		
Damage response		

Shi, 2015

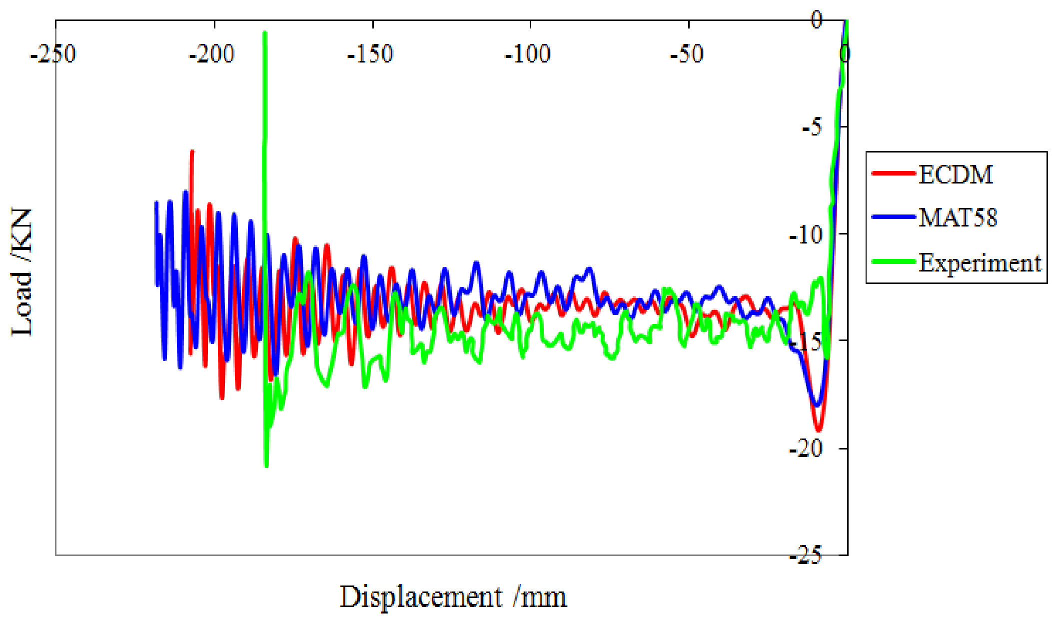
ECDM vs. MAT58

MAT58



ECDM

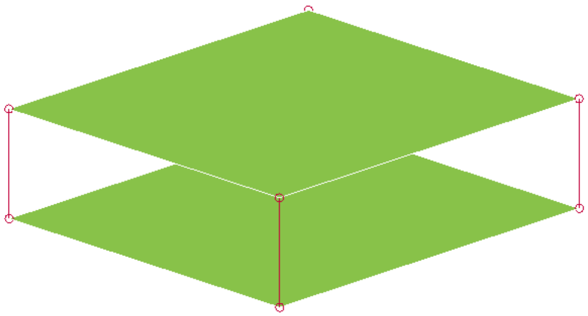
Experiment

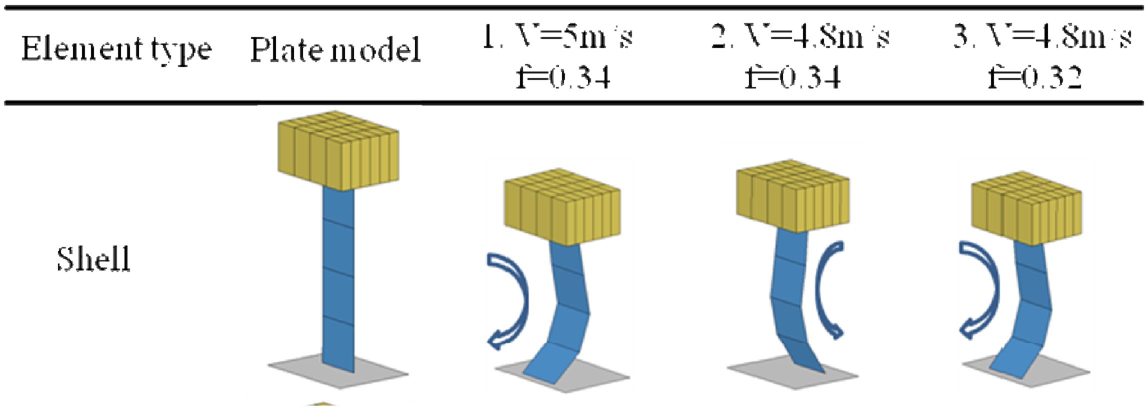


More realistic crush front morphology

Slightly better Force-Displacement responses

A Shell-Beam Modeling Method for Crash Simulation of Thin-Walled Composite Tubes



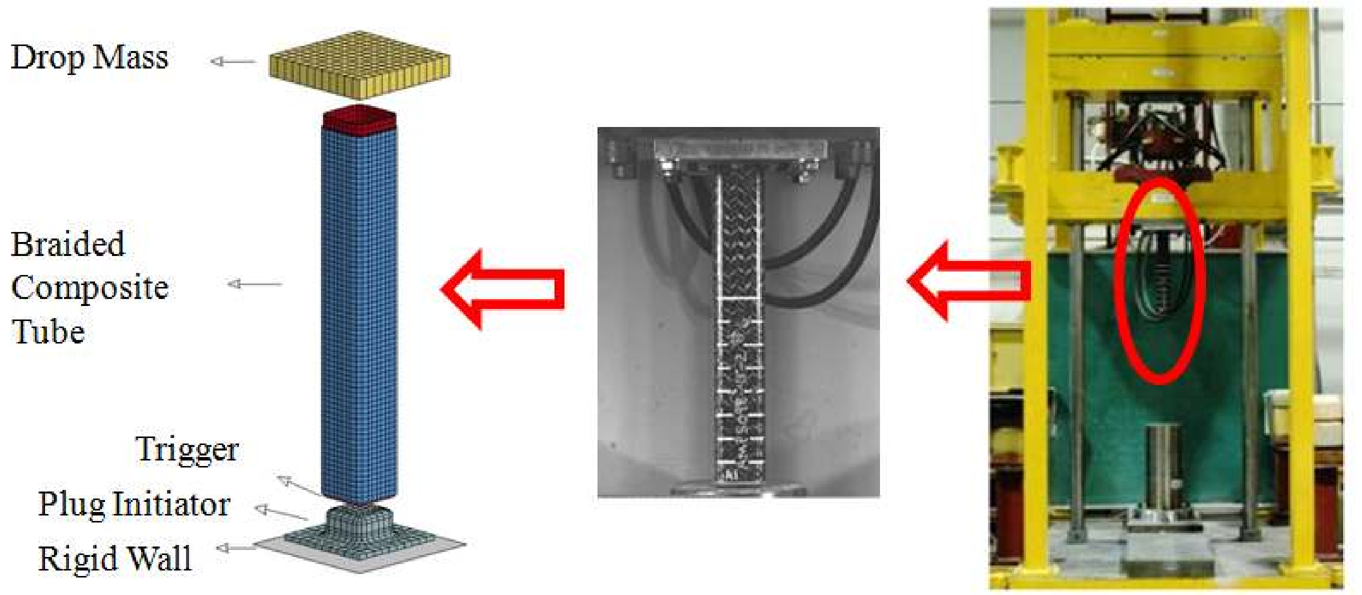


- A shell-beam element consists of 2 shell elements and 4 beam elements.
- A composite layer is represented by a shell-beam element.

➢ The shell-beam element is as stable as the solid element but much more efficient.

Shi, Xiao, Composite Structures, 2017.

Evaluation of the ECDM Model



- Triaxial braided composite tubes, [0/±45] braid architecture, 5 configurations
- The crash front edge was machined with 45° chamfer
- Tested with or without a plug initiator
- Tubes were modeled with four-node fully integrated shell elements
- Each ply was modeled with one layer of shell
- *CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK

