DIN

DEPARTMENT OF INDUSTRIAL ENGINEERING

PhD Course in Mechanics and Advanced Engineering Sciences (DIMSAI)

YEARLY PHD STUDENT REPORT - AY *2016/2017*

Curriculum number *I*
Cycle *XXX*

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Crashworthiness of CFRP: experimental activities and computational methods for the prediction of the absorbed energy

ALMA MATER STUDIORUM ~ UNIVERSITÀ DI BOLOGNA
IL PRESENTE MATERIALE È RISERVATO AL PERSONALE DELL'UNIVERSITÀ DI BOLOGNA E NON PUÒ ESSERE UTILIZZATO AI TERMINI DI LEGGE DA ALTRE PERSONE O PER FINI NON ISTITUZIONALI

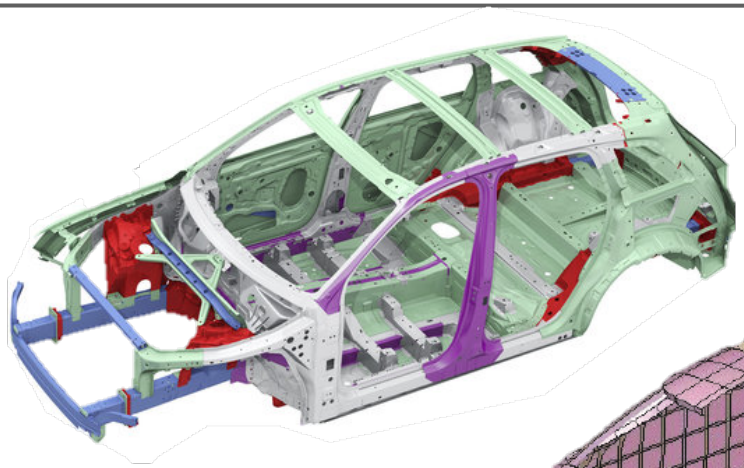
Crashworthy design principles

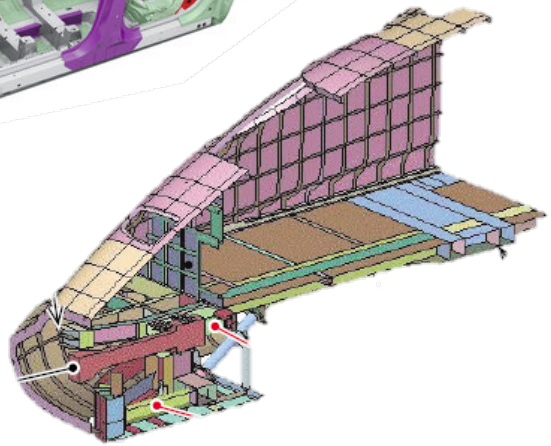
A set of requirements for vehicles (road, rail, air) to guarantee the safety and protection of their occupants.

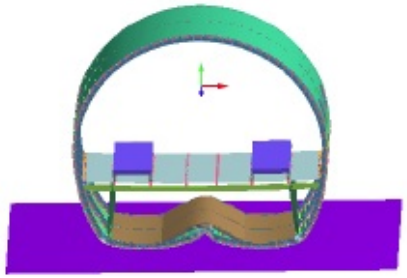
The main goals of crashworty design are:

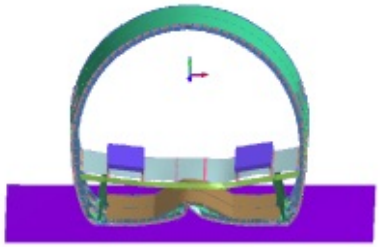
1. Maintain occupant survival space.
2. **Manage collision energy.**
3. Restrain the occupant.
4. Prevent ejection.
5. Prevent fires.

These requirements are met through both active devices (seatbelts, airbags) and passive elements (beams, pillars, anti-intrusion bars)









