# ICAF 2023 – the 38th Conference and 31st Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity

ICAF

## Delft, NL

# Meso-scale Models for the Interaction of Damage Modes in Composite Laminates


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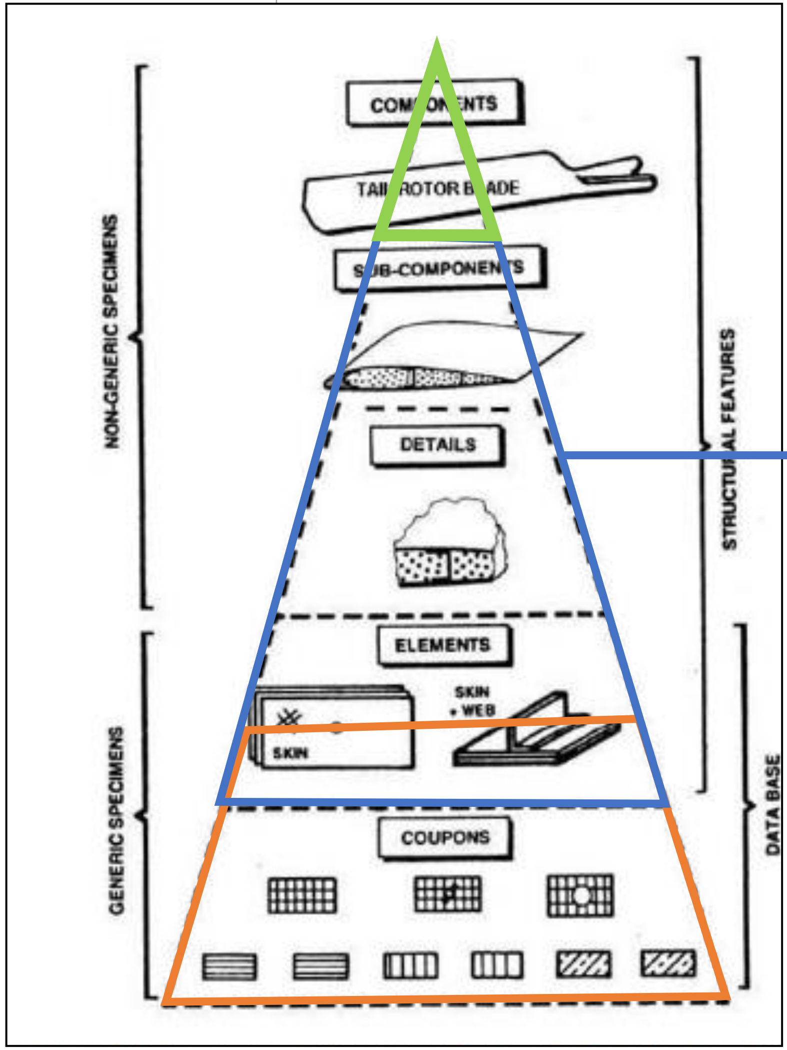
*Background*




- Digitalization of the development process of composites aerostructures & integration in BB approach
- Typical issues at elemet/details level should include complex non-linear response (non-linearity, transverse cracking, delaminations, microbuckling, fibre tensile failures)

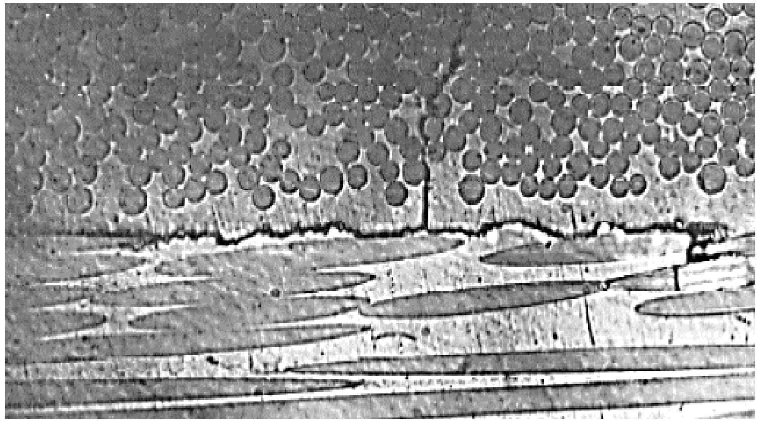
In the last decades high fidelity models developed with Continuum Damage Mechanics, Cohesive Zone Models. X-Fem

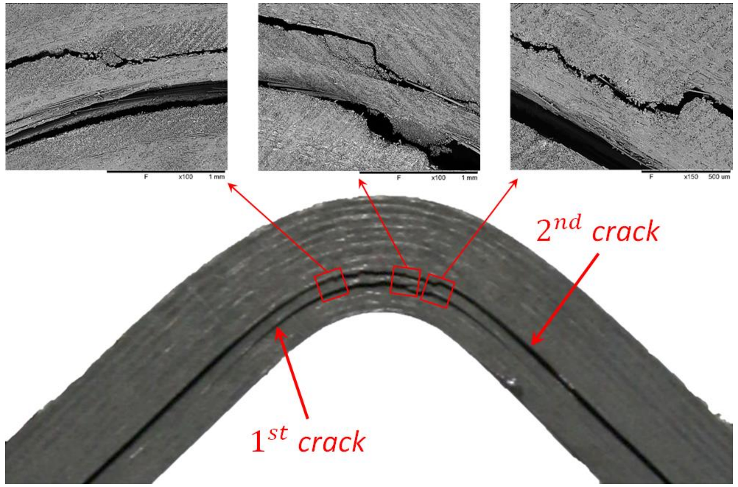
- Still some aspects needs to be properly addressed, as:
  - Fatigue growth of defects
  - **Interaction of damage modes (intra-interlaminar damages)**

*Which scale of modelling to be used for reliable predictions ?*

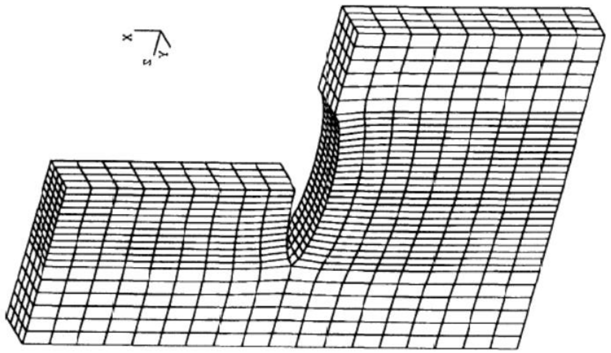
# 1 Modeling approach

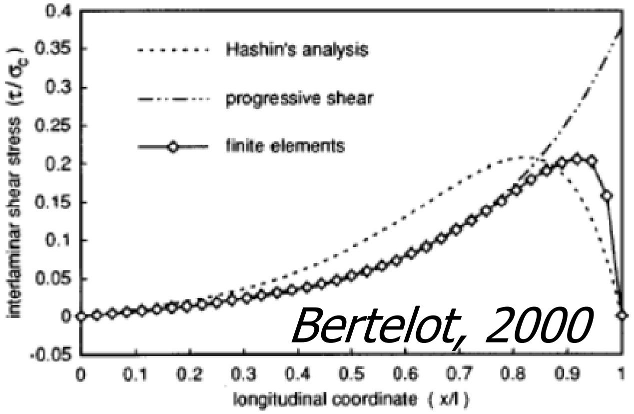
*Interaction between inter and intralaminar damages*






- Transverse matrix cracking and delamination have mutual influences and interactions
- A reliable representation of the states of stress related to such effects would require modelled developed at the sub-ply level






- Alternatives at the **meso-scale level**

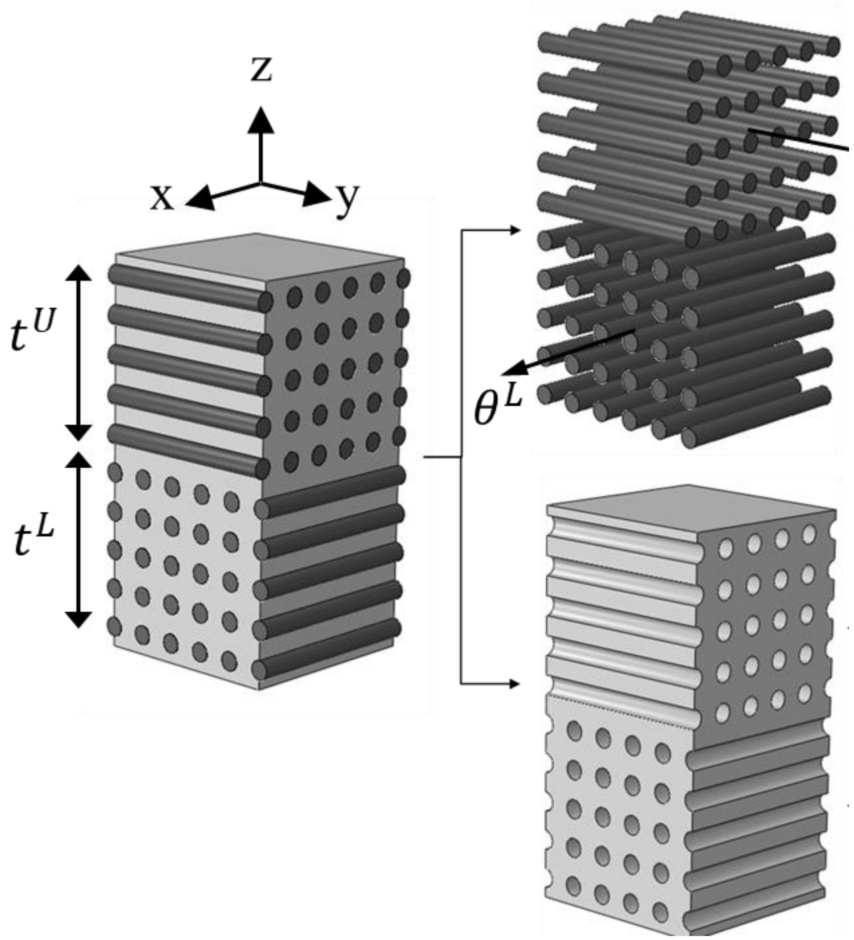
  - non-local models

  **- representation of intra and interlaminar damage within a single constitutive law**

# 1 Modeling approach

## *Bi-phasic decomposition and hybrid modelling technique*

*Identification of an idealized matrix phase with matrix cracking and delamination*