Simulations and Predictions: 2×2” [0/±45] Tubes

ECDM + Shell-beam

Correlated

2×2” $[0/\pm45]_2$ with plug

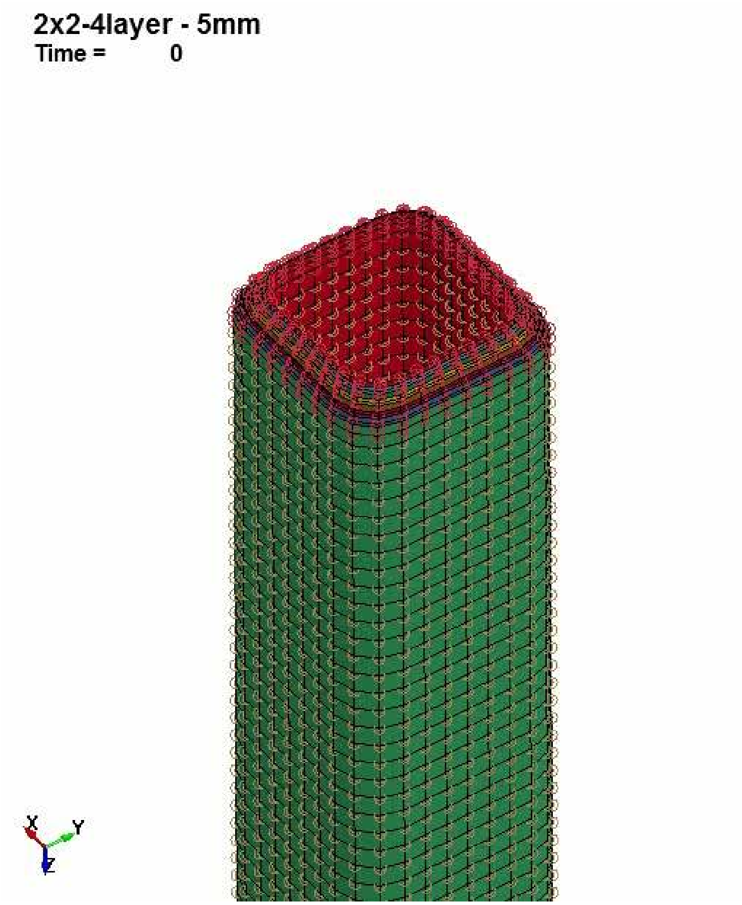
2×2” $[0/\pm45]_4$ with plug

Predicted

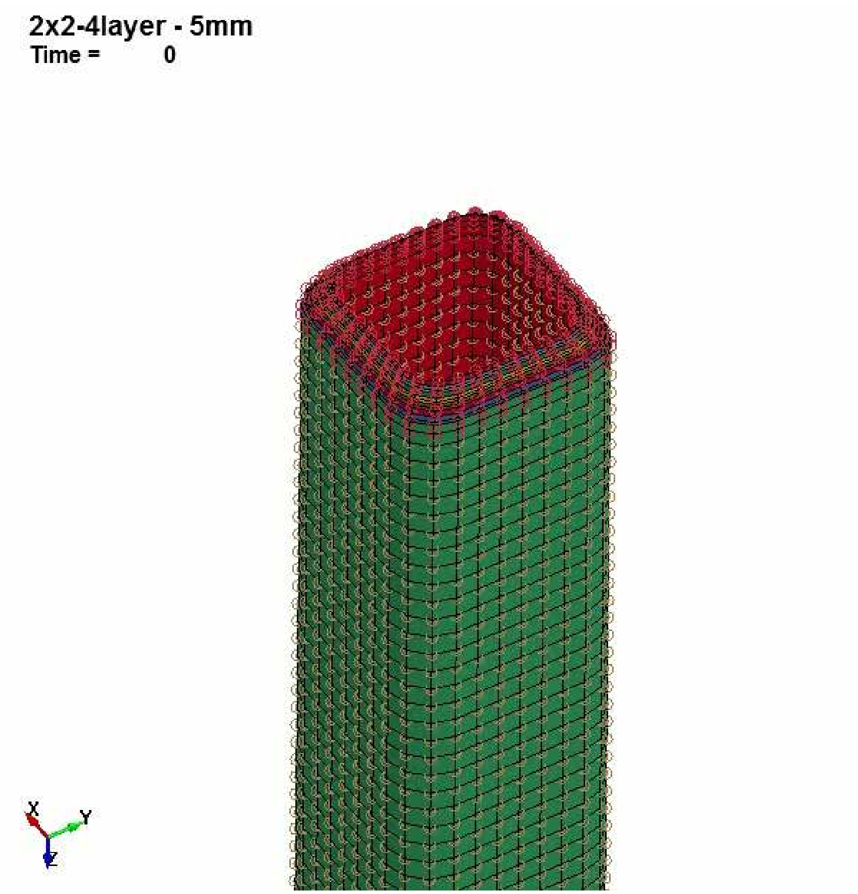
2×2” $[0/\pm45]_4$ without plug

Simulations 2×2” [0/±45] Tubes

$2 \times 2”\ [0/\pm 45]_4$ with plug



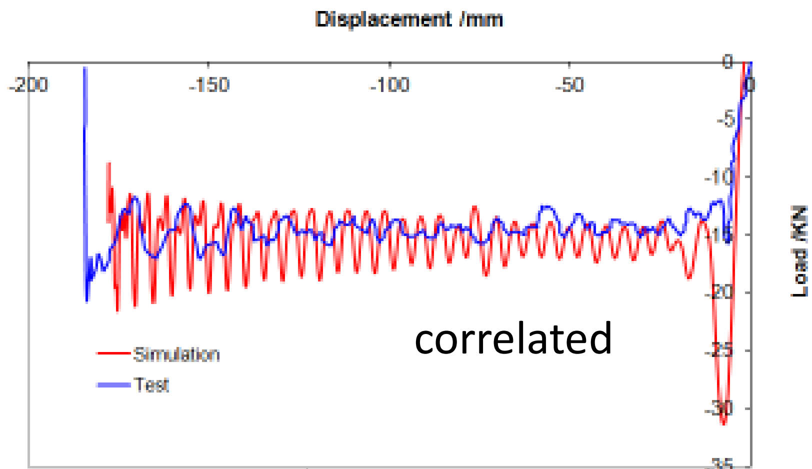
$2 \times 2”\ [0/\pm 45]_4$ without plug



