ICCS27

27th International Conference on Composite Structures

School of Engineering and Architecture

Ravenna Campus of University of Bologna, Italy

3-6 September 2024

Conference program

Nicholas Fantuzzi

Michele Bacciocchi

António J.M. Ferreira

Friday, September 6 (Early-morning)
Room DANTE
Session chair: Shuxin Li
Session chair: Marco Riva

Delamination, damage, fracture, failure and durability of composites

09h00
1024 | Mechanism based Paris Law Approaches for Delamination Growth Characteristics of Composite Laminate under Fatigue Loading
Li, Shuxin; *Duan, Qingfeng*; *Hu, Haixiao*; *Cao, Dongfeng*

Composite structures and materials

09h20
–online–
1102 | The Effects of Pore Morphology on Mechanical Response and Hot-Spot Formation in Pre-billets of HMX-Based PBXs under Press Loading Process
Zhang, Wei; *Liu, Rui*; *Chen, Pengwan*

Delamination, damage, fracture, failure and durability of composites

09h40
1301 | Numerical and experimental investigation of non-linear response in Ceramics Matrix Composite for reusable space vehicles
Riva, Marco; *Novembre, Edoardo*; *De Stefano Fumo, Mario*; *Cavalli, Lorenzo*; *Airoldi, Alessandro*

10h00
–online–
1030 | Multiscale-based multiaxial fatigue model of short fiber reinforced polymer composites under high-cycle proportional loading
Zhang, Lei; *Zhang, Hanyu*; *Liu, Zhao*; *Zhu, Ping*

10h20
1319 | Effect of damage evolution on low-velocity impact simulation of Kevlar-fibre woven composites
Zhang, Shunqi; *Ma, Dayou*; *Manes, Andrea*

10h40
1118 | STRAIN RATE-DEPENDENT PERFORATION OF WOVEN FIBRE COMPOSITES UNDER IMPACT
Ivančević, Darko; *Ratković, Jakov*

— Break —

Marco Riva (marco2.riva@polimi.it, Politecnico di Milano – Department of Aerospace Science and Technology (DAER), Italy)

Edoardo Novembre (edoardo.novembre@polimi.it, Politecnico di Milano – Department of Aerospace Science and Technology (DAER), Italy)

Mario De Stefano Fumo (m.destefano@cira.it, CIRA – Centro Italiano Ricerche Aerospaziali, Italy)

Lorenzo Cavalli (cavalli@petroceramics.com, Petroceramics S.p.A., Italy)

Alessandro Airoldi (alessandro.airoldi@polimi.it, Politecnico di Milano – Department of Aerospace Science and Technology (DAER), Italy)

Numerical and experimental investigation of non-linear response in Ceramics Matrix Composite for reusable space vehicles

The past decade witnessed a doubling of space launches, fueled by the entering of private companies into the market and by technological advancements aimed to provide affordability. For these reasons, the economic and environmental sustainability are key research areas. Focusing on structural design, the development of fully reusable spacecraft can significantly enhance the cost-effectiveness and minimize the environmental footprint of the space industry. Achieving this goal requires that the material selected is characterized by good structural properties and good damage tolerance combined with the capability to resist to multiple exposure to severe environments. Ceramic Matrix Composites (CMC) are the perfect candidate in this sense, and this research focuses on the usage of C/SiC (Carbon fiber reinforced Silicon Carbide) composite for a hot structure, which provides both thermal protection and structural functions. To verify the material suitability, V-shaped specimens, representative of a supersonic leading edge, were subjected to Plasma Wind Tunnel (PWT) exposure, thus simulating the reentry conditions. The damage tolerance of the material was investigated using a subset of specimens, that was manufactured with artificial delaminations and butt joints. The specimens were then tested mechanically to assess the PWT-induced properties degradation and the internal state was evaluated using CT scans. To perform numerical-experimental correlation, a detailed ply-wise Finite Element model of the test was developed. This model was based on the hybrid biphasic model formulation, where the fiber properties are assigned to shells and the matrix properties are assigned to layers of solid element, which share nodes with the fibers layers. The formulation is paired with a Continuum Damage Mechanics (CDM) approach, thus providing the model with the capability to represent delaminations between every layer, which was considered fundamental to replicate the experimental behavior that was characterized by the development of an extensive crack network. Moreover, the model reproduces the in-plane, matrix dominated, nonlinear response of the CMC and is able to take into account coupling between out of plane and in plane damages. This method provides a numerically effective technique to model both the in plane and the out of plane response of the material, and was calibrated with cross ply, angle ply, and Double Cantilever Beam (DCB) tests. By looking at the CT scans of the specimens it was found that they were characterized by noticeable manufacturing defects, and, to have a good correlation, these defects were replicated in the FE model. The results of the study were found to be encouraging in terms of reusability, with a good damage tolerance and no indicator of degradation for the PWT tests at design conditions. Degradation was noticeable for specimens subjected to off design condition, but the material kept an acceptable load carrying capability. The numerical experimental correlation provided valuable insight into the failure mode of the specimens and proved that a fundamental role in the failure is played by the presence of artificial and manufacturing defects.

The activity presented is a part of AM3aC2A project funded by Italian Space Agency (ASI).

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SIAMS Structural Integrity of Advanced Material and Structures

PETROCERAMICS Turn natural complexity into technology

CIRA Italian Aerospace Research Centre

Numerical and experimental investigation of non-linear response in Ceramics Matrix Composite for reusable space vehicles

Marco Riva[1], Edoardo Novembre[1], Mario De Stefano Fumo[2], Lorenzo Cavalli[3] and Alessandro Airoldi[1]

[1] *Department of Aerospace Science and Technology (DAER), Polytechnic of Milan*

[2] *CIRA, Italian Aerospace Research Center*

[3] *Petroceramics S.p.A.*

0 Introduction

Focus of the work

Scope of this work:
Investigate the mechanical response of a representative specimen in CMC for reusable spacecraft or hypersonic vehicle

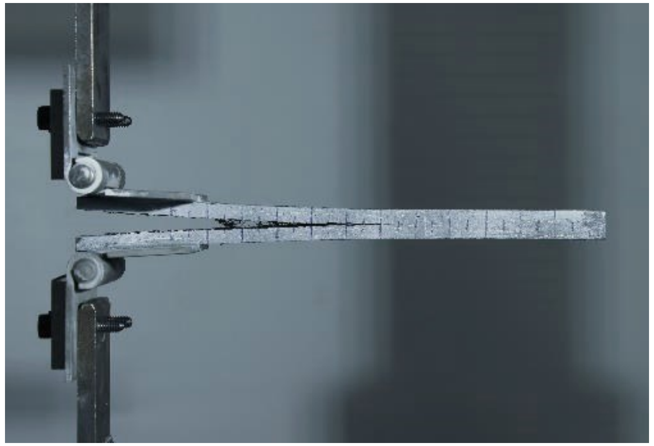
ISiComp characteristics:
- C-C/SiC Ceramic Matrix Composite (CMC)
- Liquid Silicon Infiltration (LSI)