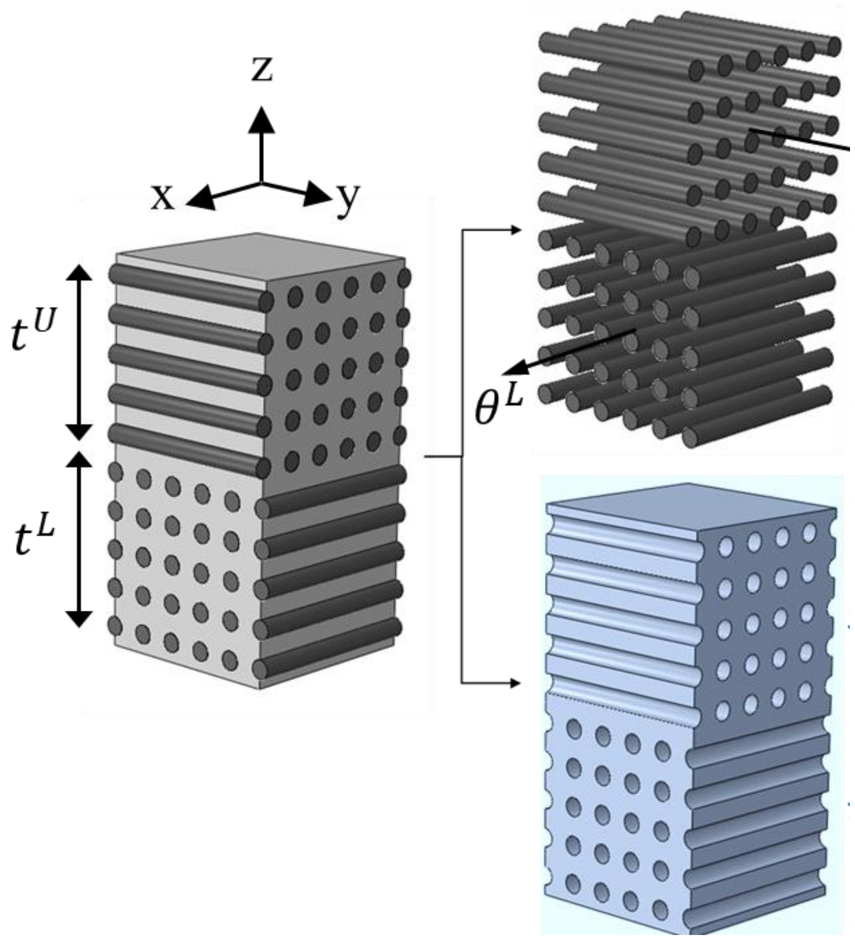

- Modelling technique used @DAER for several years
  - Computational advantages
  - Effective for modelling intra-interlaminar interaction

- **First Step**: **Decomposition** of material into idealized fibre and matrix phases

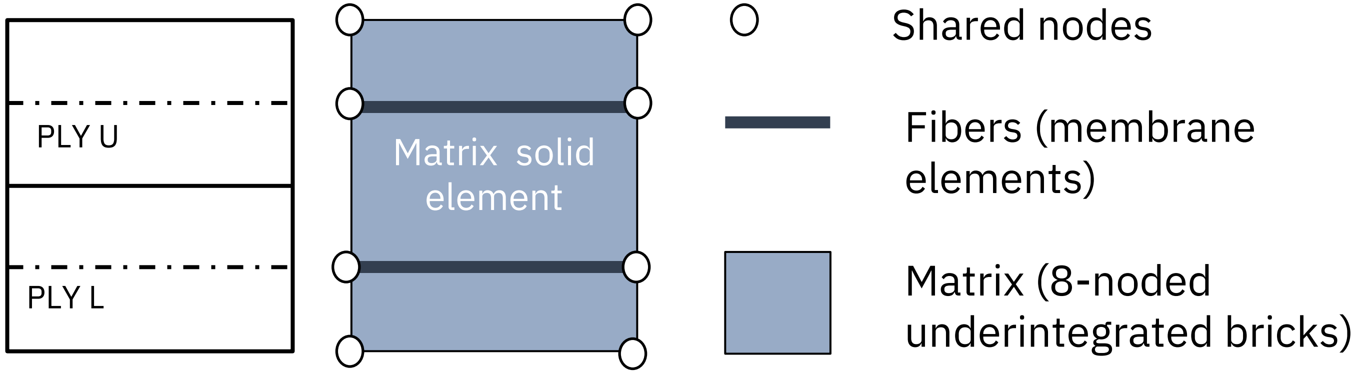
$$
\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{Bmatrix}
=
\begin{bmatrix}
E^{f-eff}V^f & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
+
\begin{bmatrix}
D_{11}^m & D_{12}^m & D_{13}^m & 0 & 0 & 0 \\
D_{21}^m & D_{22}^m & D_{23}^m & 0 & 0 & 0 \\
D_{31}^m & D_{32}^m & D_{33}^m & 0 & 0 & 0 \\
0 & 0 & 0 & D_{44}^m & 0 & 0 \\
0 & 0 & 0 & 0 & D_{55}^m & 0 \\
0 & 0 & 0 & 0 & 0 & D_{66}^m
\end{bmatrix}
\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{Bmatrix}
$$

# 1 Modeling approach

## *Bi-phasic decomposition and hybrid modelling technique*

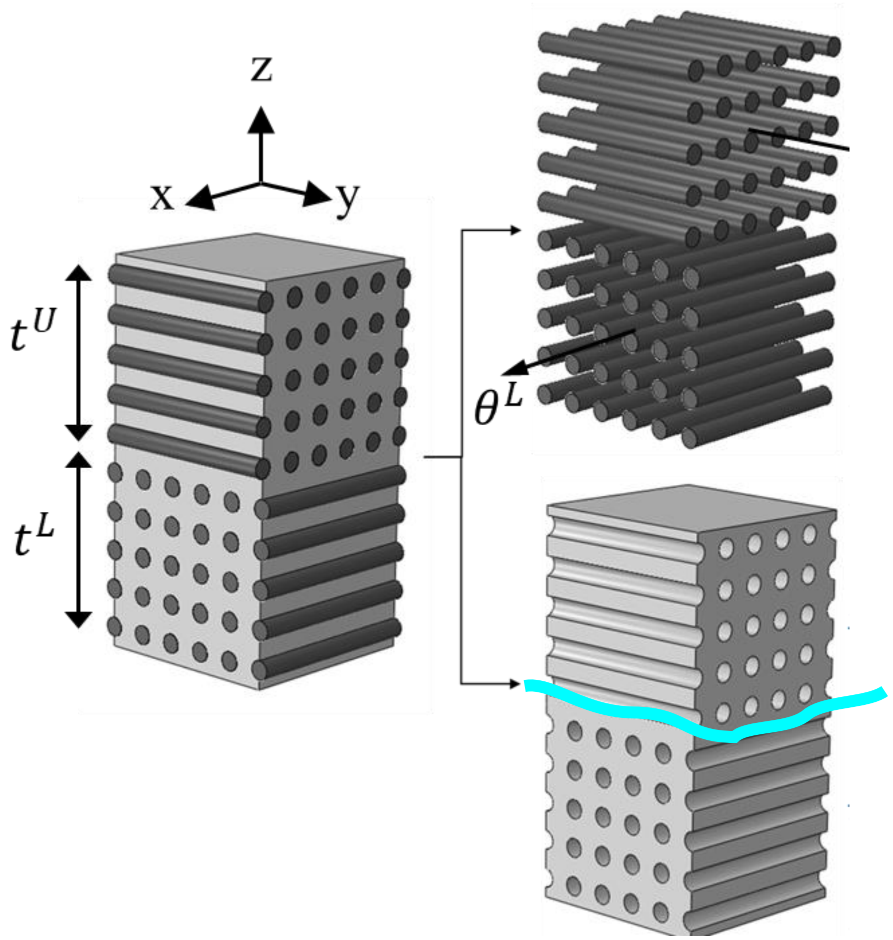



- **Second Step** : Modelling of fiber phase with membrane elements and matrix phase with solid elements sharing the same nodes



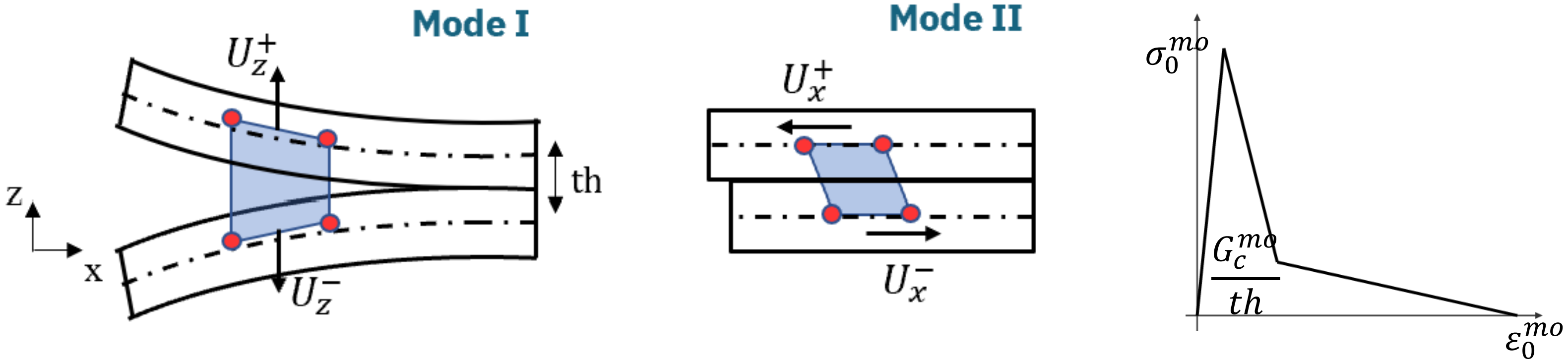
# 1 Modeling approach

## *Bi-phasic decomposition and hybrid modelling technique*




- **Third step**: Material characterization
  - Fiber Material Elastic Brittle
  - Cohesive Zone Models embedded in the matrix element for:

**modelling of delamination**

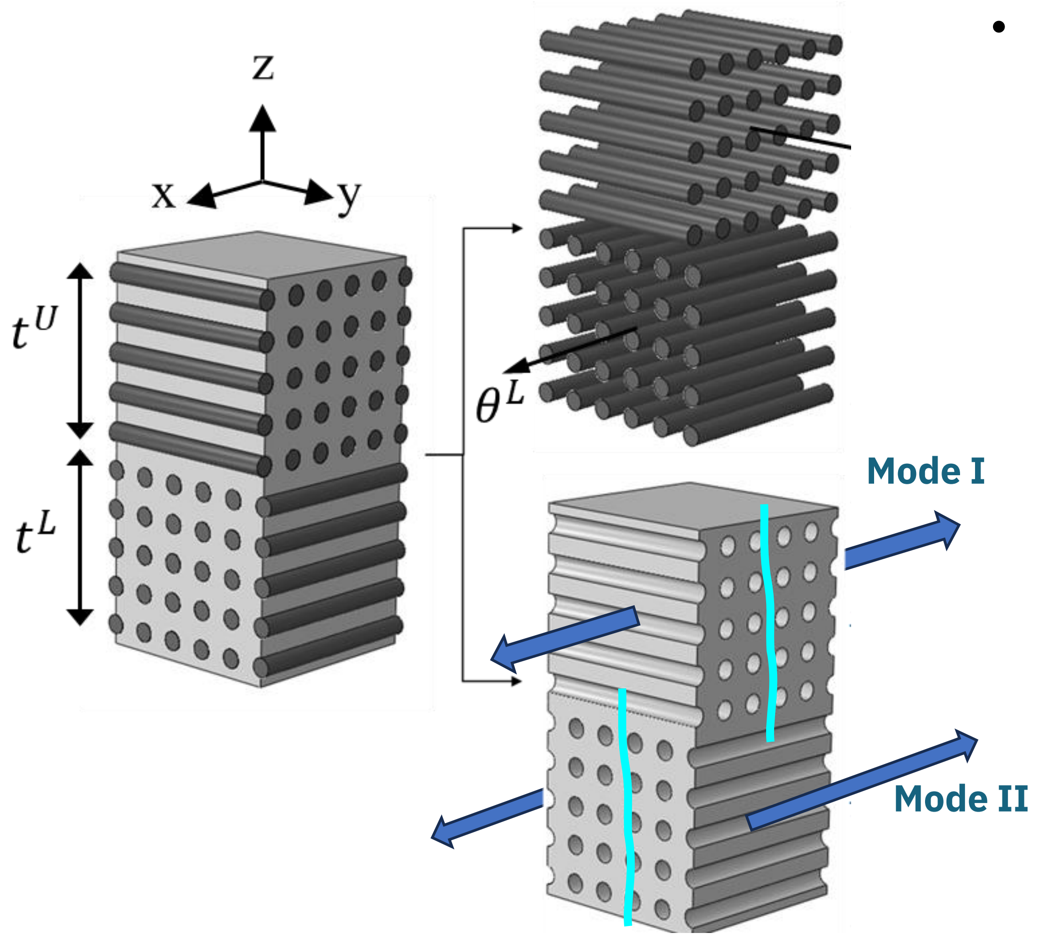



*Controlling the energy required to separate the mid-plane of the plies modelled with the membrane elements*