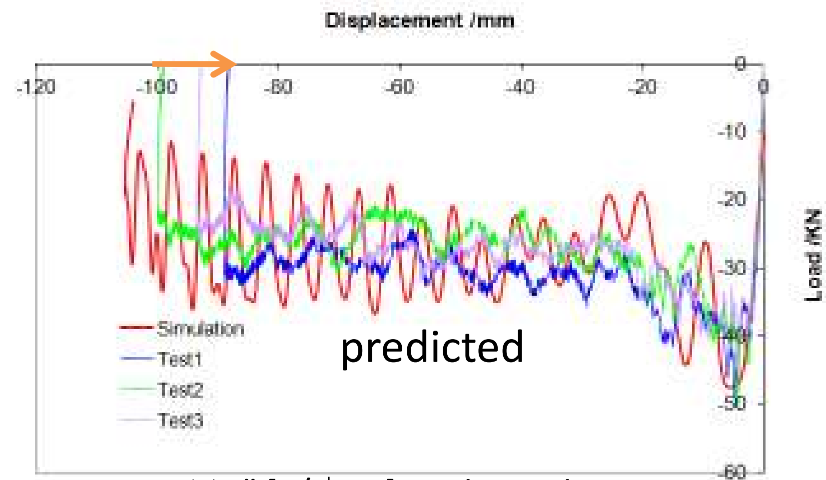
Simulations and Predictions: 2×2” [0/±45] Tubes