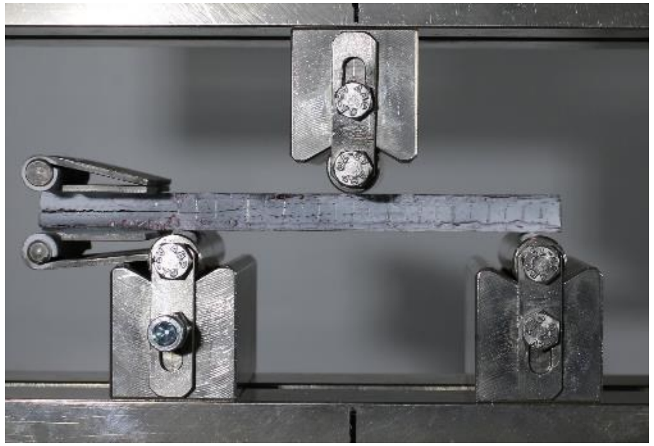
Liquid Silicon Infiltration (LSI)

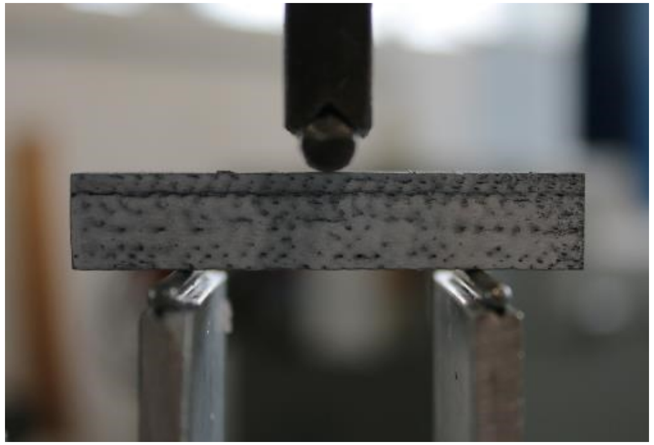
Pre-preg → Lamination and curing of the precursor → Pyrolysis in Nitrogen → Silicon infiltration → Finite piece