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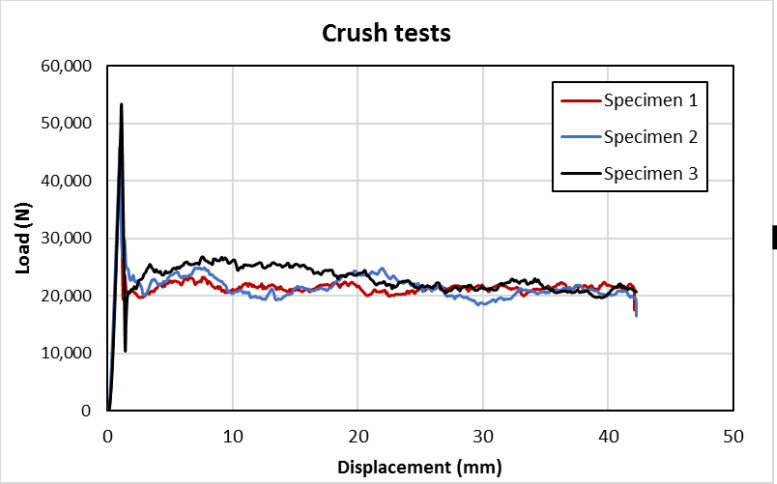
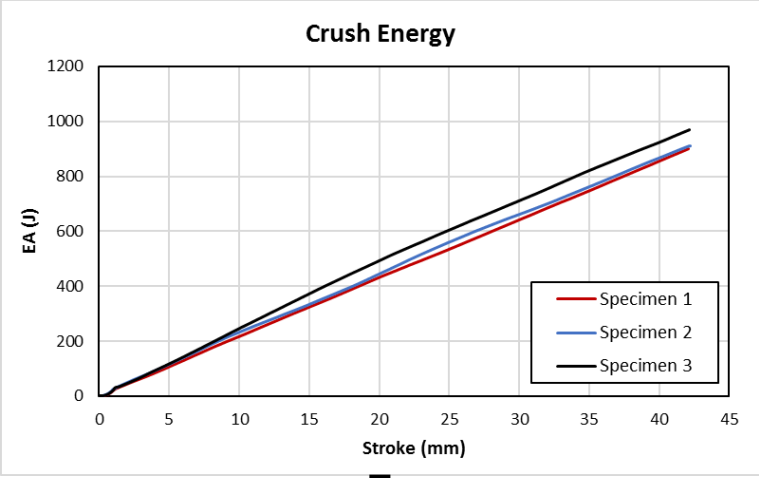
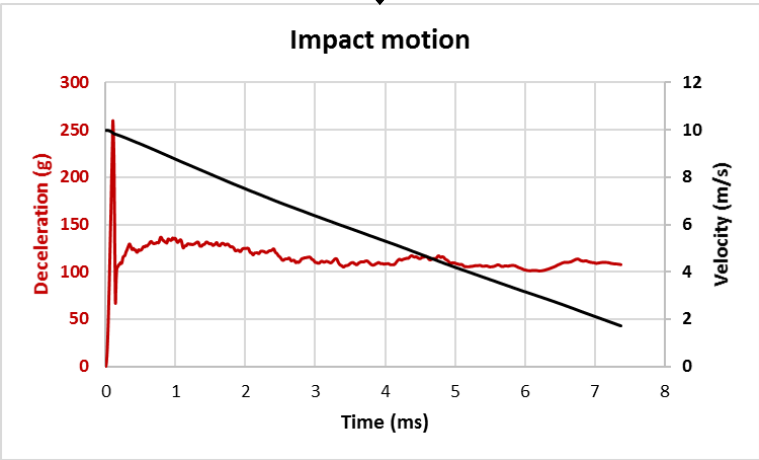
Crashworthy design principles

2. Manage collision energy:







A constant load curve is required for efficient crush, predictable and safe **deceleration** during impact:

$$K_0 - F\,dx = \frac{1}{2} m_v \left(\frac{dx}{dt}\right)^2$$

$$F(x) = const \;\rightarrow \begin{cases} \ddot{x}(t) \approx m_v \\ x(t) = f(m_v, F) \end{cases}$$

(assuming F is rate independent)

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Crashworthy FRP design

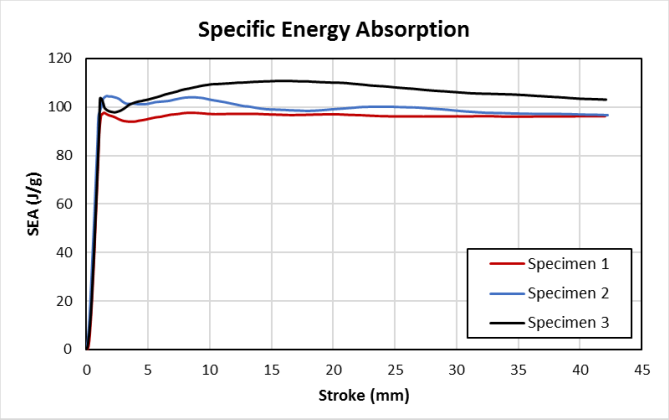
Typical SEA values
Aluminum: <30J/g
CFRP: ~100J/g

$$SEA = \int \frac{F}{m_c} dx = \frac{\int F\, dx}{\rho A * \delta}$$

Material utilization is also higher: crushable length is lower for aluminum tubes (length occupied by folds)

Issues

- Failure modes and collapse mechanisms are complex.
- Energy associated with different failure modes can vary up to an order of magnitude.
- The influence of configuration (geometry, layup, etc.) on failure modes is not yet fully understood.