1

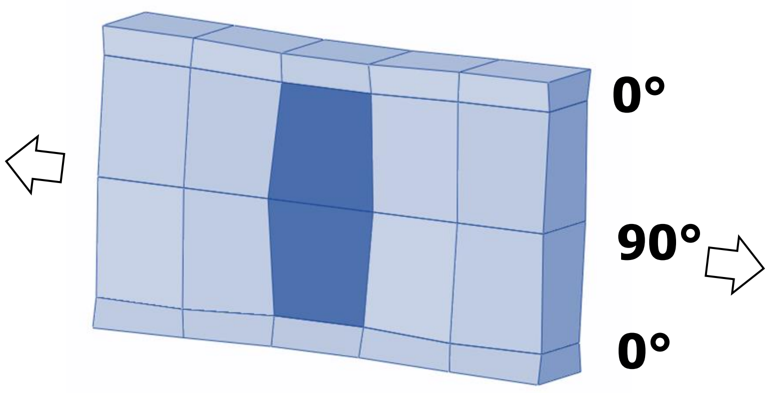
# Modeling approach

## *Bi-phasic decomposition and hybrid modelling technique*




- **Third step**: Material characterization
  - Fiber Material Elastic Brittle
  - Cohesive Zone Models embedded in the matrix element for:

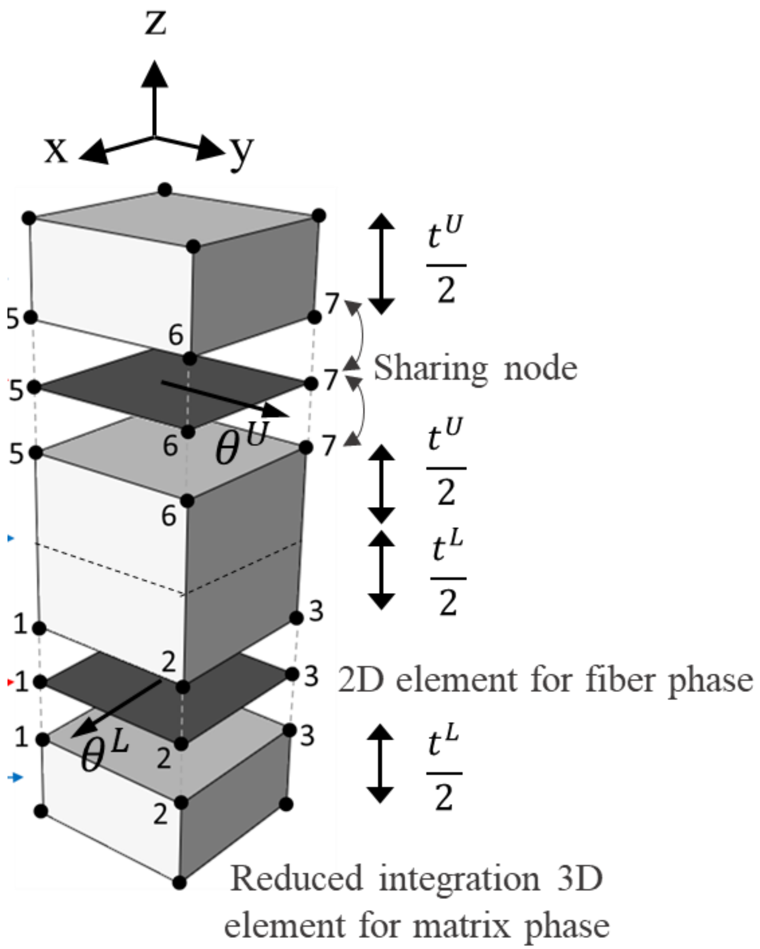
**and modelling of matrix cracking with smeared crack technique**




*All within the same matrix element*

# 1 Modeling approach

## *Advantages*




Unconventional technique, thoroughly validated with comparison with refence models and experiments

It requires decomposition and special meshing approach, but

Cohesive zone models are spread into "matrix" solid elements

No need of zero-thickness cohesive elements "everywhere"

No need of penalty stiffness

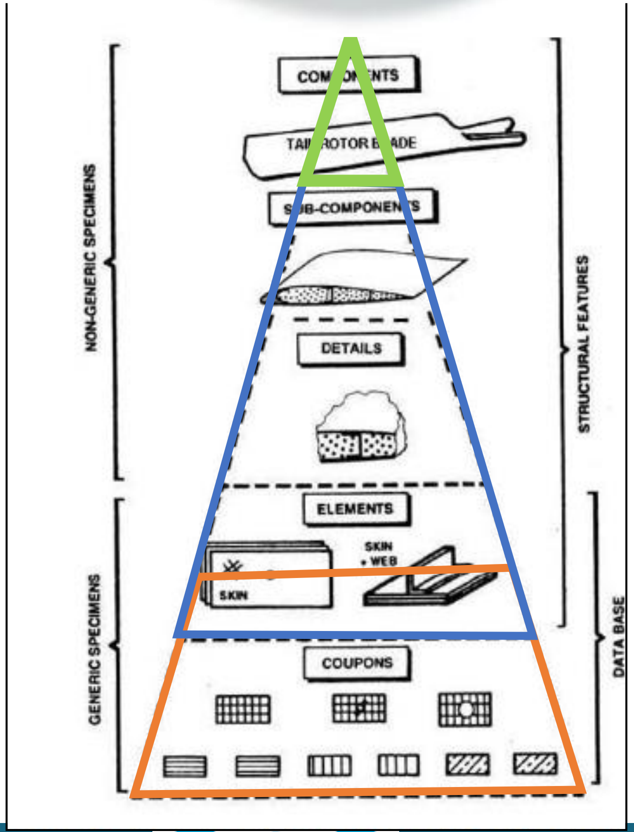
High computational efficiency in explicit simulations

+

**Favorable standpoint for modellign the interaction between intra and interlaminar damage with a meso-scale model developed with conventional elements**

# 1 Modeling approach

*Representative of phenomena occurring in helicopter structures*




**Helicopter composite structures** are characterized by different types of structural details including:

- Typical stressed-skin constructions
- Thick laminates with 3D stress states
- Tapered and curved laminates subjected to critical load conditions

**High fidelity models at the elements/detail levels**

modelling intralaminar damage events, delaminations and mutual interactions

**Transverse cracking and delamination in curved laminates represent basic benchmarks for the modelling approach**

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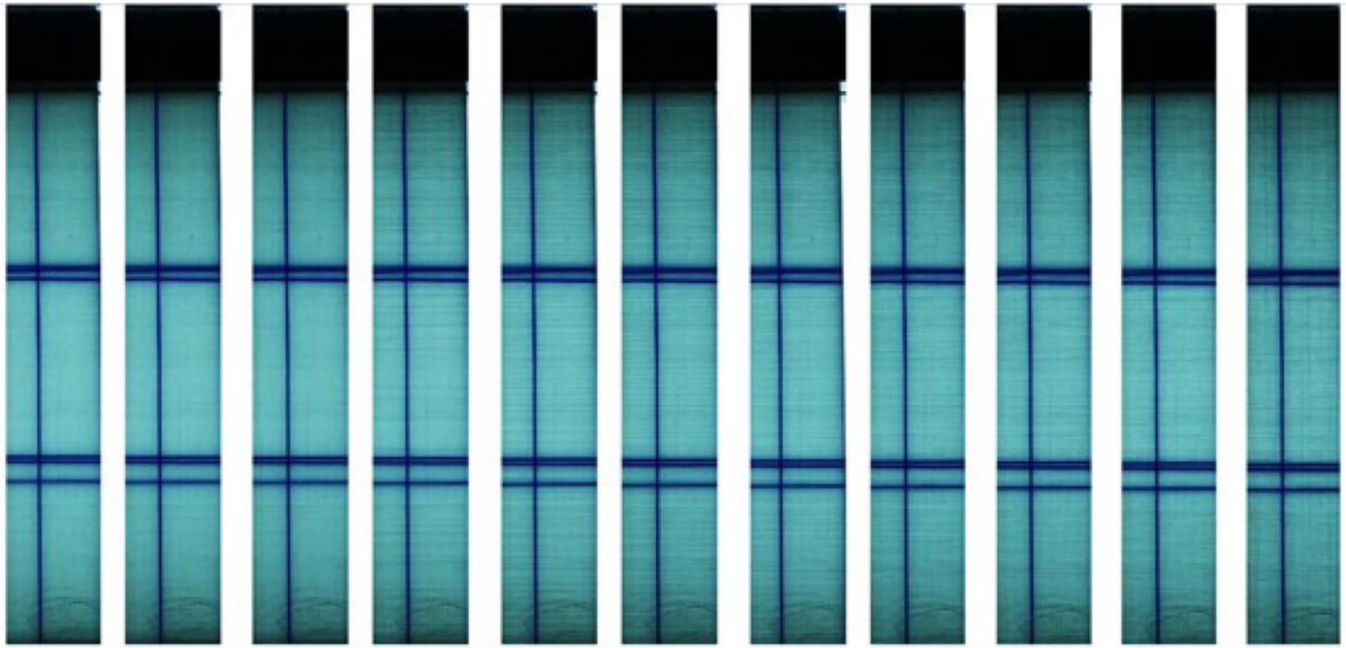
# Application: Transverse Cracking

## *Experiments with glass-reinforced specimens*


Tests performed on cross-ply **[0/90$_3$/0]** specimen at room temperature on

- as-produced specimens: **dry**
- humidity saturated specimens (after conditioning in 70° C water): **wet**



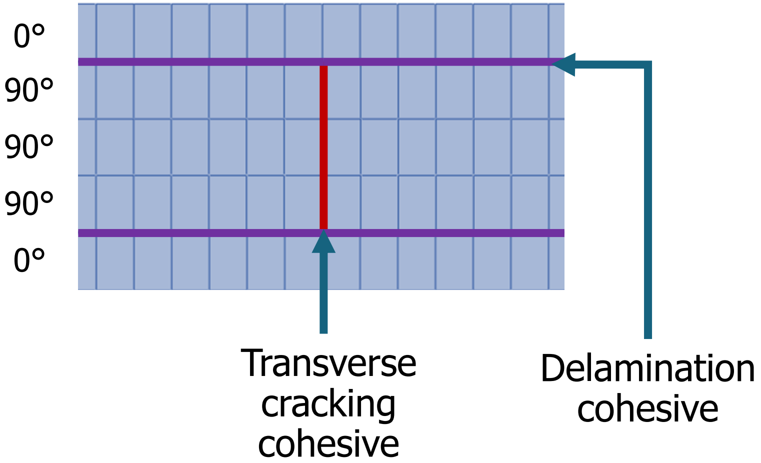
# 2 Application: Transverse Cracking

## *Comparison for single crack opening*

Single-crack model for a specimen segment. The delamination between 0° and 90° must be modeled to obtain acceptable results.