1 Experimental tests

Material interlaminar tests







DCB

$G_I = 0.51 \text{ kJ/m}^2$

ENF

$G_{II} = 1.54 \text{ kJ/m}^2$

SBT

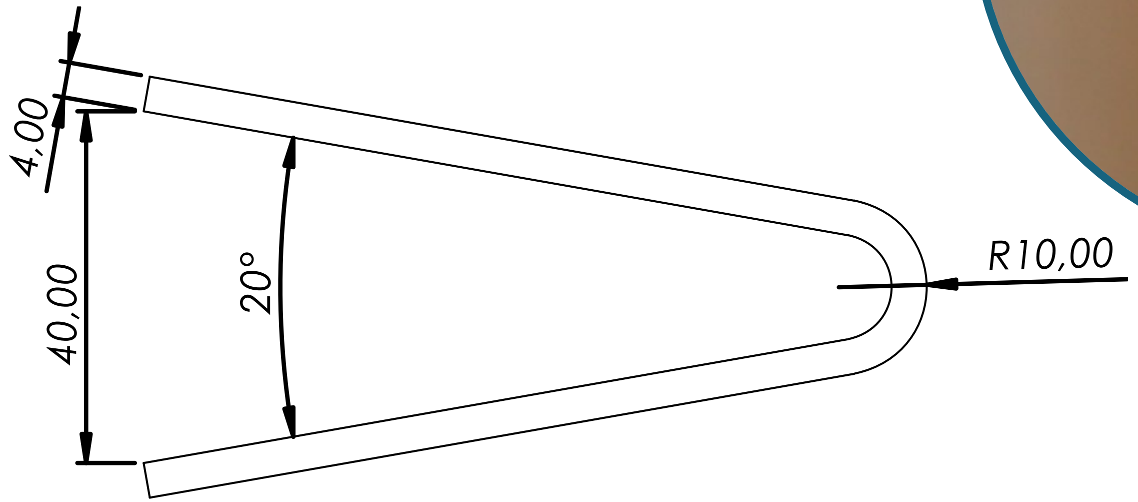
$\sigma_{II} = 28.5 \text{ MPa}$

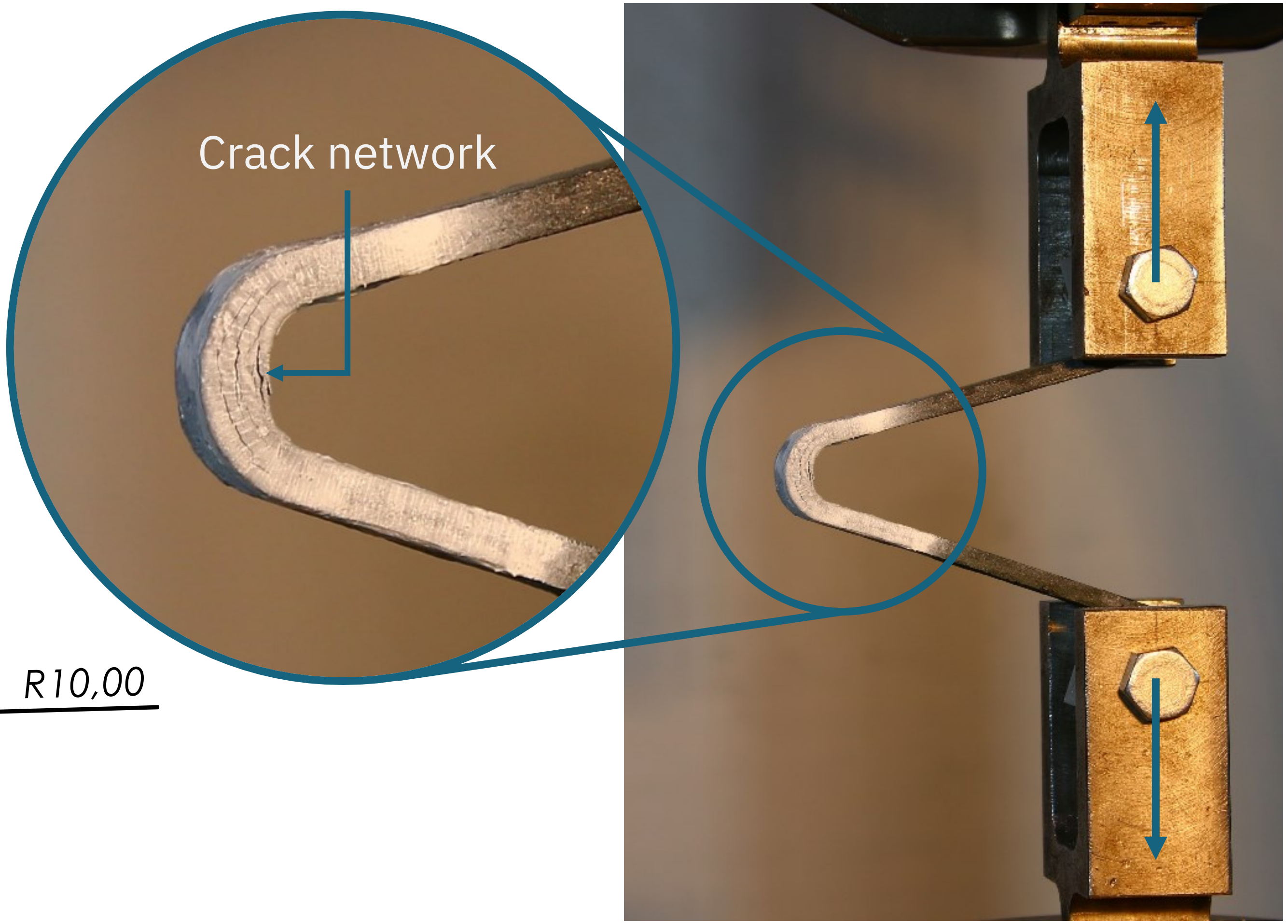
1 Experimental tests

Angular specimens testing

12 specimens tested $[45_6/0_{10}/45_6]$

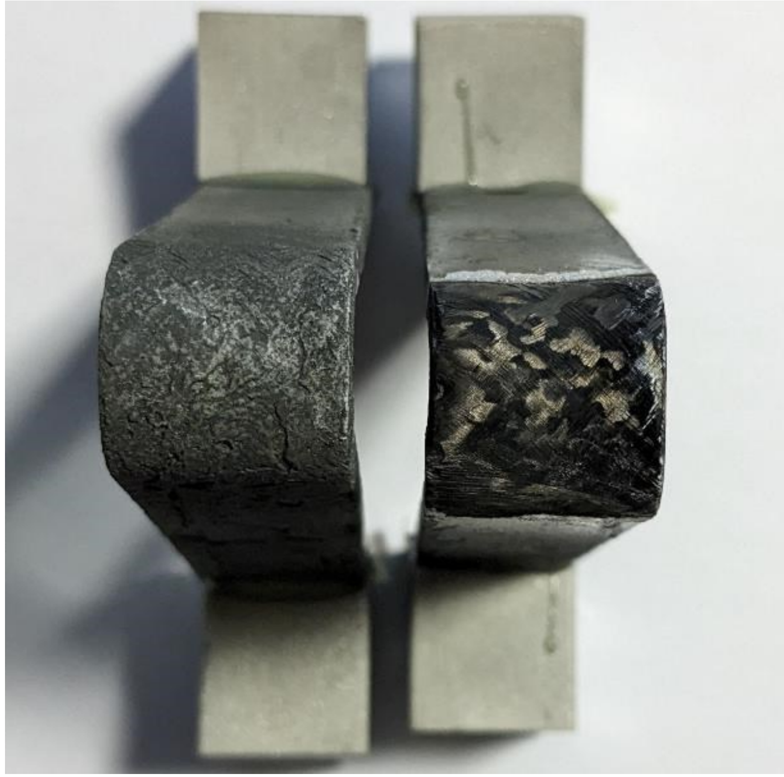
6 Undamaged:	6 Artificially Delaminated
3 – *A* no *PWT*	3 – *B* no *PWT*
3 – *AP* with *PWT*	3 – *BP* with *PWT*