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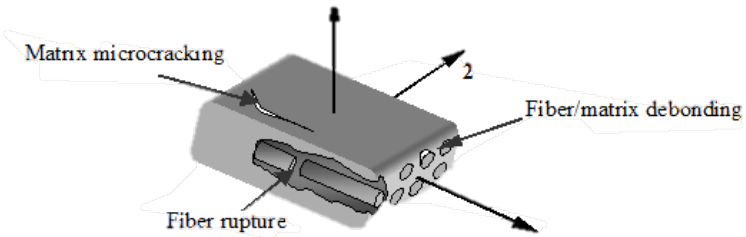
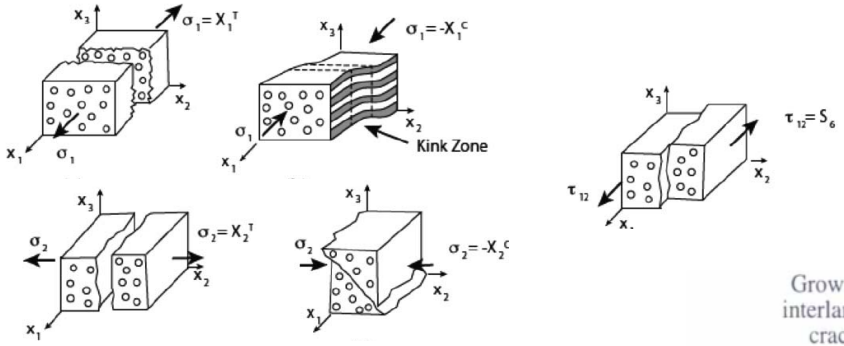
Failure modes and energy

3 Micro-scale failure modes:
- Fiber rupture
- Matrix cracking
- Fiber/matrix debond

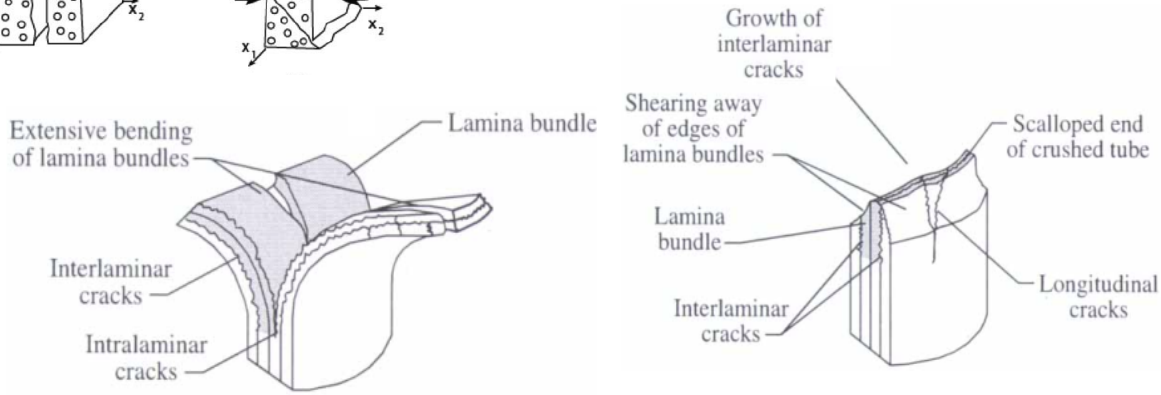


Specific fracture energy:
- High
- Medium
- Low

5 Meso-scale failure modes:
- Fiber tensile
- Fiber compressive (kink)
- Matrix compressive
- Matrix tensile
- Matrix shear (3 directions)



2 Macro-scale failure modes:
- Fragmentation
- Buckling
- Splaying



Micro-scale failure is not a viable modeling approach for engineering numerical problems. **Need simplified criteria!**

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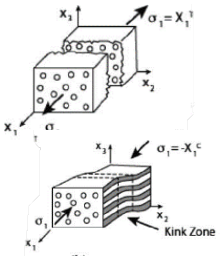
Ladevèze CDM in Pam-Crash

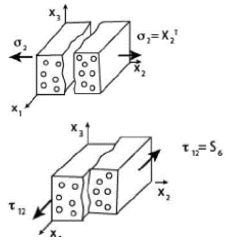
5 distinct modes of damage:

- Tensile fiber rupture
- Compressive fiber rupture/kinking
- Matrix transverse cracking
- Ply shear (~fiber/matrix debonding)
- Shear plasticity

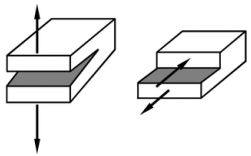
+ Delamination (opening and shearing)



Based on **limit strains** with linear stress reduction between two threshold values.



Based on **strain energy**, **exponential** laws for $f(d_i)$. Shear plasticity is allowed.



Standard CZM with mixed mode interaction.

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BBA test Campaign

Base Lamina Properties (Level zero): E_{11t}, E_{11c}, E_{22}, v_{12}, G_{12}.
tensile and compressive tests in fiber $[0]_x$ and matrix $[90]_y$ direction, in-plane shear tensile $[+/-45]_{2ns}$

First level BBA: strength and damage model:

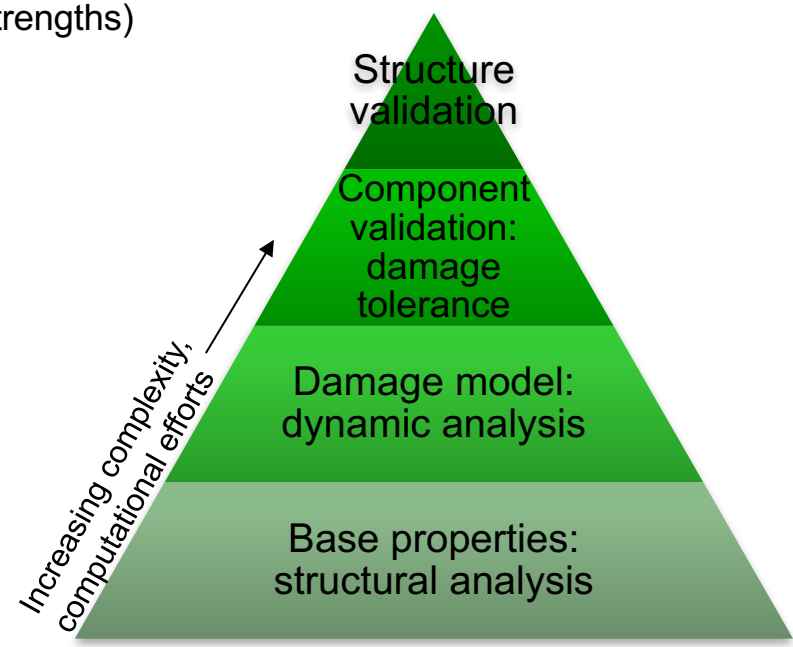
- Full stress-strain curves of the tests described above (ultimate strengths)
- Cyclic tensile shear $[+/-45]_{2ns}$ (for plasticity and shear damage)
  - Optional: cyclic tensile on $[+/-62.5]_{2ns}$
- DCB and ENF cohesive delamination model

Second level BBA: advanced calibration

- Tension and compression on selected layups
- Compact tension, Compact compression (fracture energies)
- Open hole tension and compression on selected layups
- Drop weight impact
- Joint and bearing loading

Third level BBA:

- Component and small structure validation



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Level Zero: base lamina properties

Prepreg studied:

150gsm Supplier's prepreg

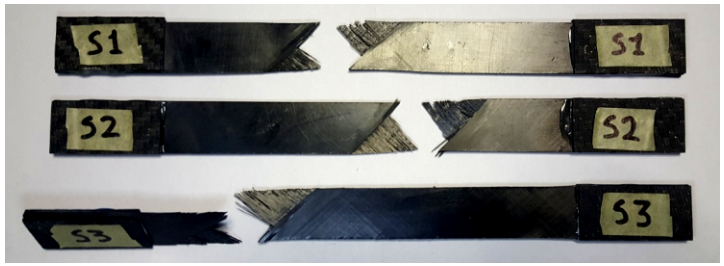
High toughness epoxy resin

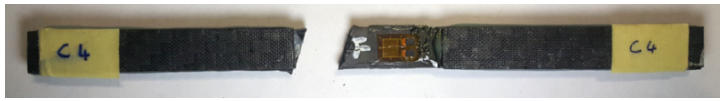
Basic lamina tests:

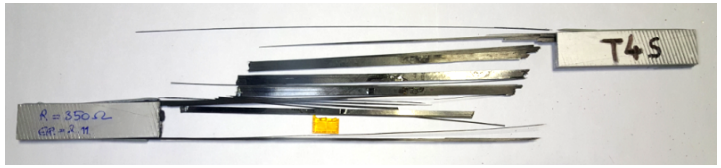
Tensile ASTM D3039 on $[0]_8$ and $[90]_{20}$

Compressive ASTM D3410 on $[0]_{20}$ and $[90]_{20}$

Tensile Shear $[+45/-45]_{4s}$







Prop.	Value (GPa)
E_{11t}	
E_{11c}	
v_{12} (-)	
E_{22}	
G_{12}	
F_{11t}	
F_{11c}	
F_{22t}	
F_{22c}	
F_{12}* (0.2%)	

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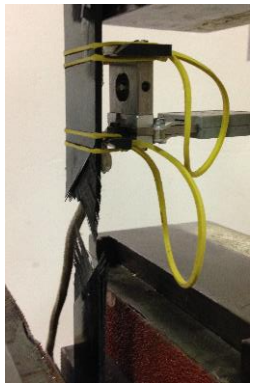
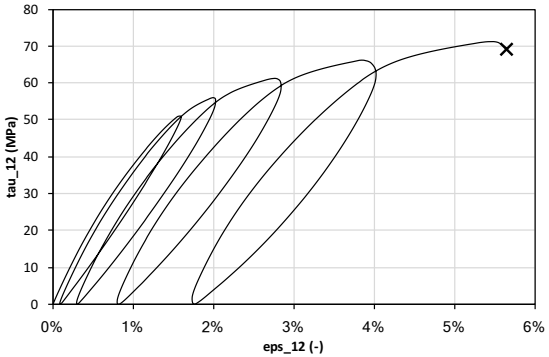
First Level BBA: damage model

Cyclic tensile shear
Used to calculate ply shear damage and shear plasticity, requires 4-5 cycles at increasing load until failure.