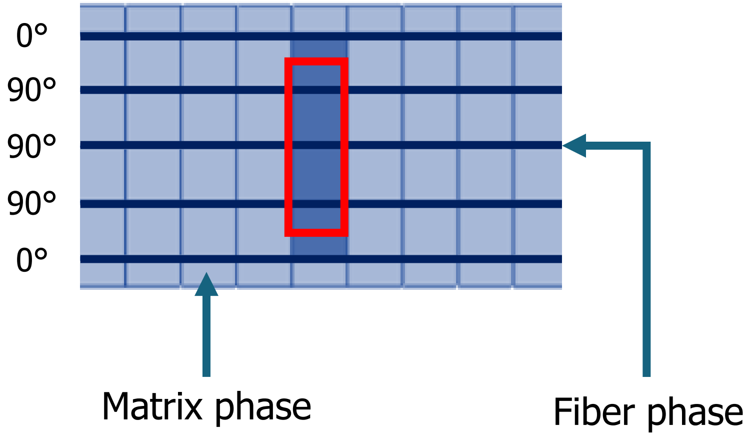
### Cohesive Elements

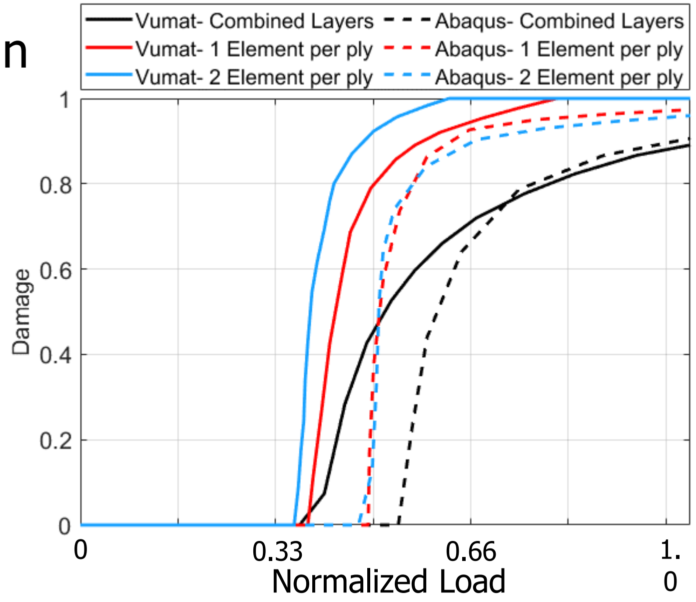
Solid elements connected by cohesive elements for delamination and transverse cracking




### Bi-phasic

Cohesive Zone Models embedded in the constitutive law of matrix element



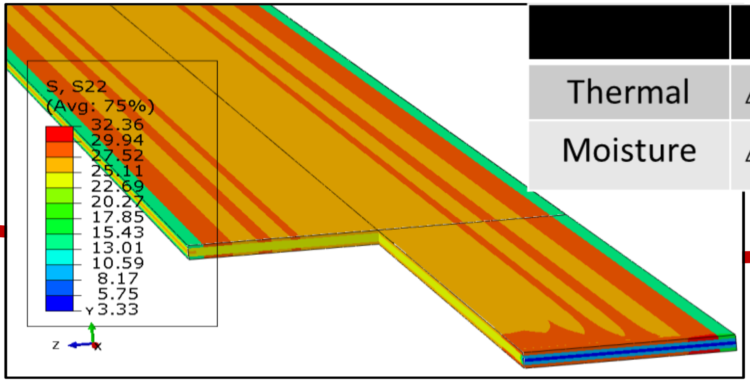

**Damage remains < 1 with cohesive elements**

**Damage = 1 reached by bi-phasic approach with 1 element per ply**

# 2 Application: Transverse Cracking

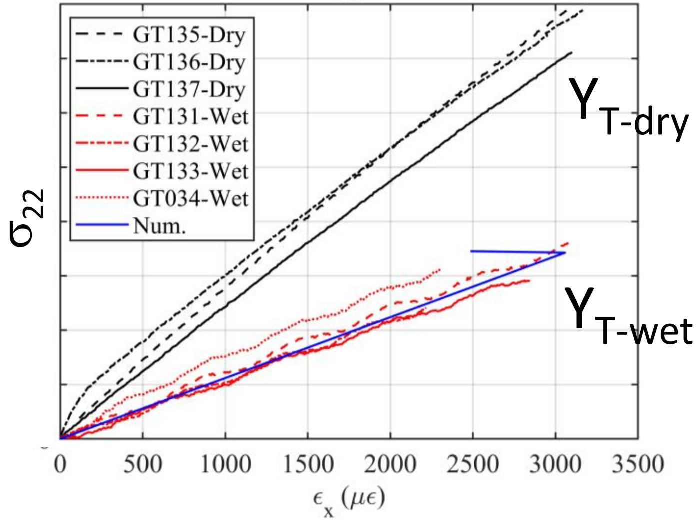
## *Model preparation*

### Thermal residual and moisture induced stress fields



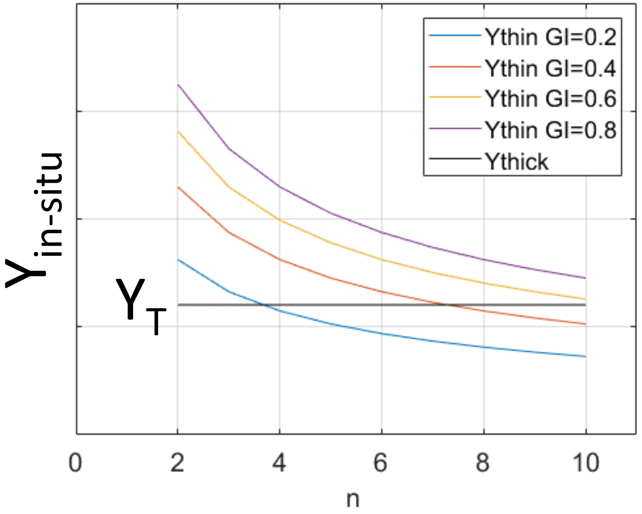

| | | $\sigma_{22}\ (MPa)$ |
|---|---|---|
| Thermal | ΔT = -100°C | 22 |
| Moisture | ΔM = 1.6% | -50 |

### $[90]_n$ tensile test: $Y_T$

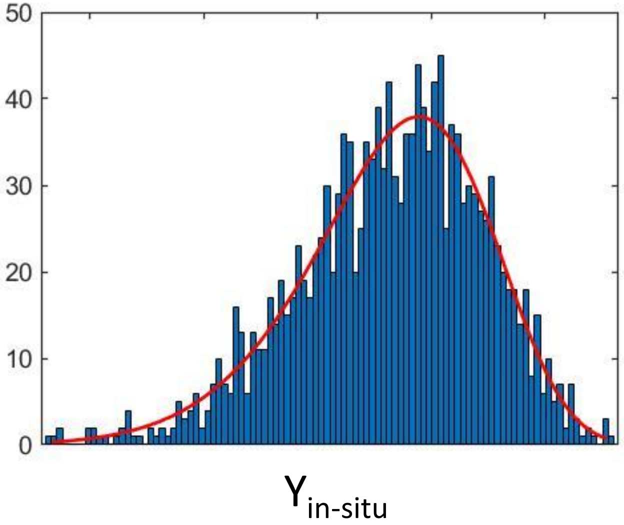



$$Y_T = \sqrt{\frac{8G_{Ic}}{\pi t \Lambda_{22}^0}}$$

### In situ strength




### Statistical distribution



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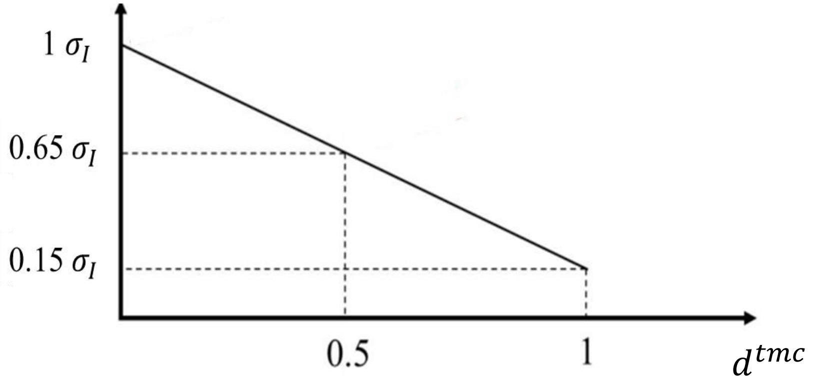
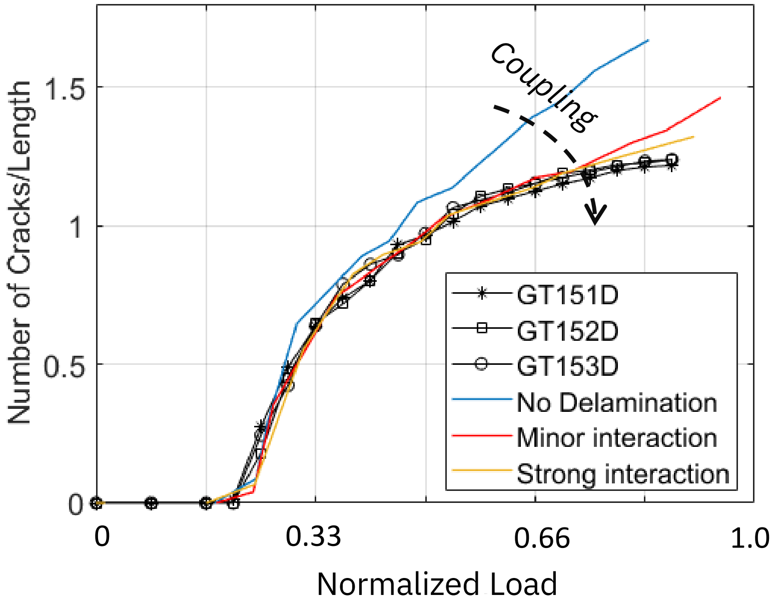
# Application: Transverse Cracking