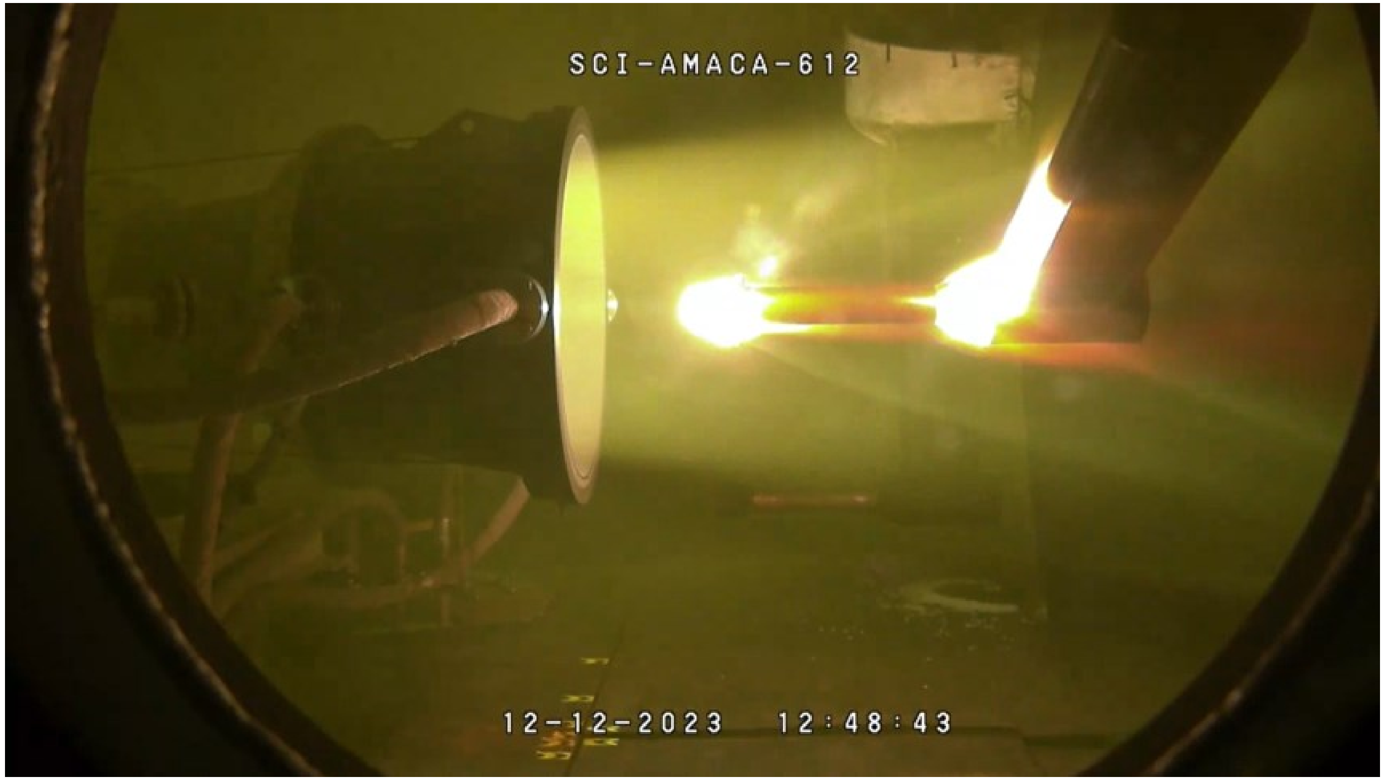




1 Experimental tests

Effects of PWT



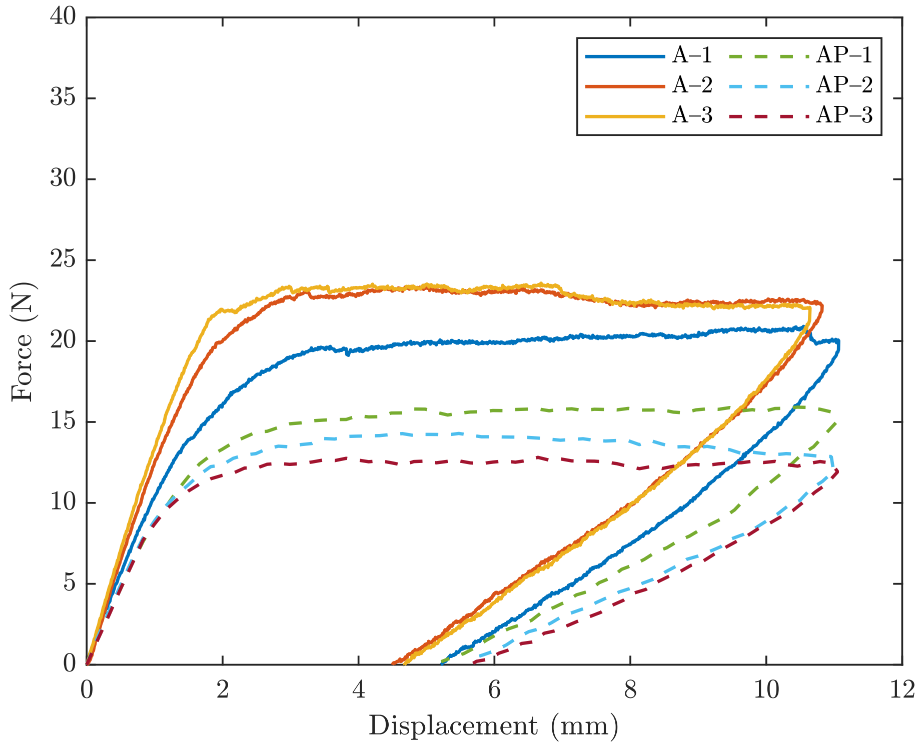


The batch was exposed to off design PWT condition with high degradation

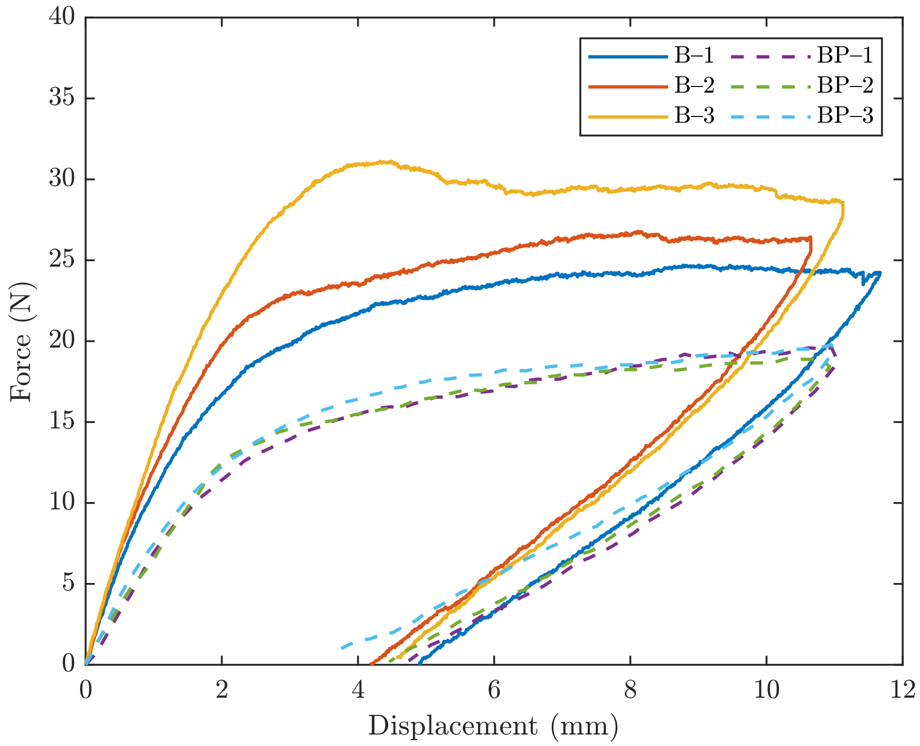
1 Experimental tests

Response of the angular specimens

Non delaminated (Type *A* and *AP*)

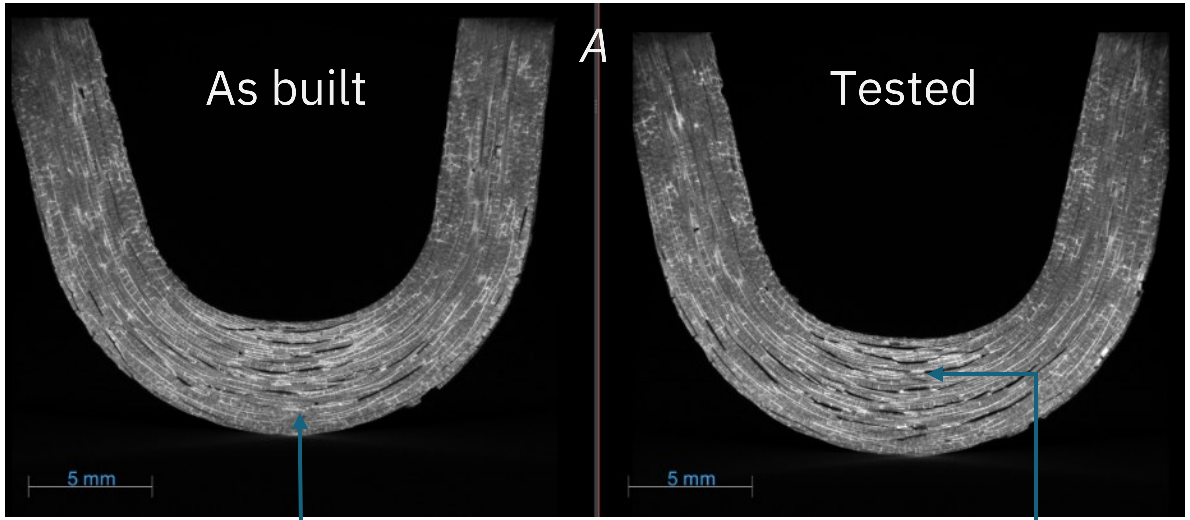


Artificially delaminated (Type *B* and *BP*)