ECDM + Shell-beam

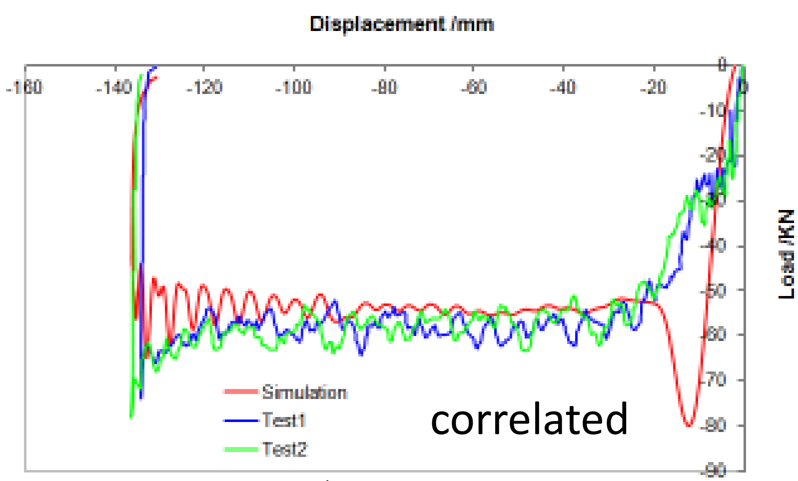
Force-displacement response



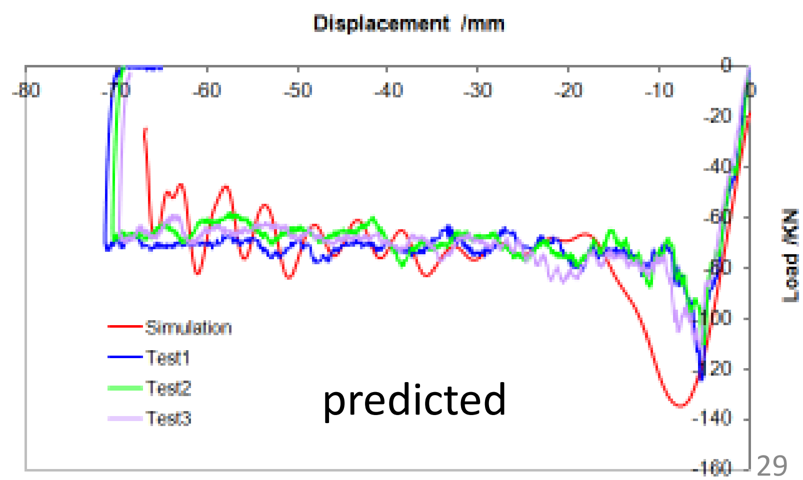
2×2” $[0/\pm45]_2$ with plug



2×2” $[0/\pm45]_2$ without plug



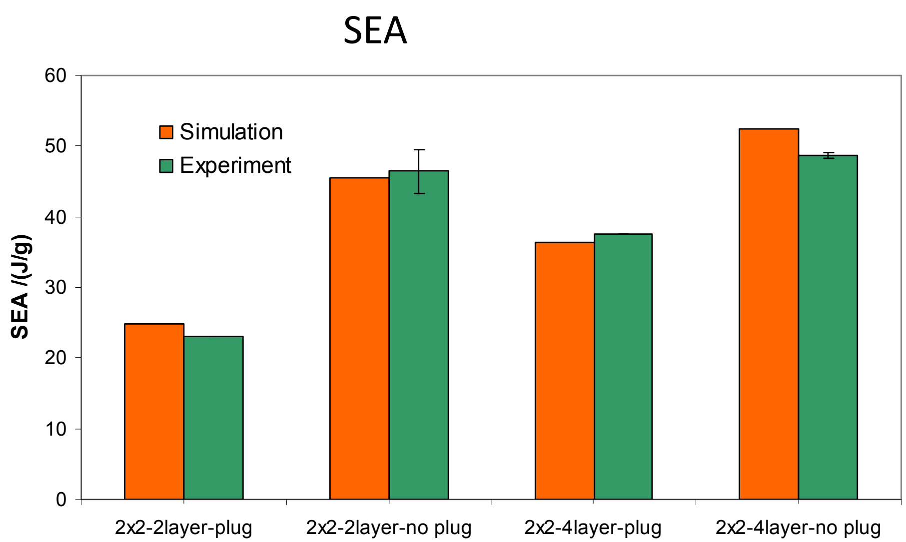