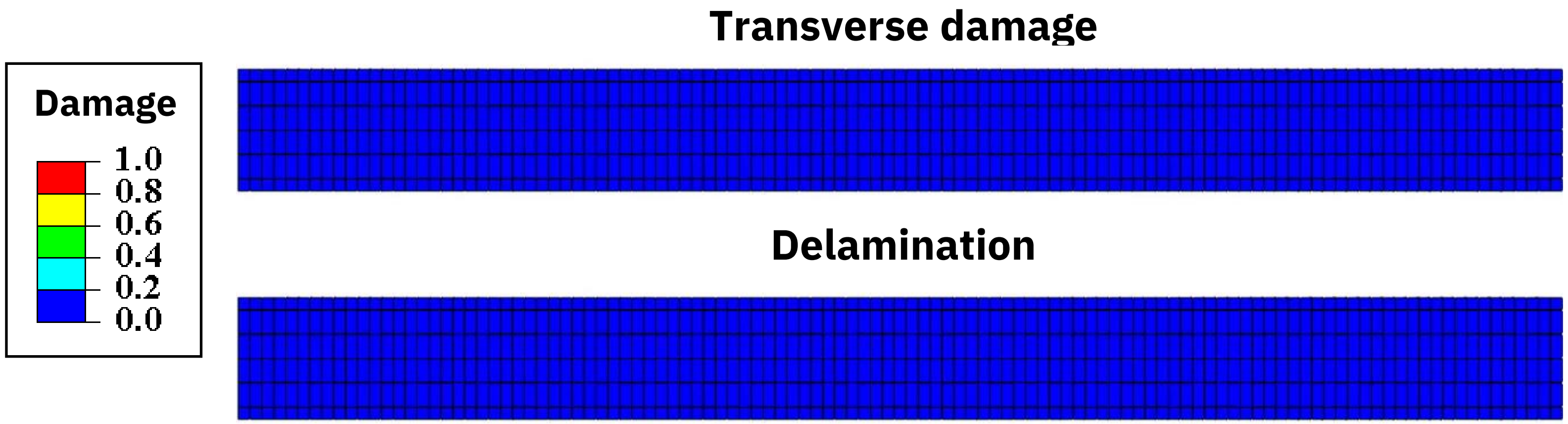
## *Modelling of interaction*

The complex interaction between transverse cracks and mode II delamination represented as a **degradation of interlaminar properties with intralaminar damage** within the matrix element




$$Interlaminar\ Strength\ and\ Toughness = Original\ Value(1 - \boldsymbol{h} \cdot intralaminar\ damage)$$

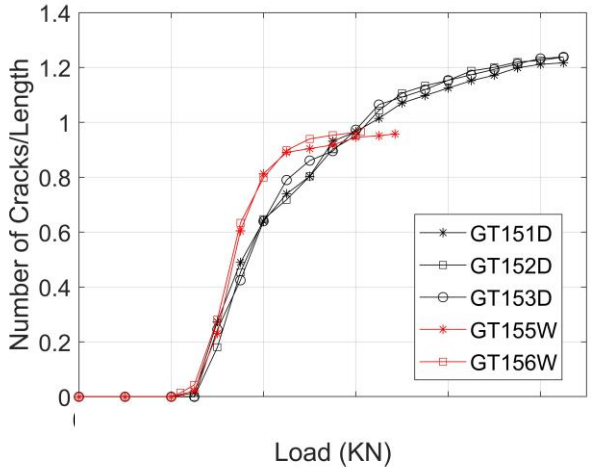



Results confirm Bethelot’s findings: the crack density evolution cannot be captured without including delamination

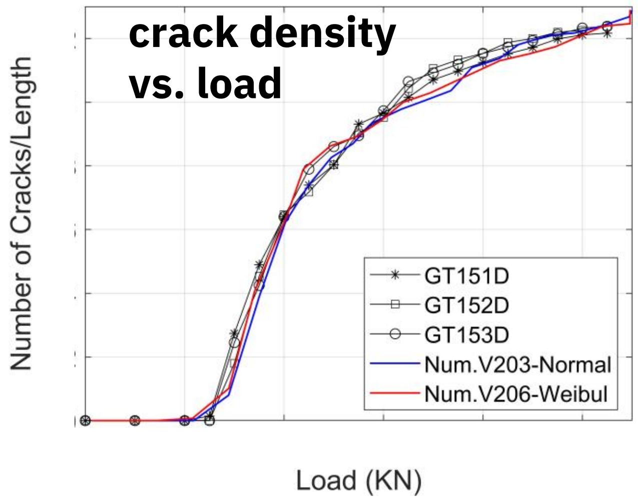
# 2 Application: Transverse Cracking

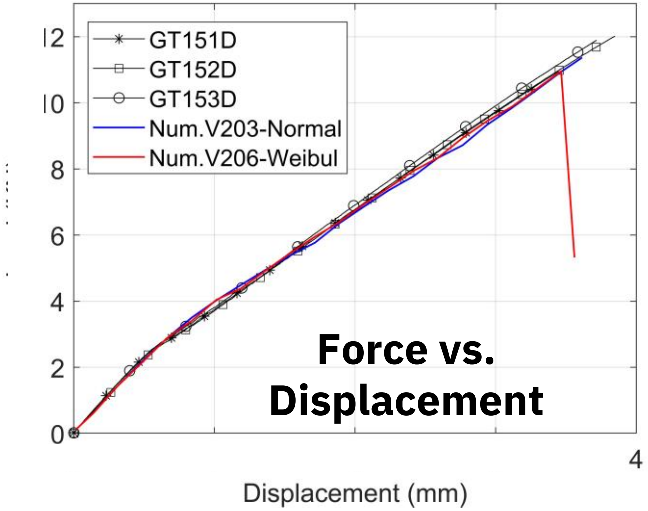
*Results*



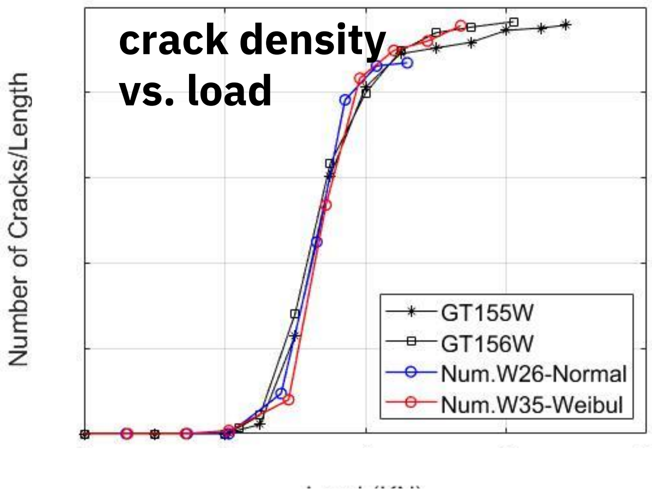

**Experimental crack density evolution (dry & wet)**

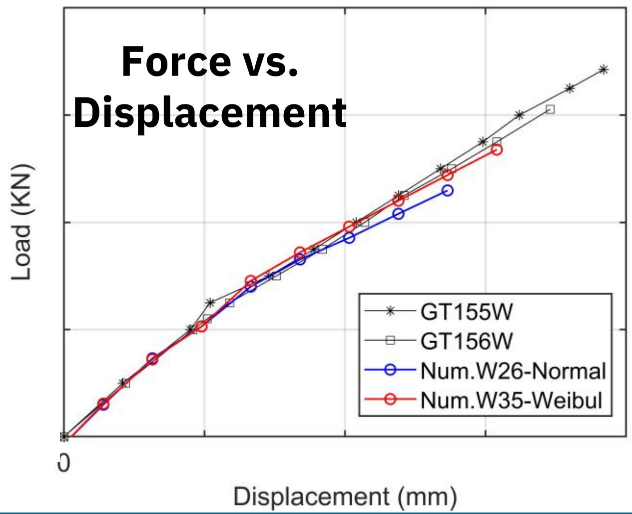
**dry case h=0.68**




**wet case h=1.00**

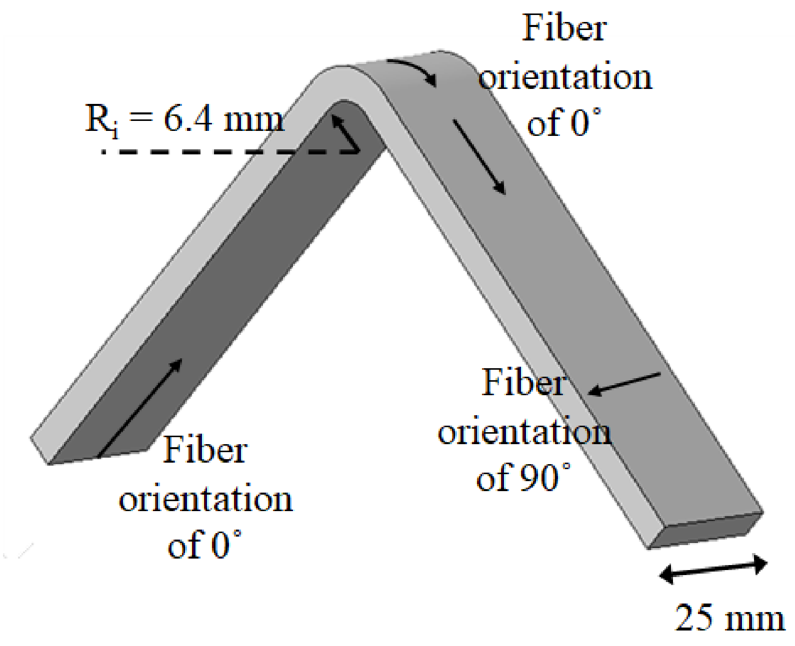


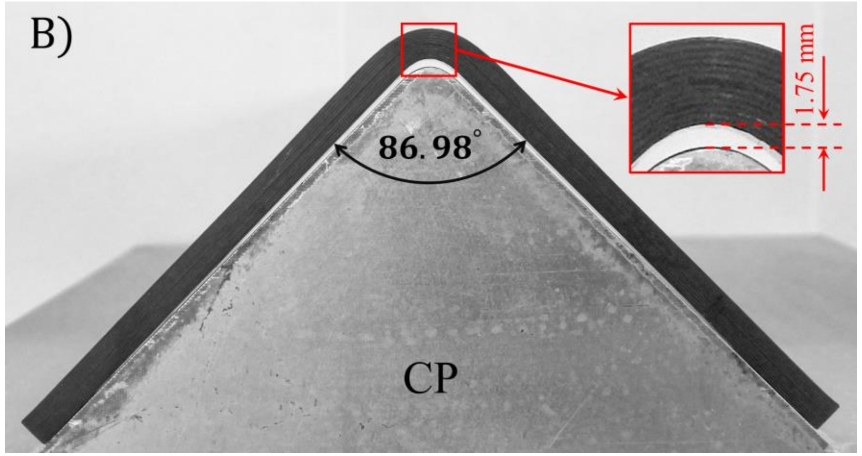



# 3 Application: Curved Laminates

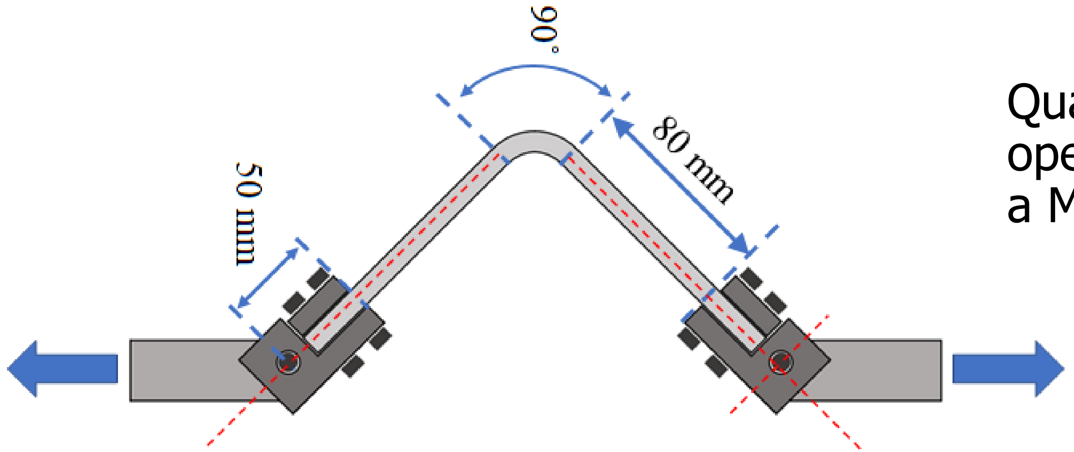
## *Experiments with carbon-reinforced elements*