1 Experimental tests

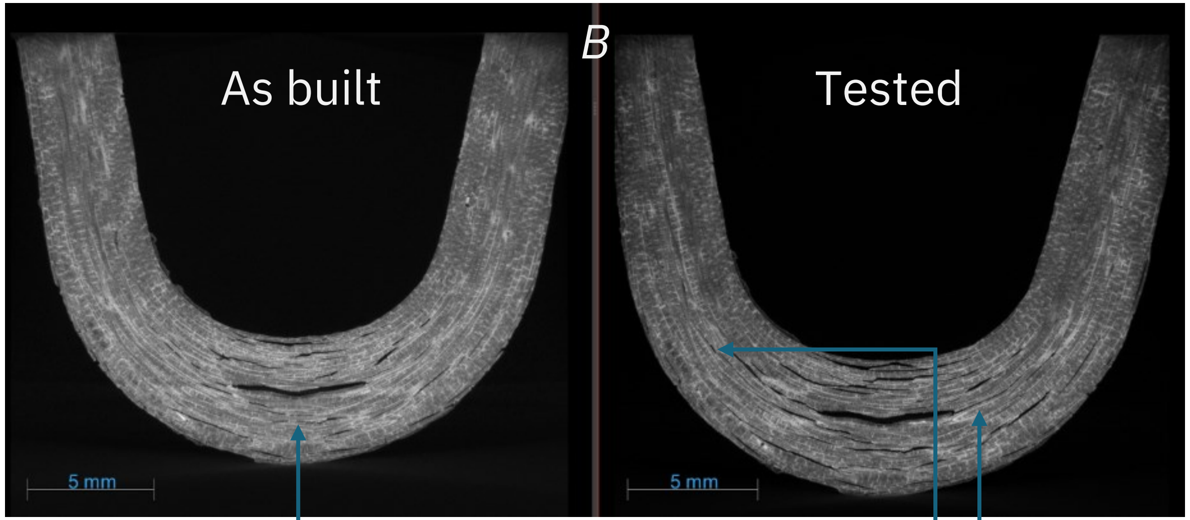
CT Scans



Widespread manufacturing damage

Crack network:

- New cracks
- Advance of defects



Manufacturing damage comparable with artificial delamination

New cracks

Delamination progression

2 Numerical modeling

Biphasic decomposition and hybrid mesh

Decomposition in two idealized phases

Fibers idealized phase:

Accounts for the continuity of the reinforcement

Matrix idealized phase:

Effective medium for matrix dominated responses

Hybrid mesh FE discretization

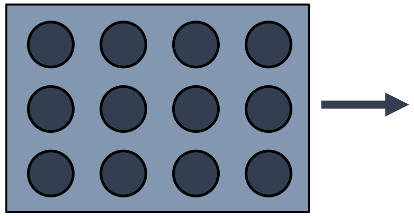
2D elements (Fiber phase)

Are placed at the mid-planes of each lamina

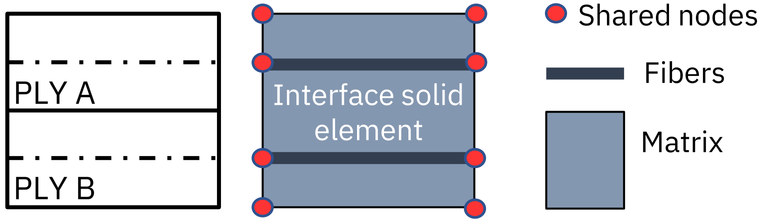
Solid elements (Matrix phase)

Connect the 2D elements (same nodes are used)

Physical lamina with distinct constituents



Idealized in two **superimposed phases** that share the same volume and are subjected to the same strain



Airoldi et al. (2020)

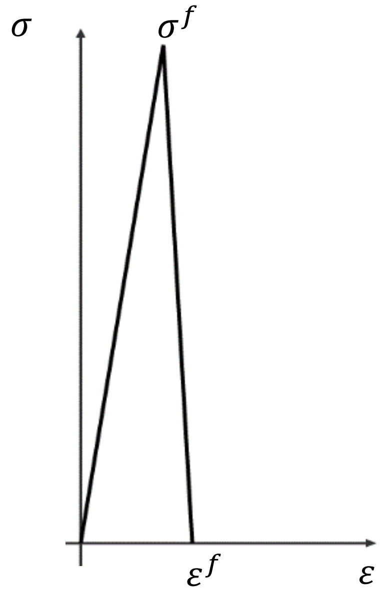
2 Numerical modeling

Damage laws

In plane

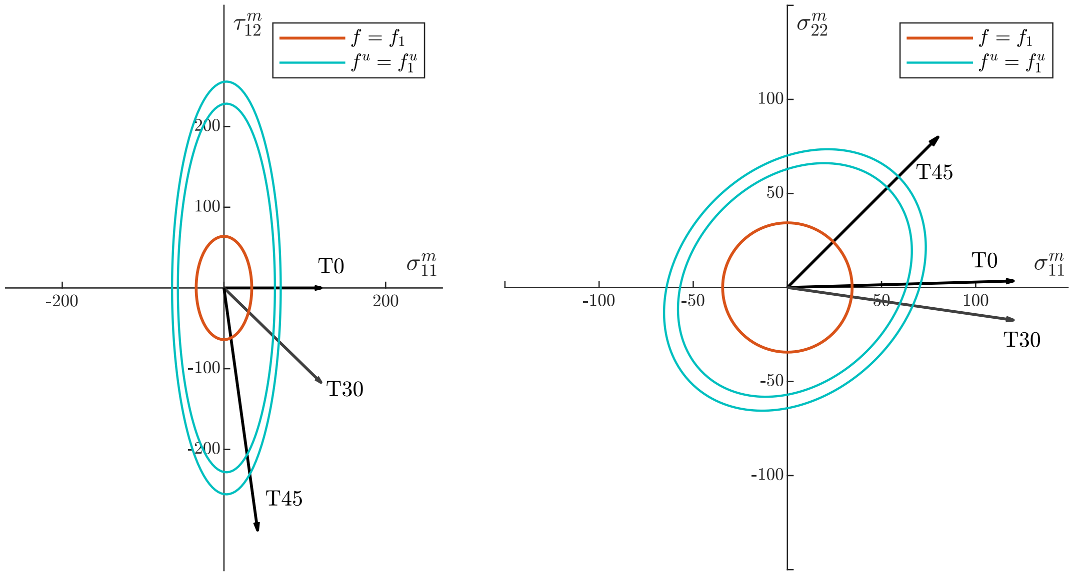
Fibers

Brittle failure



Matrix

Tsai-Wu with statistical distribution

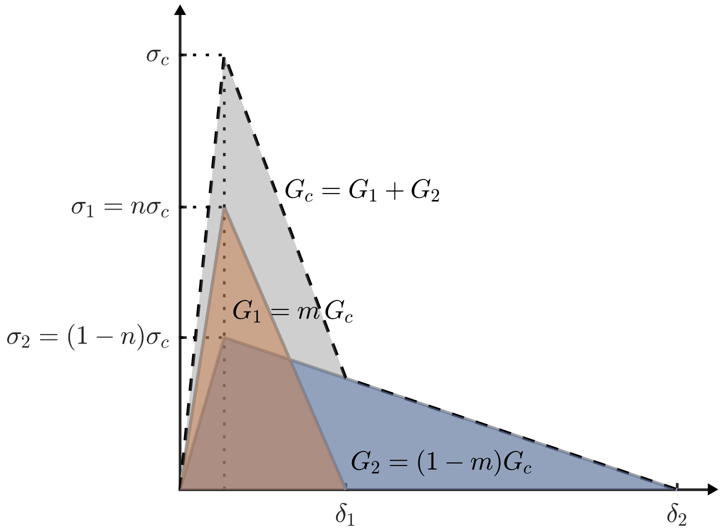


Novembre et al. (2024)

Out of plane

Matrix

Statistically distributed trilinear CZM



Riva et al. (2023)