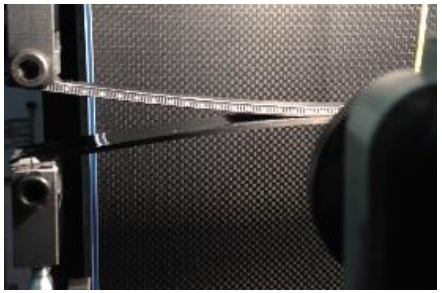


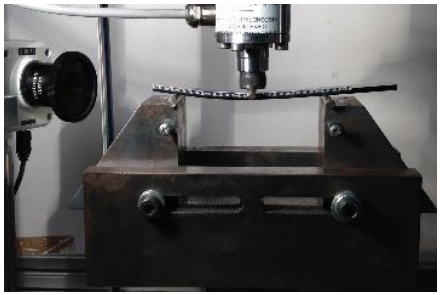


Prop.	Value
Sigma_0.2%	
Sigma_5%	
Eps. at break	

DCB test ASTM D5528, $[0]_{12}$ layup.

ENF test ASTM D7905, $[0]_{12}$ layup.





Compliance Calibration method

Prop.	Value (J/m^2)
G_{IC}	
G_{IIC}	

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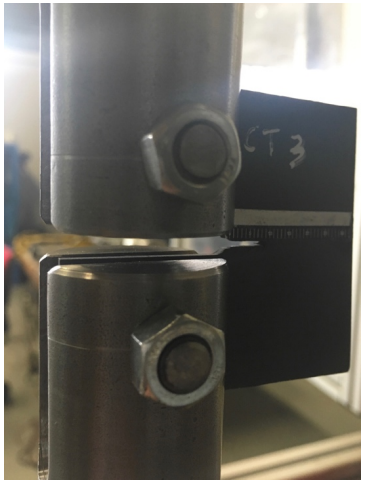
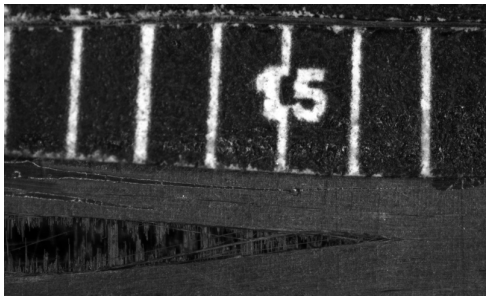
Higher Level BBA

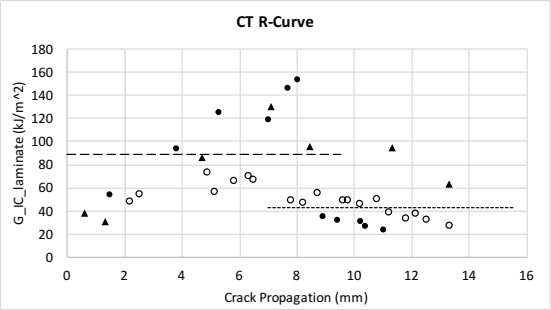
Compact Tension on $[90/0]_{4s}$

Compact Compression on $[90/0]_{4s}$

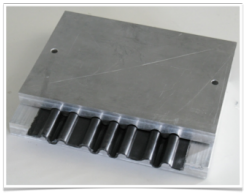


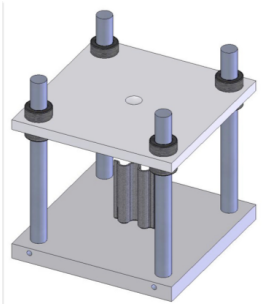


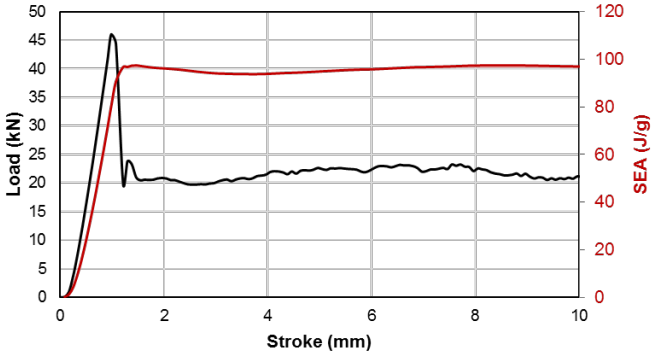
$$G_{Ic} = \frac{P_c^{\,2}}{2t}\frac{dC}{da}$$



CMH-17 CWG Corrugated Specimen
$[0/90]_{3s}$ Layup, quasi static loading.







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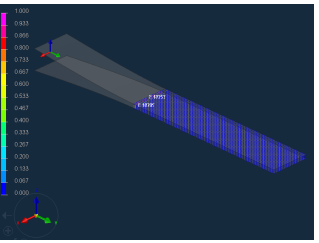
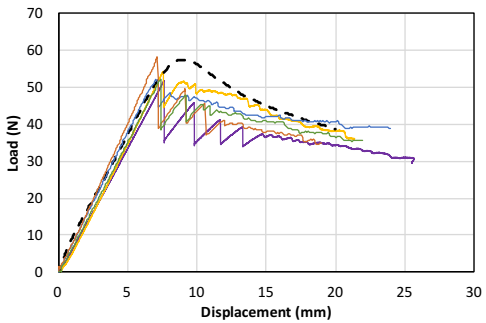
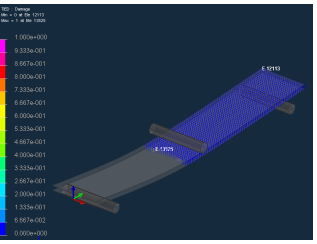
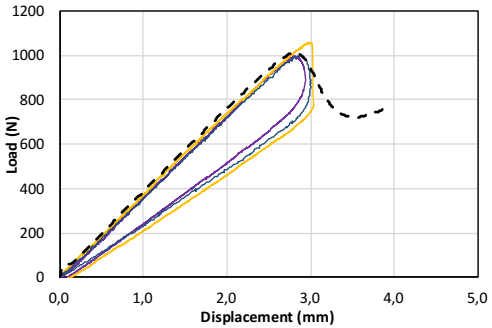
Interface damage (CZM)