- 6 mm thick curved laminates
- Two lamination sequences: $\mathbf{[0]_{48}}$ ("Zero") and $\mathbf{[0_2/90_2]_{6s}}$ (Cross-ply -CP)




Spring-in measured after production

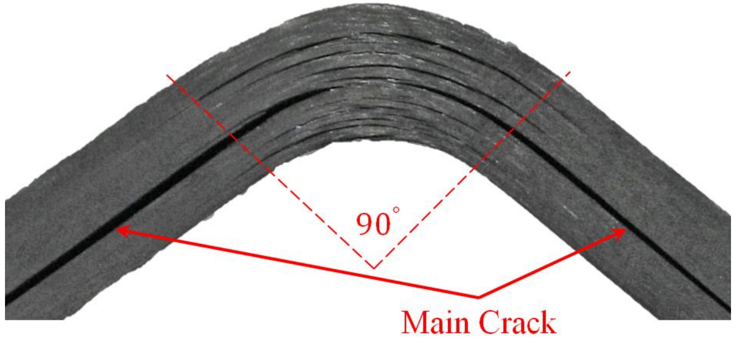


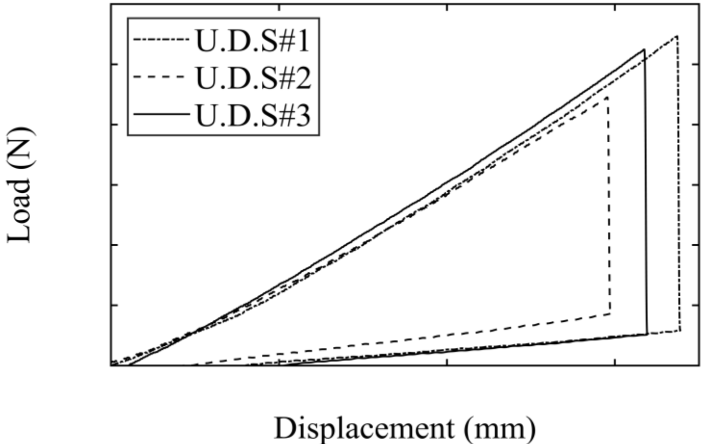

Quasi-static opening test in a MTS System

# 3 Application: Curved Laminates

## *Experimental results*

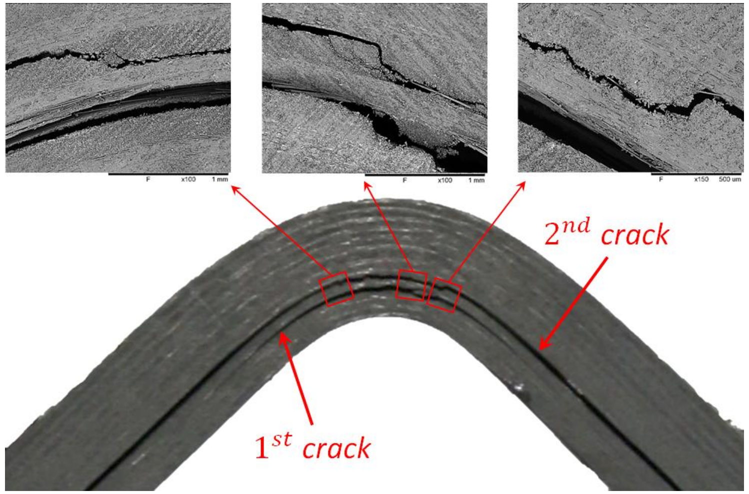
**ZERO**

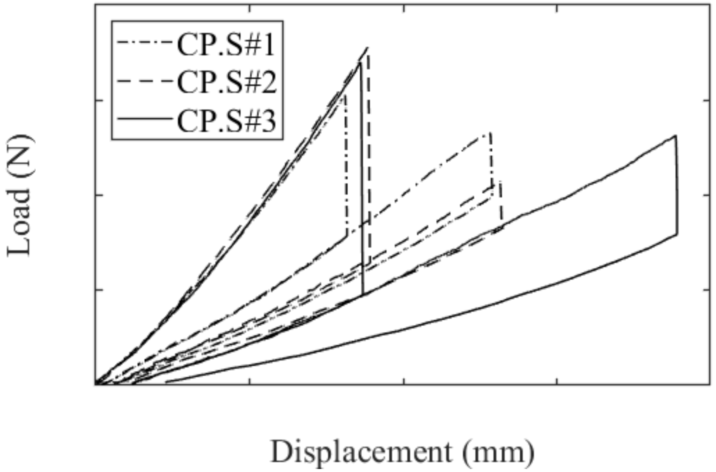



- Linear response until catastrophic failure
- Multiple crack in the central zone
- Main cracks propagated in unstable mode along the legs

**CP**

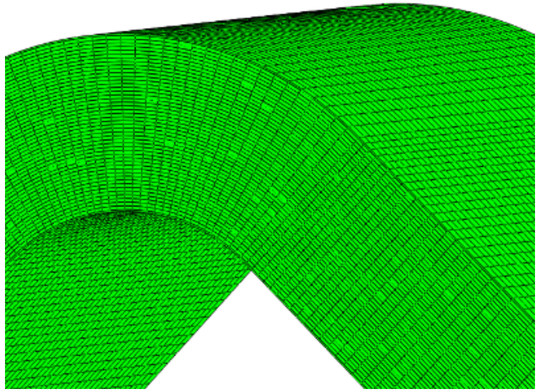


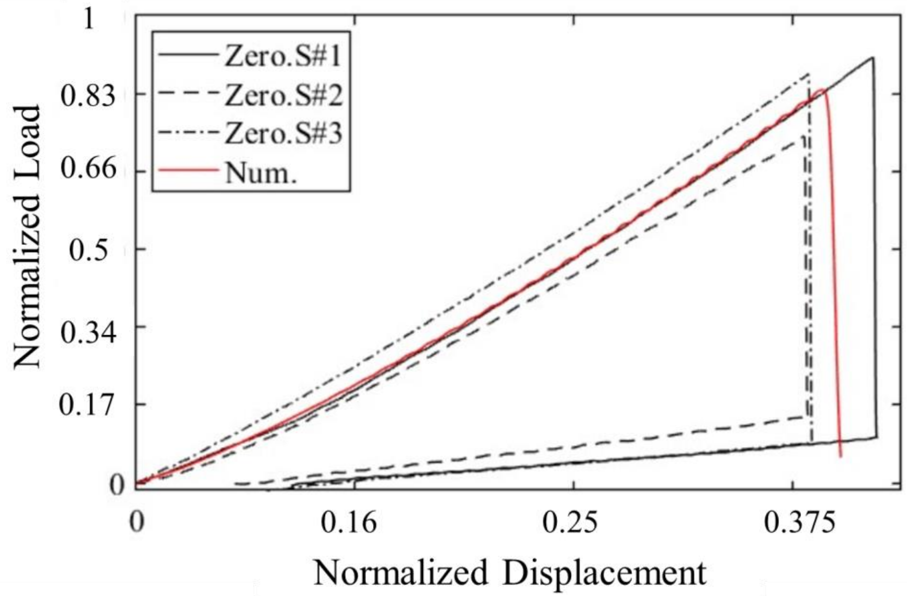

- First crack with significant but non complete loss of load carrying capability
- Test continued until second crack
- Crack migration through the 90° plies

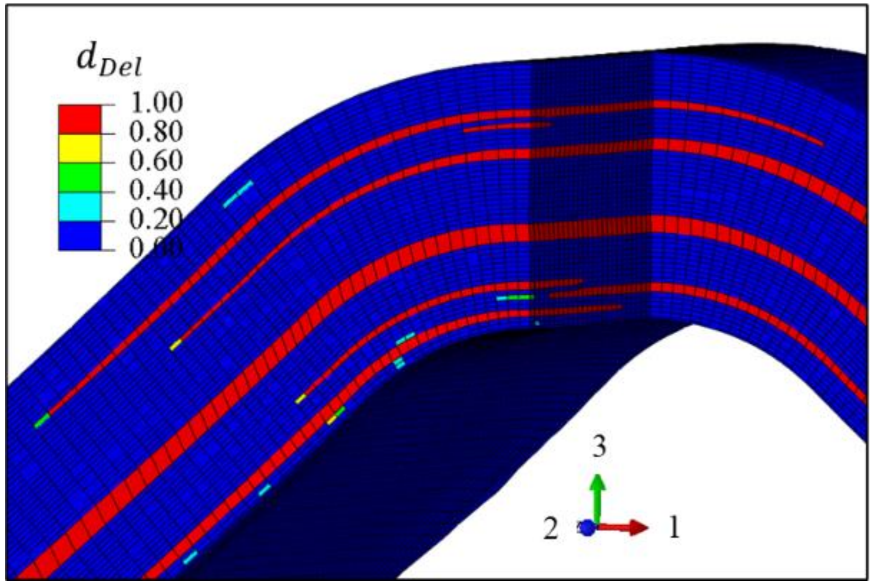
# 3 Application: Curved Laminates

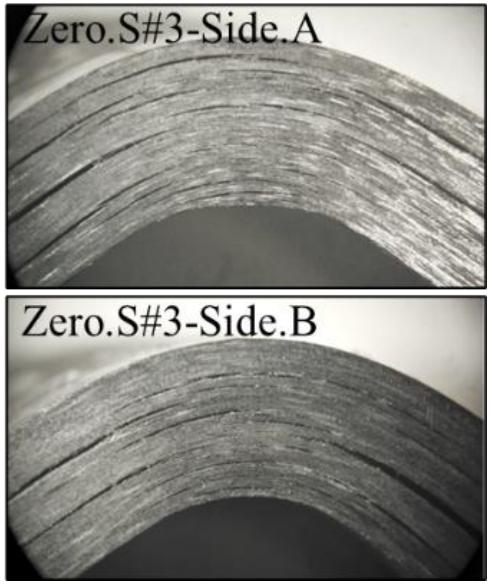
## *Numerical model of “Zero” specimen and results*



- All 47 interlaminar layers embedded in the matrix elements
- Interlaminar strength calibrated
- Interlaminar toughness from literature
- Appreciable quantitative and qualitative results