2×2” $[0/\pm45]_4$ with plug

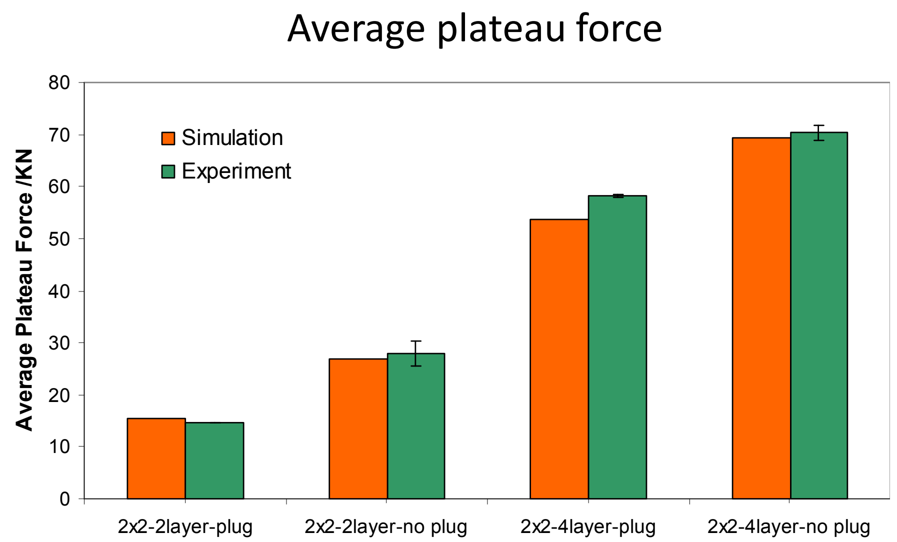


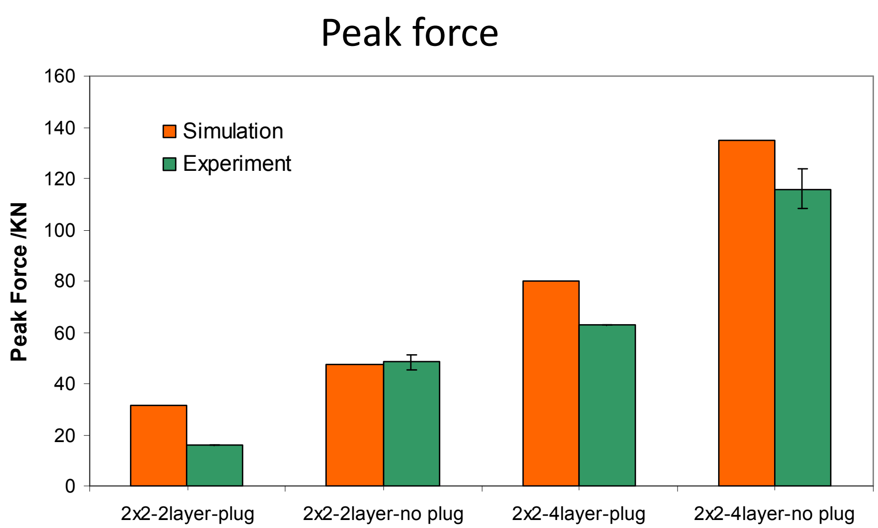
2×2” $[0/\pm45]_4$ without plug

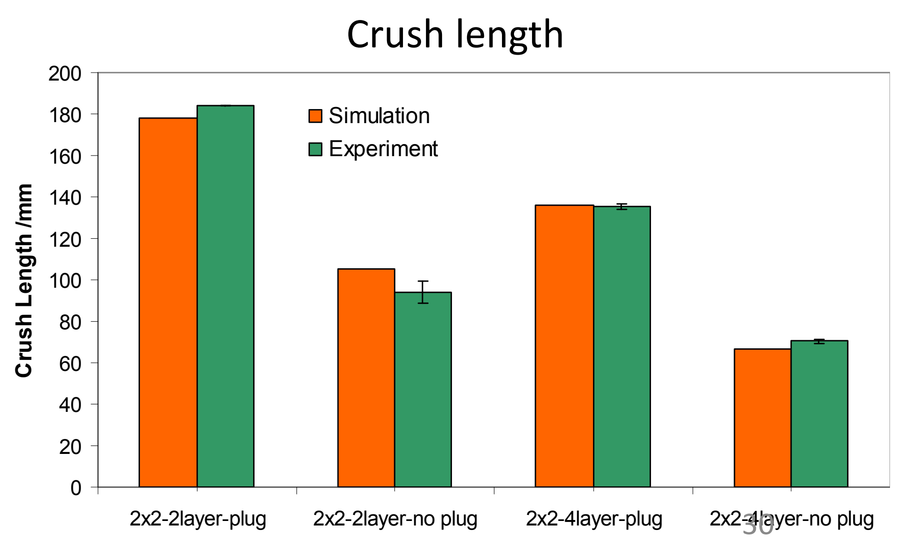
Simulations and Predictions: 2×2" [0/±45] Tubes