2

Numerical modeling

Finite Element Model and manufacturing damage modeling

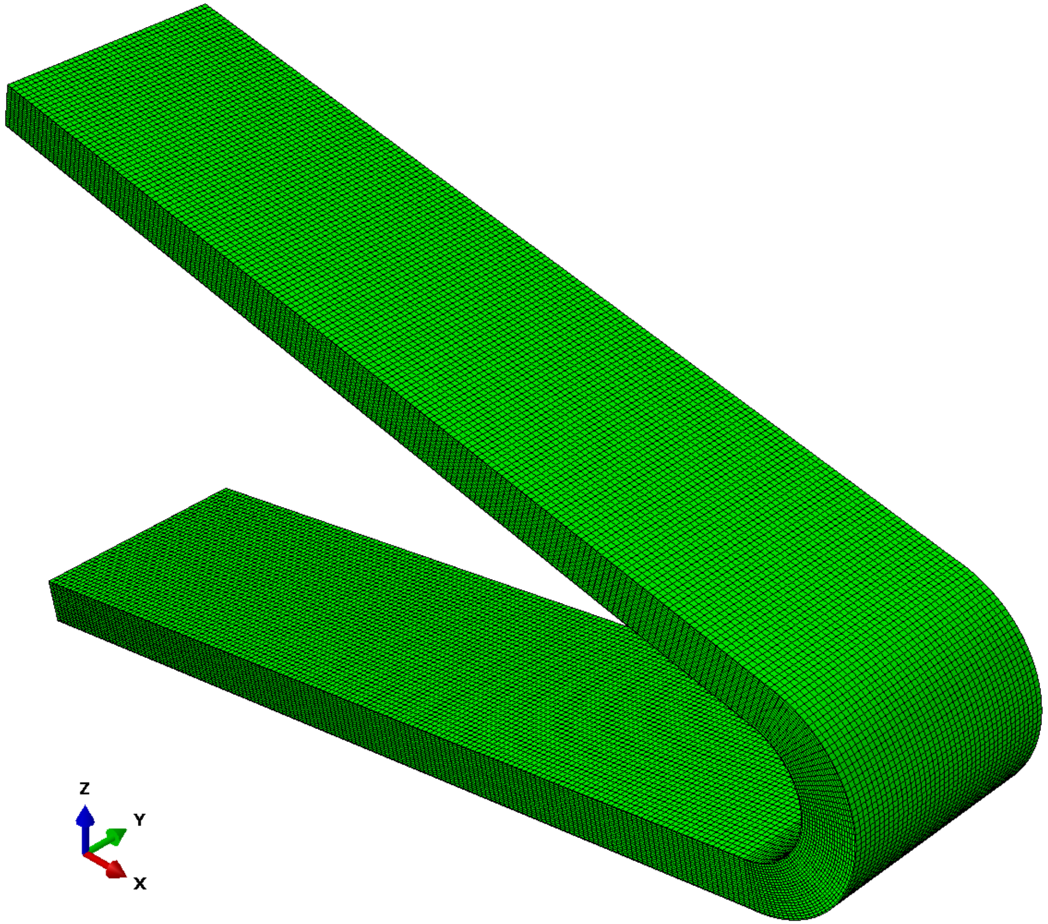
Hybrid mesh (715000 elements):

Fibers
350000 S4R
0.5 x 0.5 mm

Matrix
365000 C3D8R
0.5 x 0.5 x 0.2 mm

Explicit simulation degrading interlaminar properties:

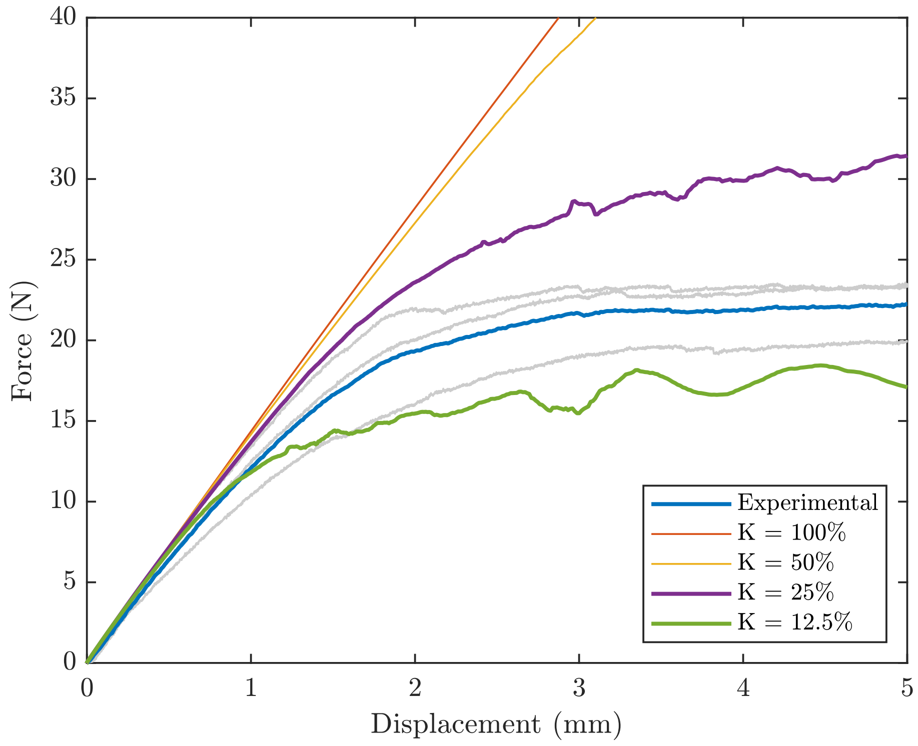
K	σ_I (MPa)	G_I (kJ/m^2)	σ_{II} (MPa)	G_{II} (kJ/m^2)
100 %	9.50	0.51	28.50	1.54
50 %	4.75	0.25	14.25	0.77
25 %	2.38	0.13	7.13	0.39
12.5 %	1.19	0.06	3.56	0.19