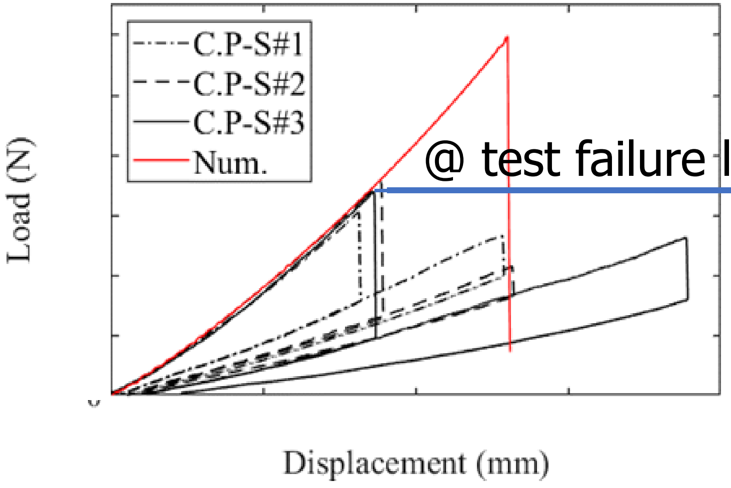



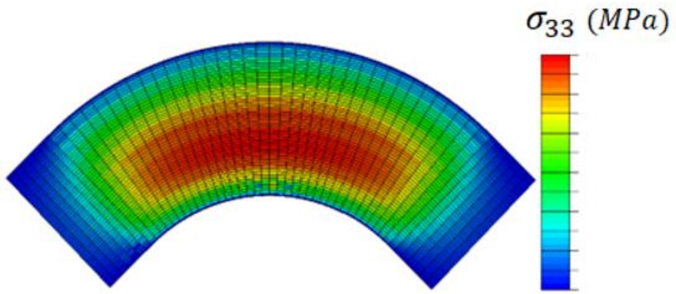



# 3 Application: Curved Laminates

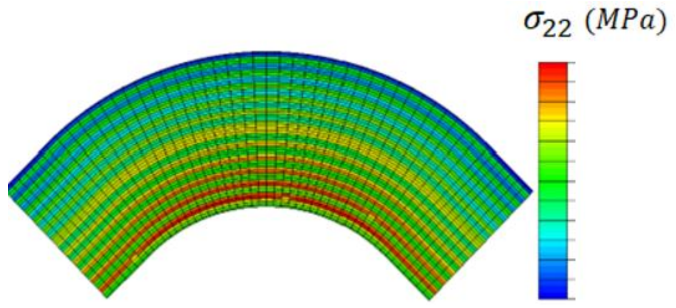
## *Issues for CP model and model preparation*

The same interlaminar strength overestimates the response of **CP model without transverse cracking**




Interlaminar stress 0.59 times the ones calibrated with Zero

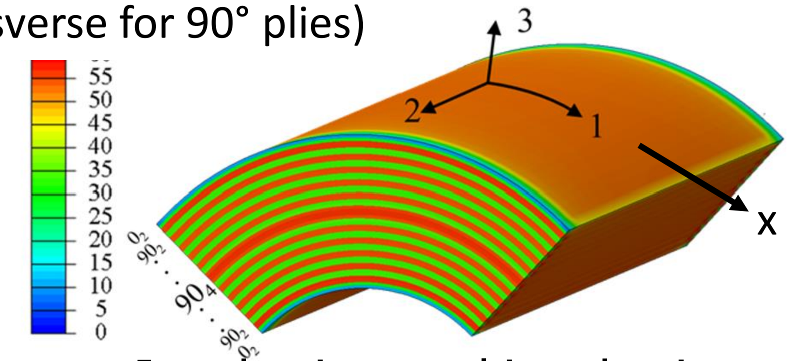


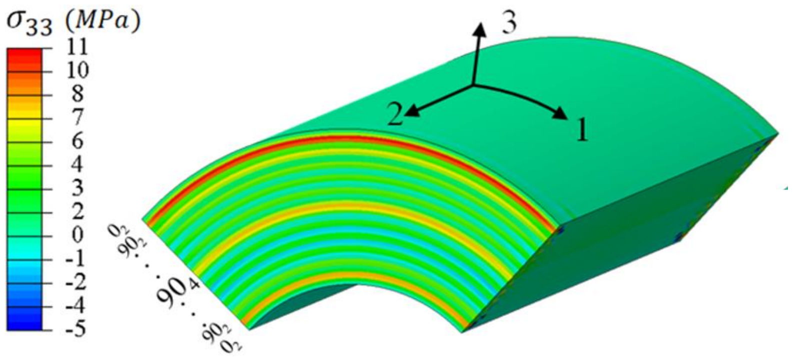

Significant transverse tensile stress in the lower part

Final model includes:

- **Thermal residual stress**
- **In Situ effect on transverse strength**
- **Statistical distribution of strengths**

$\sigma_x$ (Transverse for 90° plies)



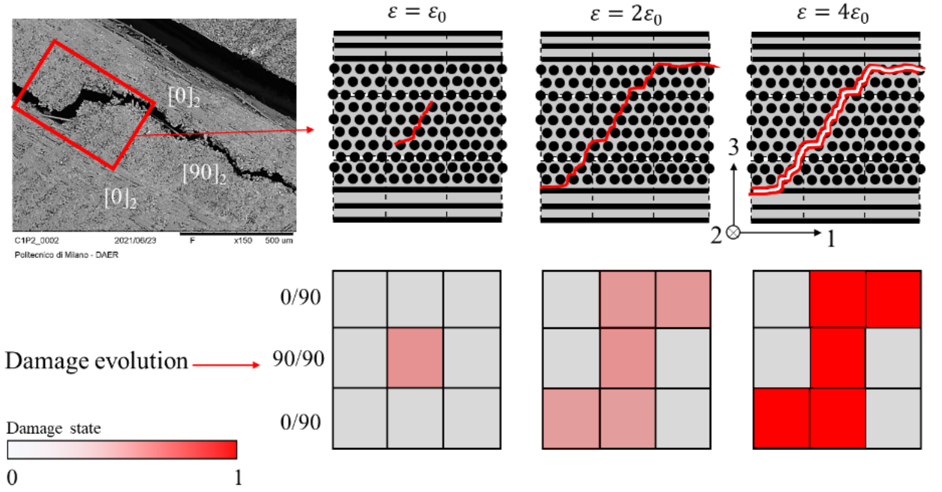

Interlaminar and intralaminar thermal residual stress in matrix

# 3 Application: Curved Laminates

## *Strategies to model the interaction*

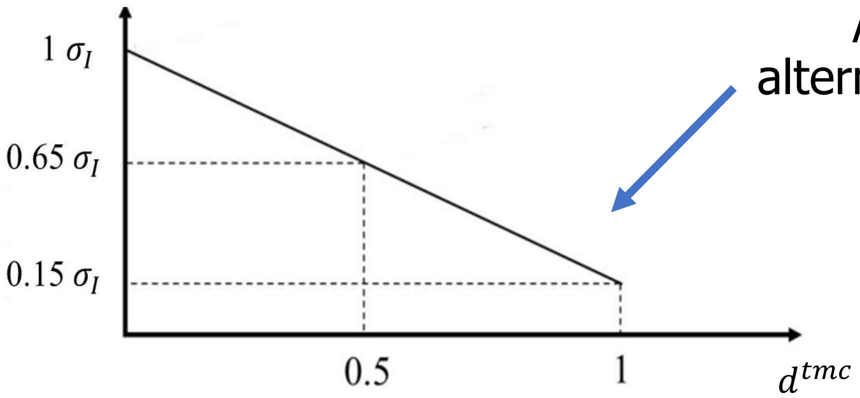
Failure is likely to start in 90° plies in central zone

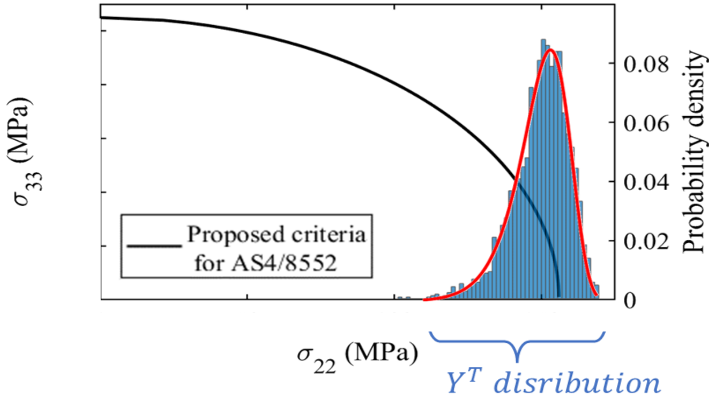
Highest $\sigma_{22}$ and $\sigma_{33}$ stress