ECDM + Shell-beam





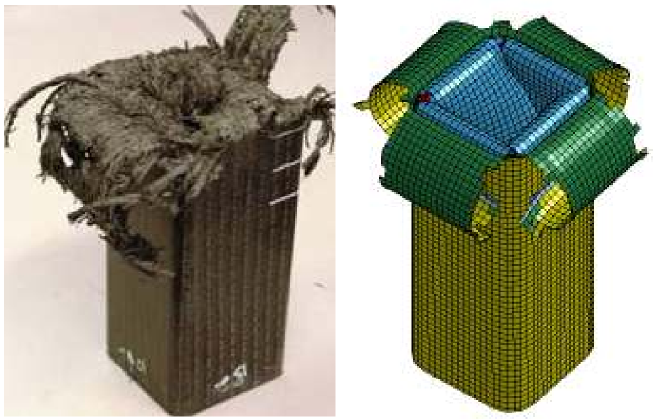




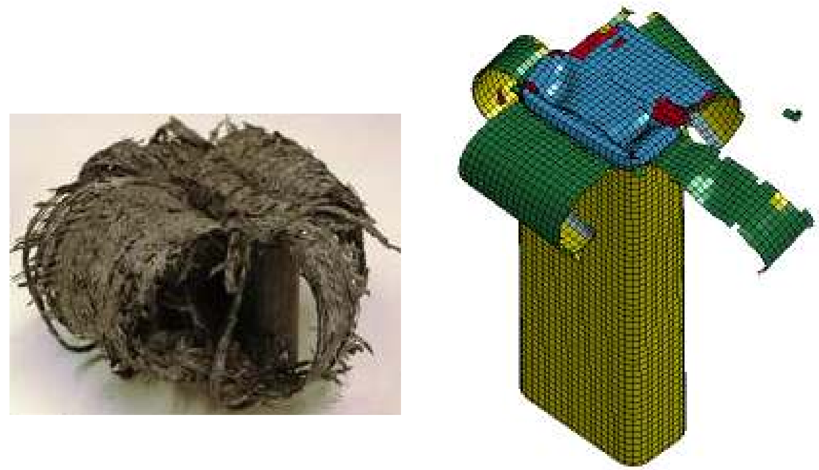
Predictions of Other Tube Geometries

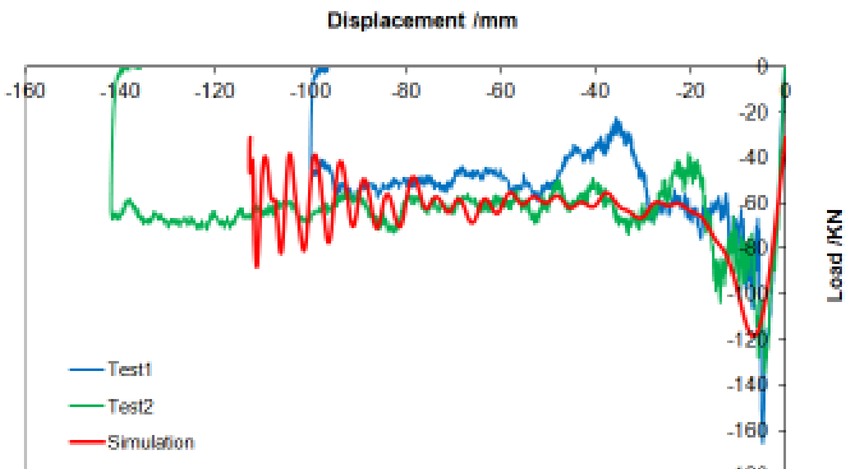
ECDM + Shell-beam

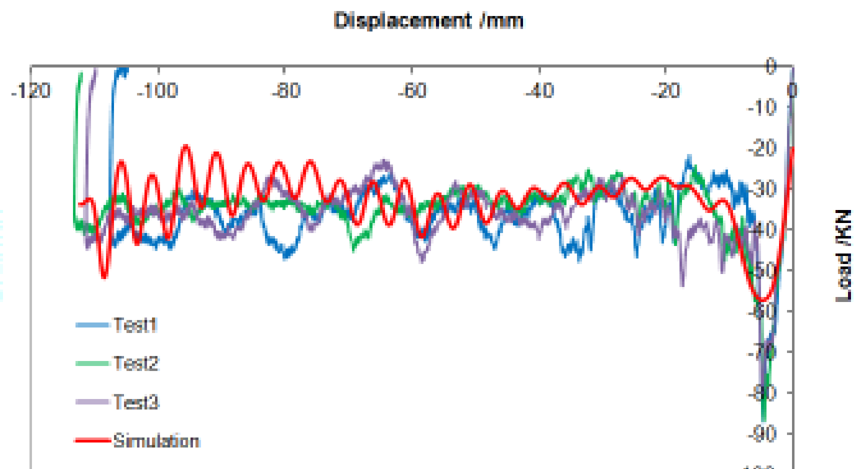
4×4” [0/±45]$_2$



2×4” [0/±45]$_2$

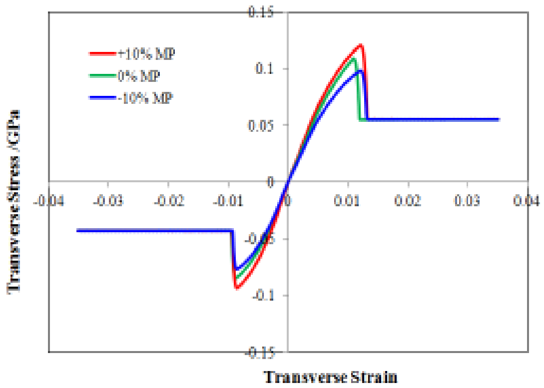


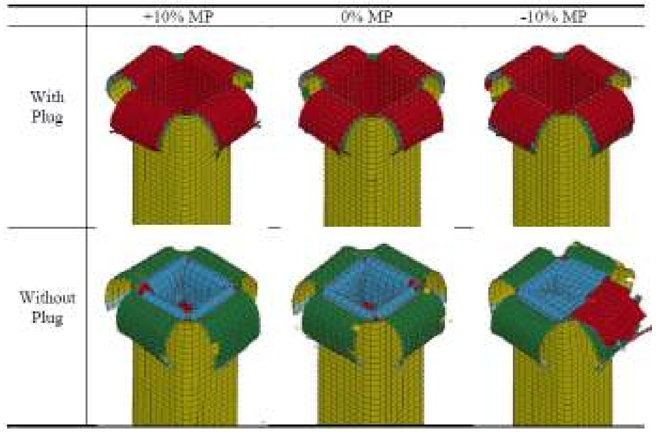


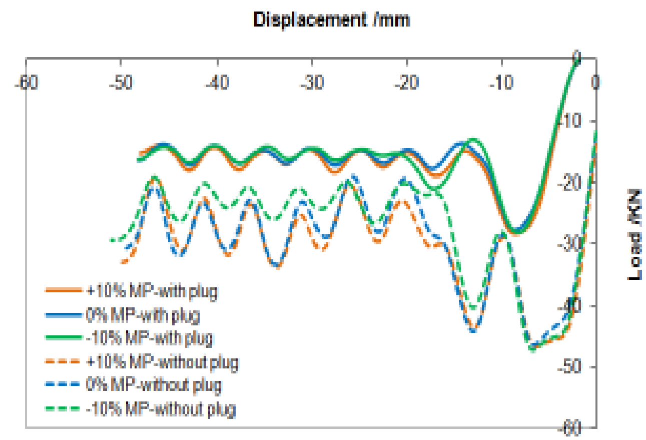


Sensitivity Study

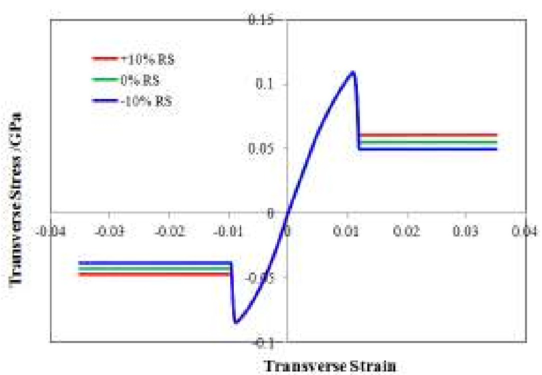
Material properties ±10%

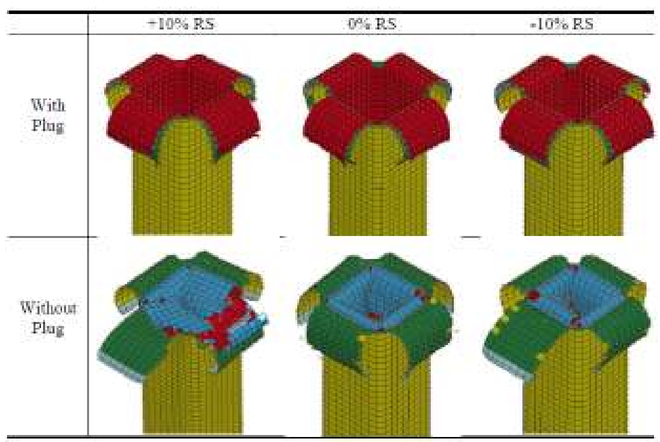


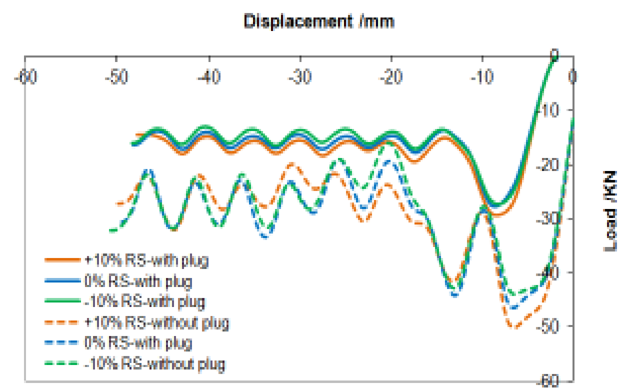




Residual strneghts ±10%







Conclusions and Outlook

Can we predict the crashworthiness performance of composite structures?

- Body panels ✓
- Primary energy absorbing structures
  - Solid progress has been made towards a robust crash model.
  - The stability of the simulations is improved by
    - Composite model with proper post-failure response, particularly the irreversible strain.
    - A shell-beam element method
  - The predicted response and morphology are close to experiment.

Conclusions and Outlook

- Further investigations
  - Examine more load cases: off-axis angles
  - Other composite materials
- Based on a stable framework, further developments
  - Failure criteria
  - Damage laws
  - Damage interaction
  - Experimental methods to characterize damage parameters.
  - Local microstructure
  - Strain rate
- Including meso-, micro-structure effects

Acknowledgement

Danghe Shi

Hamid Kia, John Morley, Mark Botkins, Nancy Johnson (GM)
Richard Jeryan, Ari Caliskan, Omar Faruque (Ford)
Khaled Shahwan (Chrysler)
Srdjan Simunovic, Mike Starbuck (ORNL)
Steve DeTeresa (LLNL)
Reza Vaziri, Carla McGregor, Anoush Poursartip (UBC)
Karl Schweizerhof (Dynamore)
Dilip Bhalsod, Isheng Yih (LSTC)
Jackie Rehkopf (Plasan)

Thank You!