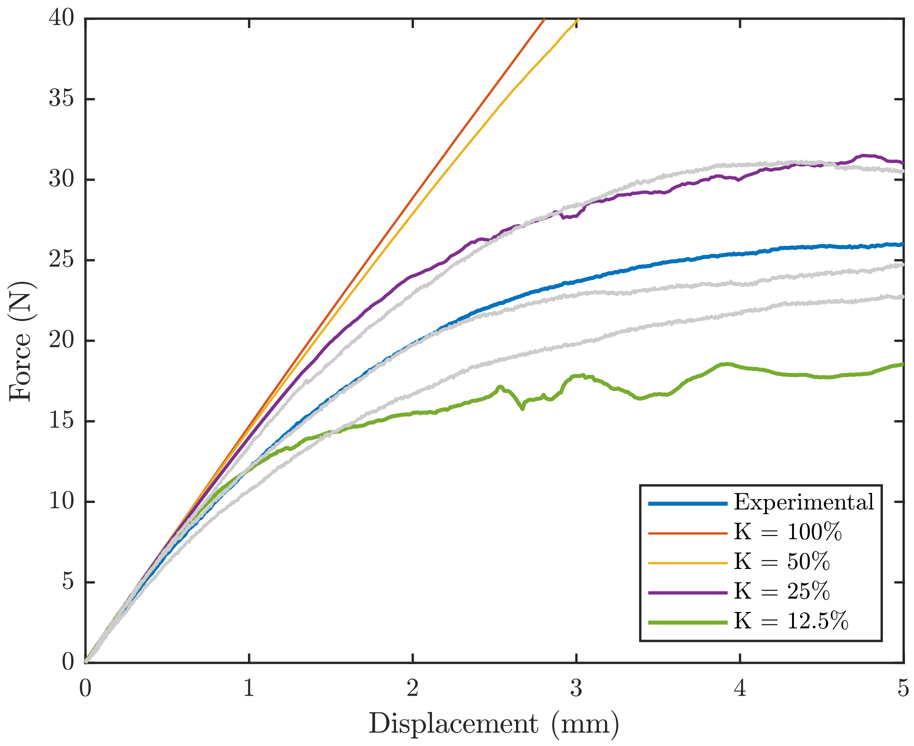
3 Preliminary results

Numerical experimental correlation

Type *A*



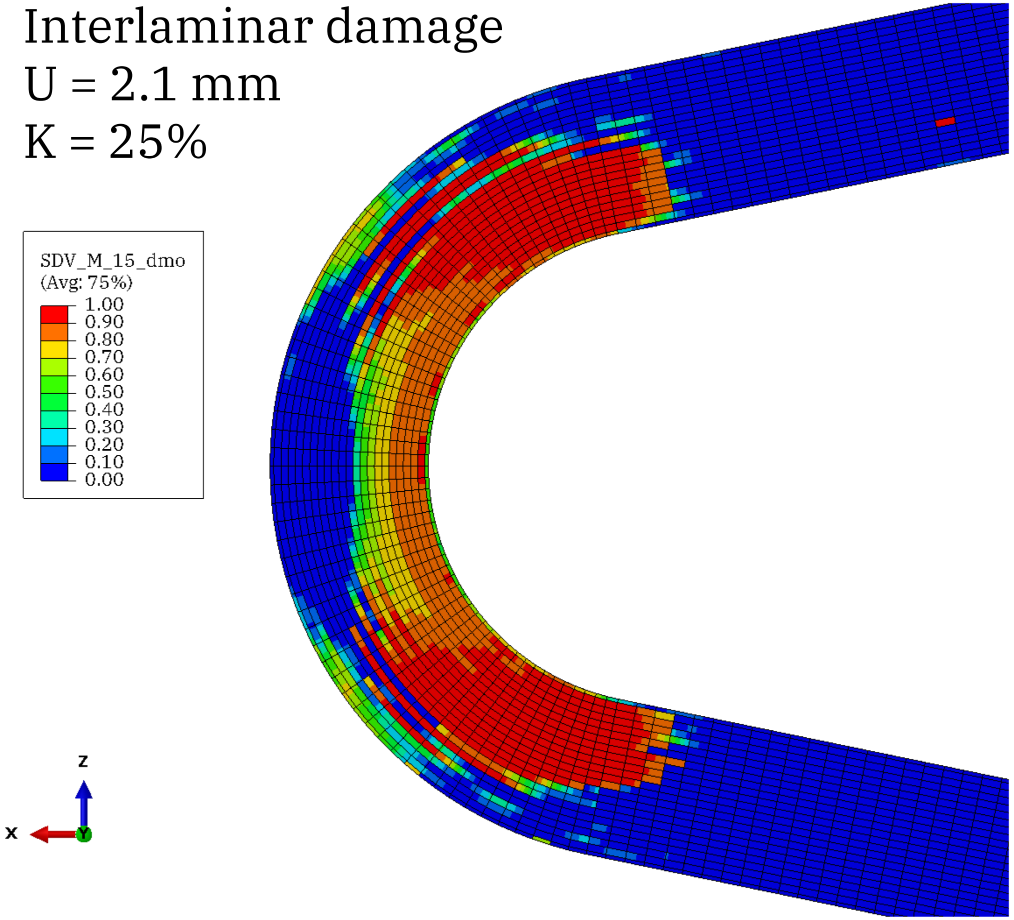
Type *B*



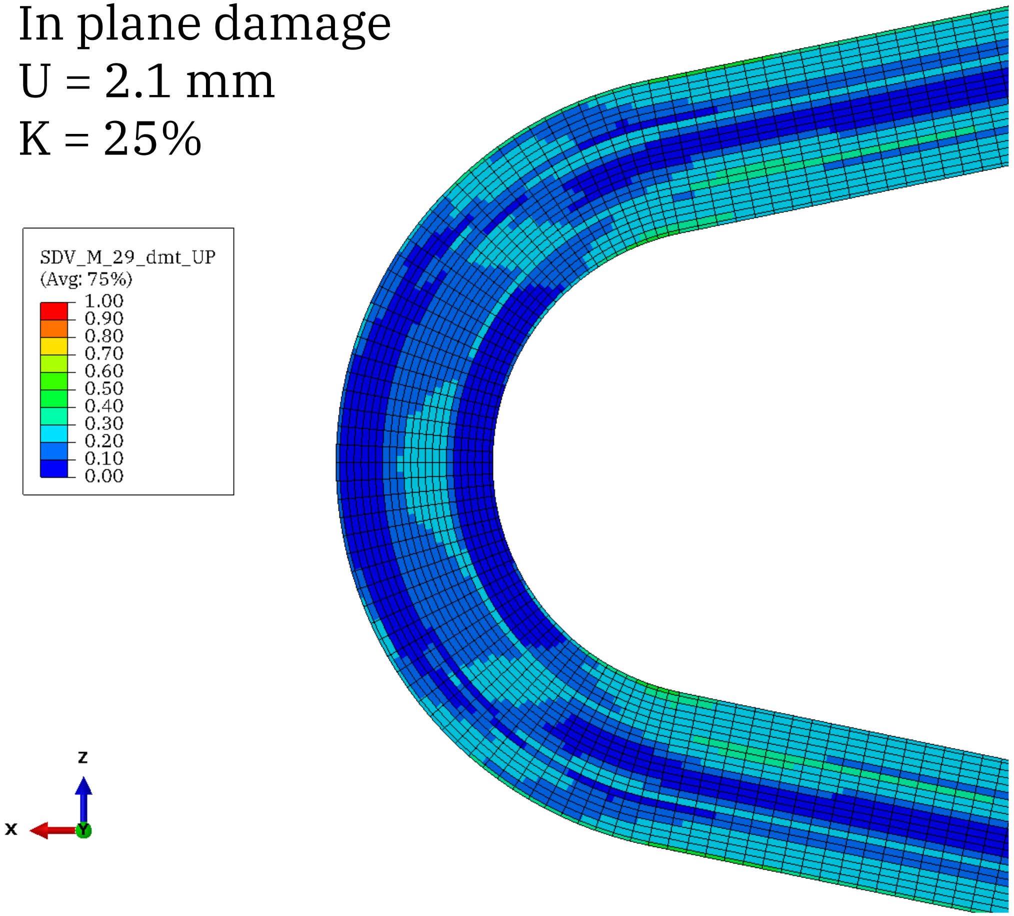
3 Results

Matrix damage distribution – Type A

Interlaminar damage
U = 2.1 mm
K = 25%



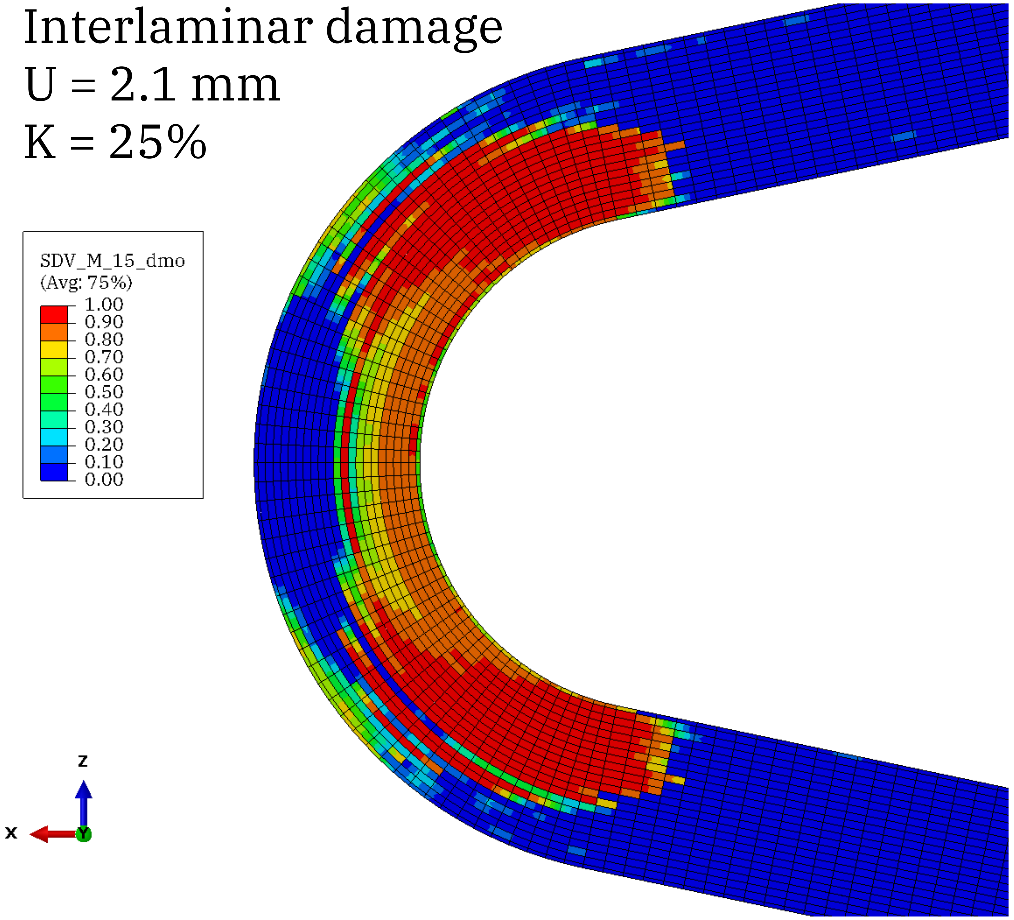
In plane damage
U = 2.1 mm
K = 25%



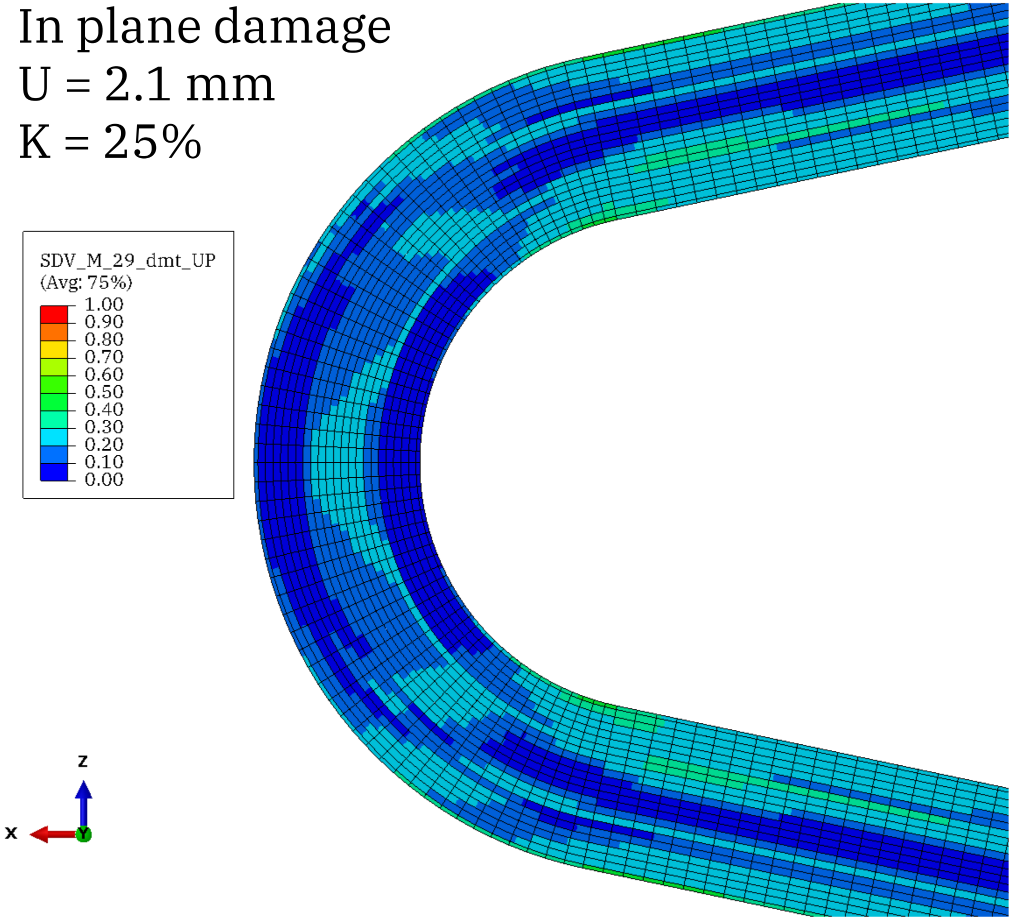
3 Results

Matrix damage distribution – Type B

Interlaminar damage
U = 2.1 mm
K = 25%



In plane damage
U = 2.1 mm
K = 25%



4 Conclusions

Summary

- The material shown good damage tolerance and survived to off design PWT exposure maintaining some residual toughness
- The manufacturing process optimization is fundamental to have good quality in high curvature regions
- The meso-scale model with hybrid technique requires a noticeable reduction of the interlaminar properties to match the experimental response
- The numerical damage pattern is not representative of the experimental one

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Thank you for your attention!

Marco Riva
marco2.riva@polimi.it