Transverse cracking evolves in delamination

Approach makes available two alternative strategies at the meso-scale level



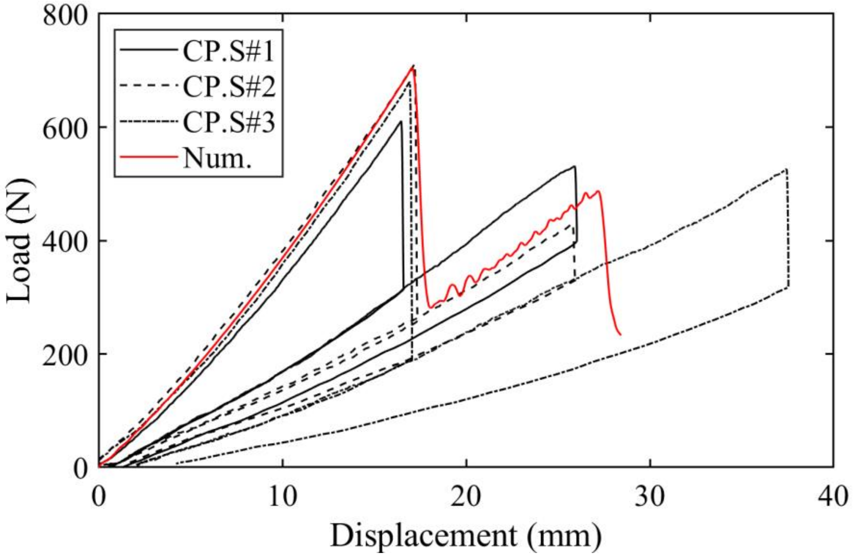



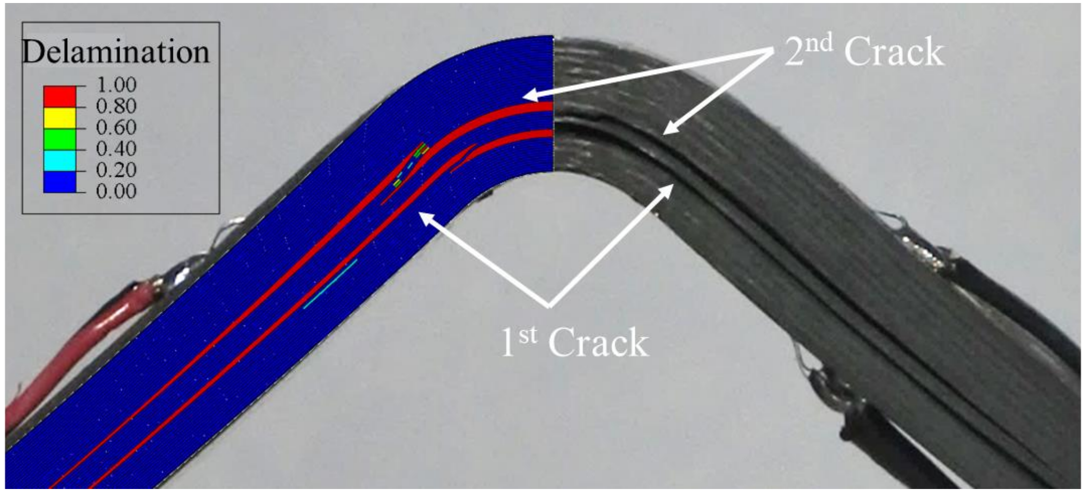

1 Transverse damage affect the interlaminar properties

2 Interactive strength criterion for damage initiation with $\sigma_{22}$ and $\sigma_{33}$ stress

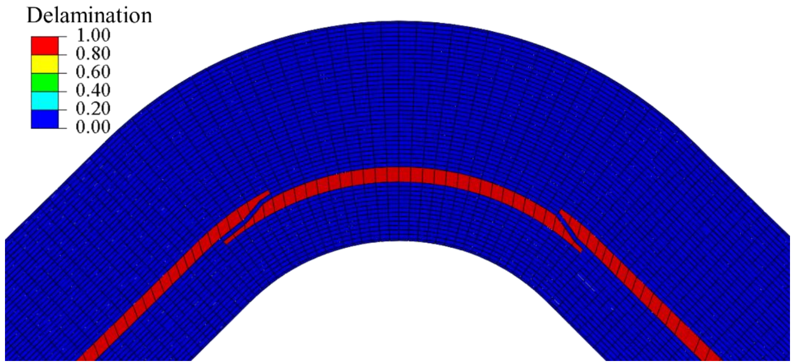
# 3 Application: Curved Laminates

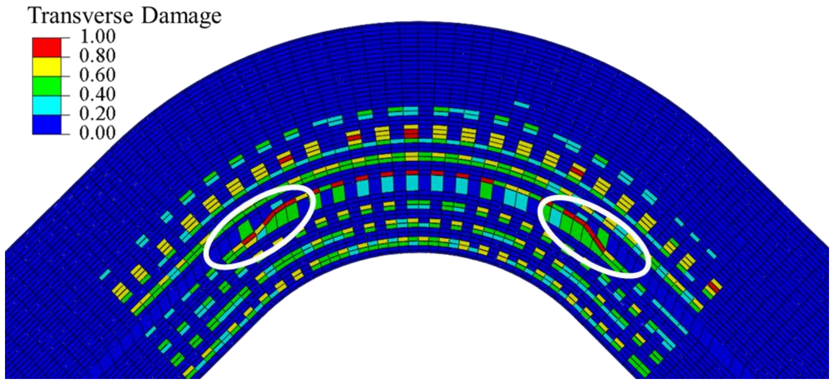
*Interaction modelled as effect of intralaminar damage*

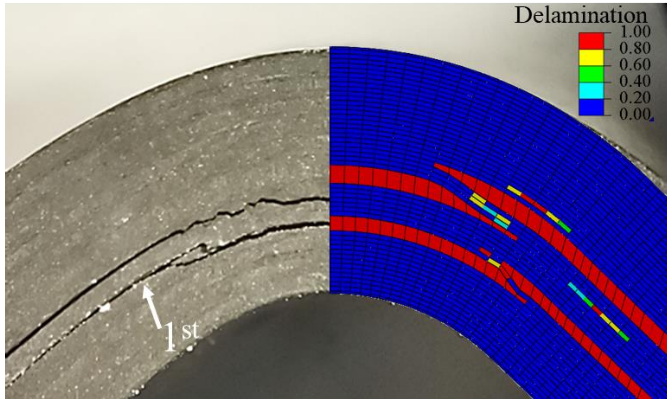



- Accurate force vs. displacement response
- Delamination locations and crack migrations captured
- Transverse cracking damage < 1 excluding the migration zone

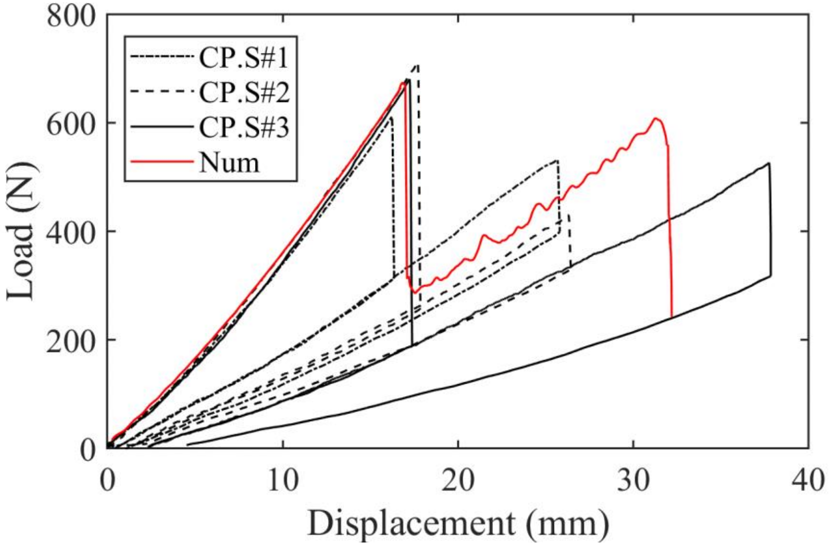


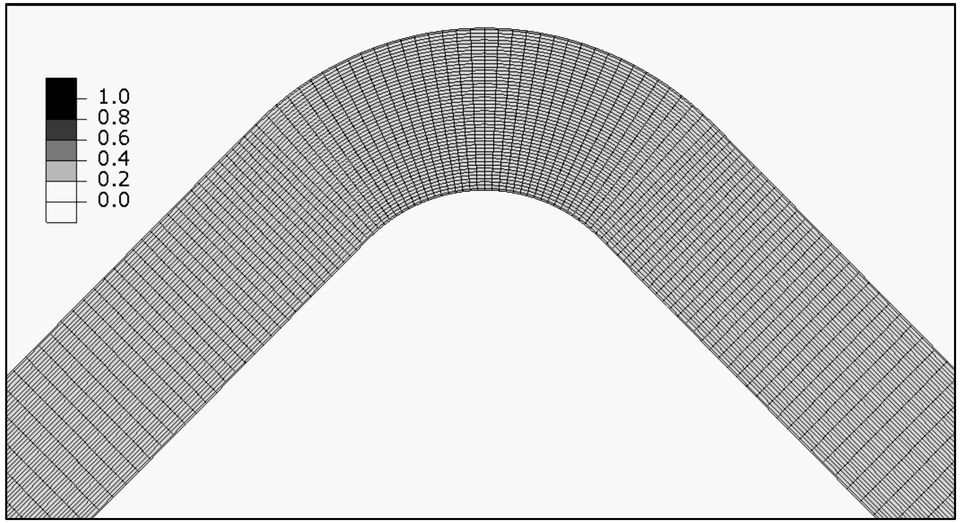



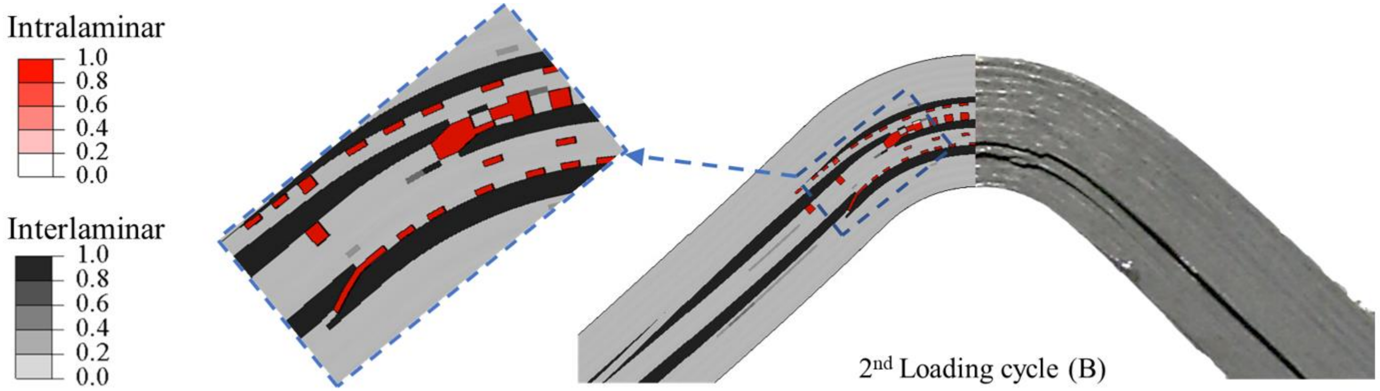
# 3 Application: Curved Laminates

## *Interaction modelled at the level of the strength criterion*



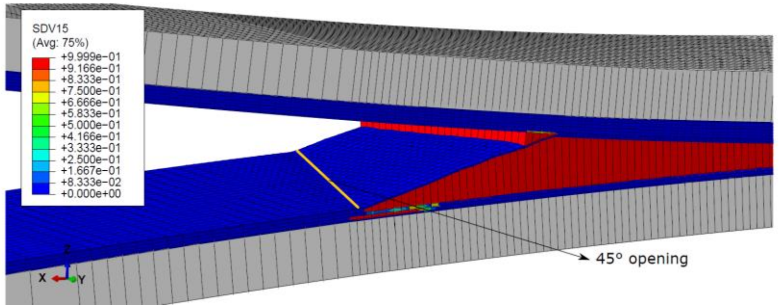

- Position and load for second crack development are not precise
- Migration correctly represented
- Less diffused transverse cracking (in better agreement with experimental evidence)

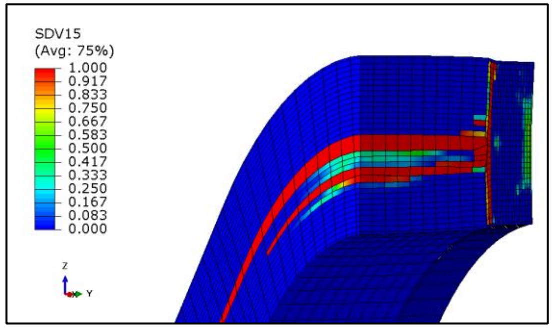


# 4 Conclusions

*Conclusion, ongoing activities, next steps*

- ❑ Unconventional technique, with numerical advantages
- ❑ Possibility of modelling and calibrating intra-interlaminar damage interaction at the meso-scale level
- ❑ Importance of statistical distribution of properties, thermal residual stress modelling for high fidelity models and inter-intralaminar interactions




- ❑ Scaling-up: multiple delamination in adhesive interfaces and complex curved composite elements

- ❑ Comparisons with more conventional techniques
- ❑ Modelling the effects of intralaminar damage on delamination without discrete matrix cracks

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Thanks!

## Meso-scale Models for the Interaction of Damage Modes in Composite Laminates


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