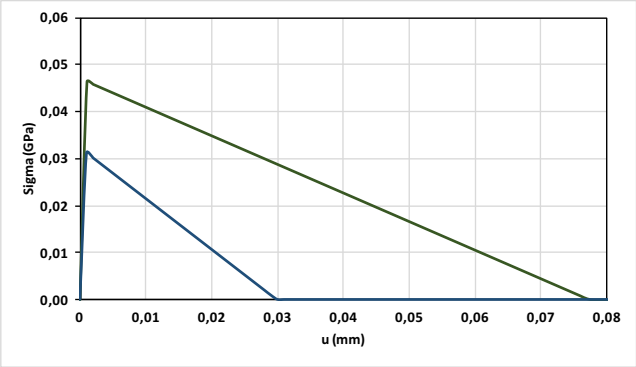
$$\sigma_{33} = k_3(1 - d_3)u_3, \qquad d_3 = \frac{u_{3m}(u_3 - u_{30})}{u_3(u_{3m} - u_{30})}$$





3 input needed:

- Fracture energy → experimental tests
- Elastic constant → lamina data
- Maximum stress → ~10 el. cohesive zone (Davila)



Prop.	Value
G_{IC}	
G_{IIC}	
Sigma_st	
E0	
Gamma_st	
G0	
Ply thick.	

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Matrix damage

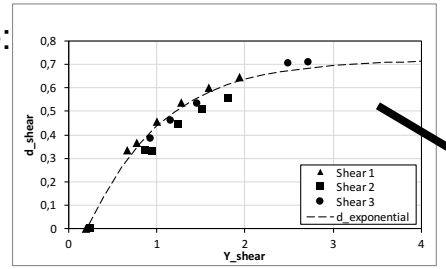
Shear damage

Obtained from plot of strain energy Y vs damage:

$$Y = \sqrt{\frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})^2}}, \quad d_{12} = 1 - \frac{G_{12}^i}{G_{12}^0}.$$

The curve is best fit with an exponential law:

$$d_{12} = d_{sat}\left(1 - e^{\frac{Y_0 - Y(t)}{Y_c}}\right)$$

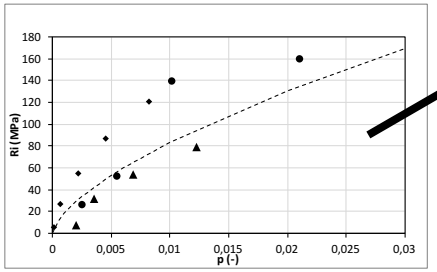


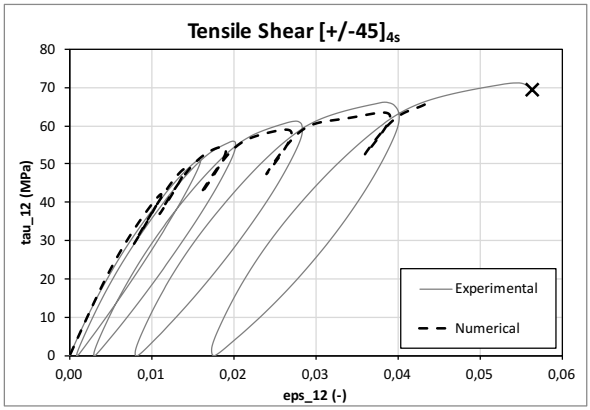
Shear Plasticity

Obtained plotting plastic stress versus residual strain.

The plasticity curve follows a power law.

$$R_i = \beta * {\varepsilon_p}^m$$





Transverse damage

Same form of shear damage, no plasticity allowed.

Assumptions made.

(alt. cyclic tension on $[\pm 62.5°]_{4s}$)

Prop.	Value
Y_{0s}	
Y_{Cs}	
d_{sat_s}	
R_i	
beta	
m	

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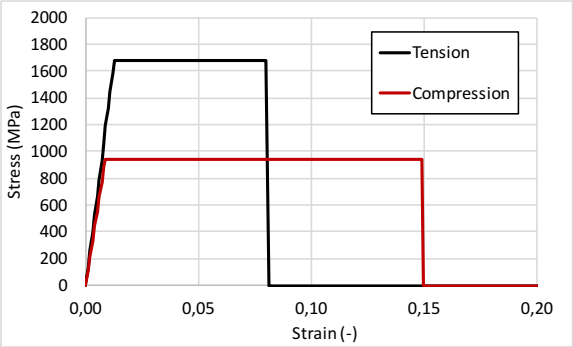
Fiber Damage

$$E_1 = E_1{}^0(1-d)$$

Where:

$$d = d_{ft}\,\frac{\varepsilon_{11}-\varepsilon_i{}^f}{\varepsilon_u{}^f-\varepsilon_i{}^f} \qquad \text{if} \qquad \varepsilon_i{}^f \le \varepsilon_{11} < \varepsilon_u{}^f$$

$$d = 1-(1-d_{ft})\frac{\varepsilon_u{}^f}{\varepsilon_{11}} \qquad \text{if} \qquad \varepsilon_u{}^f \le \varepsilon_{11} < \infty$$



Prop.	Value
eps_{it}	
eps_{ut}	
d_{ft}	
eps_{elim_t}	
eps_{ic}	
eps_{uc}	
d_{fc}	
eps_{elim_c}	

Issues

- Brittle failure of $[0]_n$ tests can only identify onset of damage
- positive tangent modulus impose flat stress curve: damage law is superseded by failure criterion (el. elimination).
- Useful inputs from CT, CC tests.
- mesh sensitivity!

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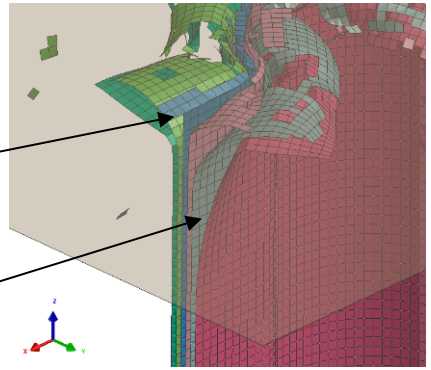
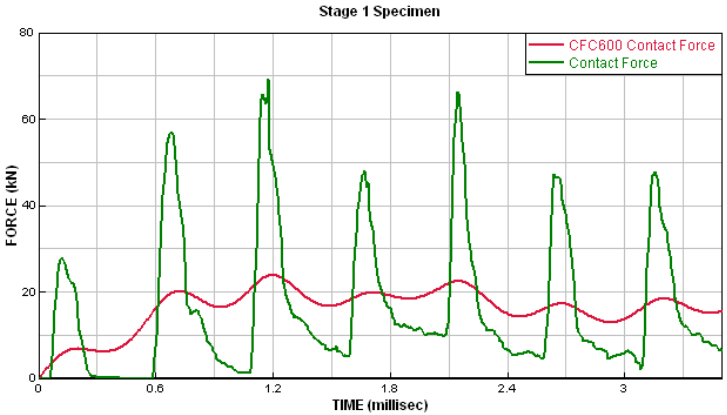
Simulation of crushing specimen

Shape of failure is correctly identified

Compressive failure of internal plies

Bending of external plies with extended delaminated length.





Issues

- No softening leads to oscillating load (CFC600)
- Mesh dependence
- Load is underestimated: High friction of internal debris wedge vs. element elimination

- Calibration increasing energies to failure until good correlation is found.

- Introduction of a fictitious element to simulate the debris (David, Johnson, DLR)
  - Only for specimen level.
  - How to solve bearing joints?

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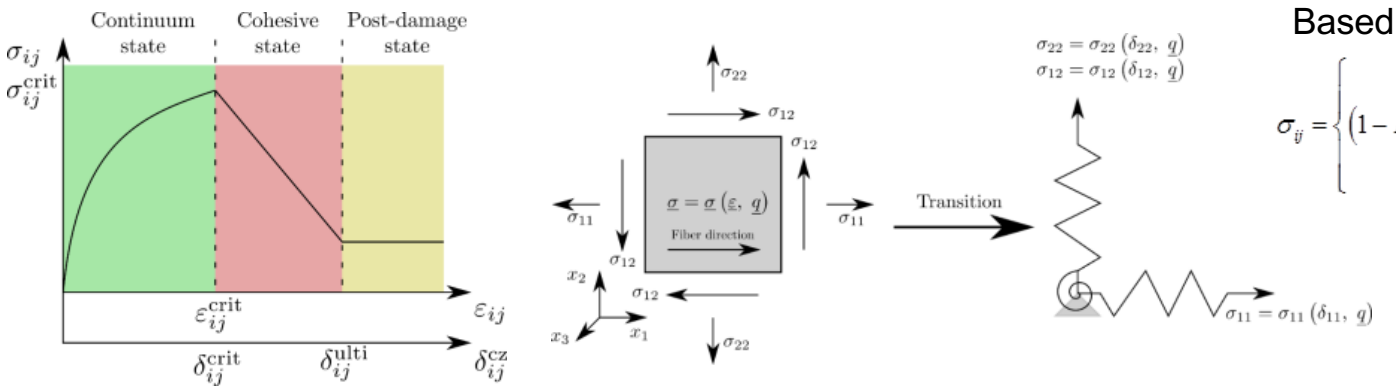
New damage model in Pam Crash 2017



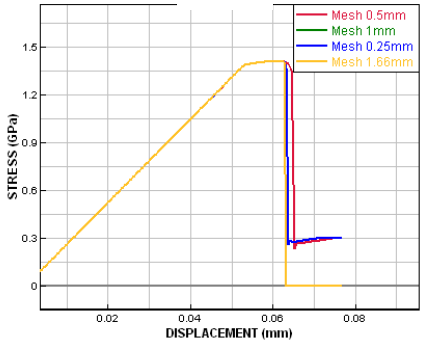
Based on A. Waas, E. Pineda, 2013

$$\sigma_{ij} = \begin{cases} K_{ij}\delta_{ij} & , \quad \delta_{ij} < \delta_{ij}^{0} \\ (1 - D_j) K_{ij}\delta_{ij} & , \quad \delta_{ij}^{0} \le \delta_{ij} < \delta_{ij}^{fail}, \; D_j < D_{max} \\ \sigma_{ij}^{res} & , \quad else \end{cases}$$

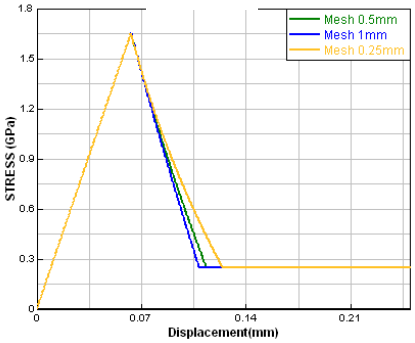
$$D_1 = \frac{\delta_{11}^{f}\left(\delta_{11} - \delta_{11}^{0}\right)}{\delta_{11}\left(\delta_{11}^{f} - \delta_{11}^{0}\right)}$$

- Quadratic stress or strain initiation rule.
- Inclusion of the characteristic mesh size for reduced mesh dependence.
- Cohesive-like behavior with direct definition of fracture toughness:
  - Fiber Tensile and compressive (CT, CC)
  - Matrix tensile and compressive (DCB, ENF)
  - Matrix Shear (ENF)

Old



New



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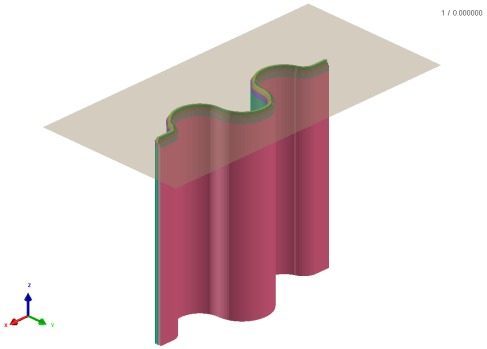
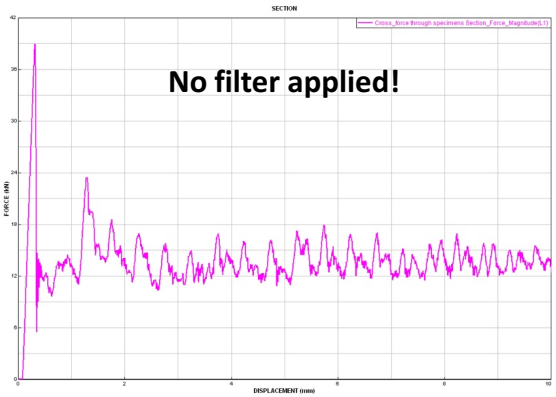
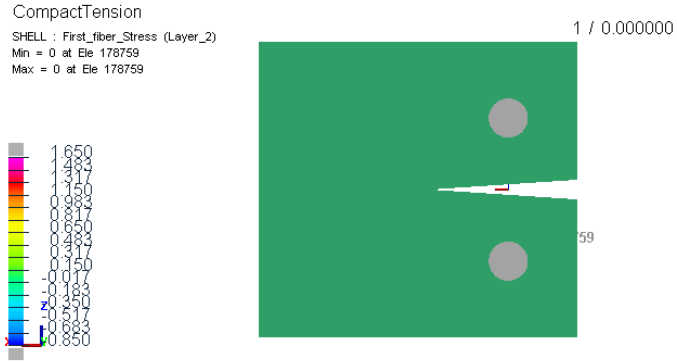
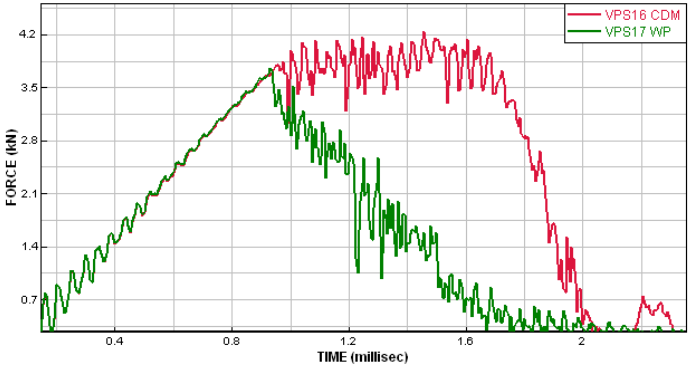
Updated simulations







Old vs. New



- Cohesive softening eliminates oscillating load issue
- Reduced mesh dependency makes setup straightforward
- Input experimental fracture energies capture SEA better, though:
- Calibration still necessary
    - Improved testing methods on fracture toughness required

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