MŰEGYETEM 1782

Budapest University of Technology and Economics (BME)

HyFiSyn

DEPARTMENT OF POLYMER ENGINEERING

PSEUDO-DUCTILITY IN LAYER-BY-LAYER HYBRID COMPOSITES THROUGH PRECISE CONTROL OF THE INTERLAYER THICKNESS

Gergely CZÉL (czel@pt.bme.hu)
Salvatore Giacomo Marino (marinos@pt.bme.hu)
Budapest University of Technology and Economics (BME)
Department of Polymer Engineering

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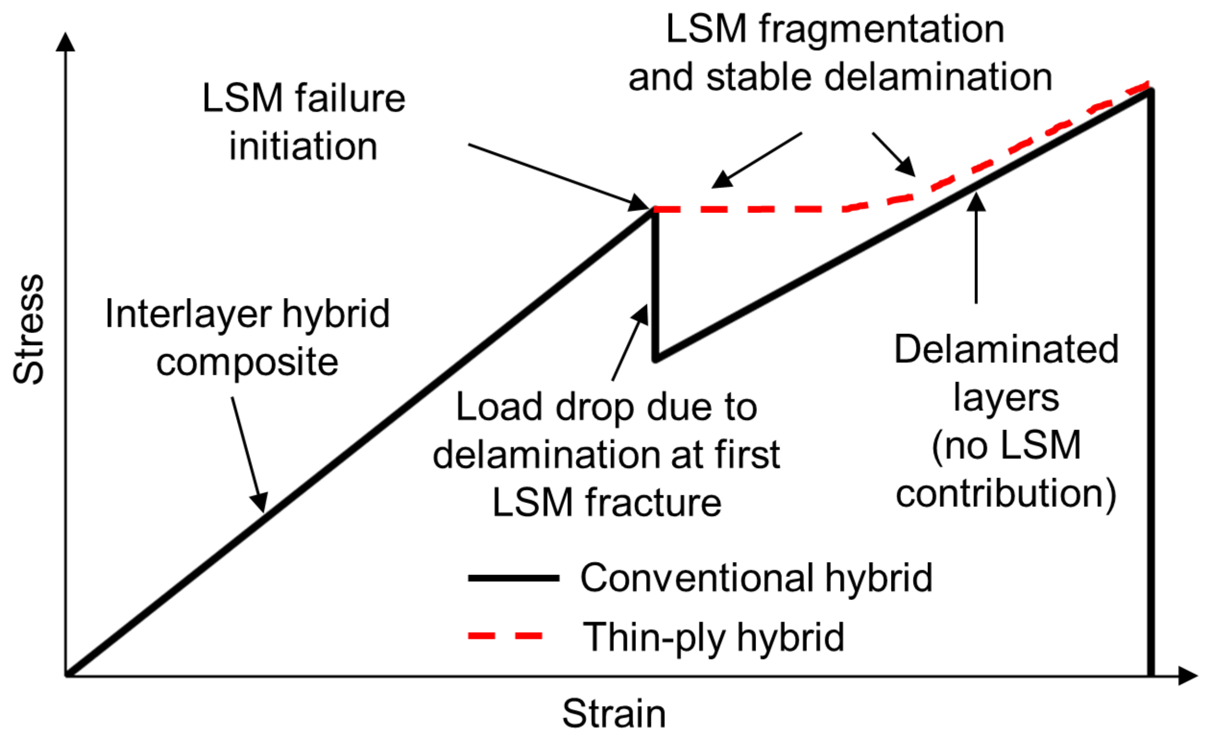
Introduction

- Composites are stiff, strong and lightweight
- But their failure is usually catastrophic
- Ductility is needed for safety
  - High deformation at break
  - Detectable damage accumulation
  - Warning before failure
  - Residual strength after severe damage

State of the art

- **High performance composites**: **stiff** and **strong**, but **failure is sudden and brittle** with **little warning** and **poor residual strength**
- **Pseudo-ductility** with an **intrinsic safety margin** could **change design** approach and offer **major benefits**
- Excellent **pseudo-ductility demonstrated first with thin-ply UD carbon/glass interlayer hybrid laminates in tension**
  - Mechanisms: **fragmentation** and **stable delamination**



State of the art

- **High performance composites**: **stiff** and **strong**, but **failure is sudden and brittle** with **little warning** and **poor residual strength**
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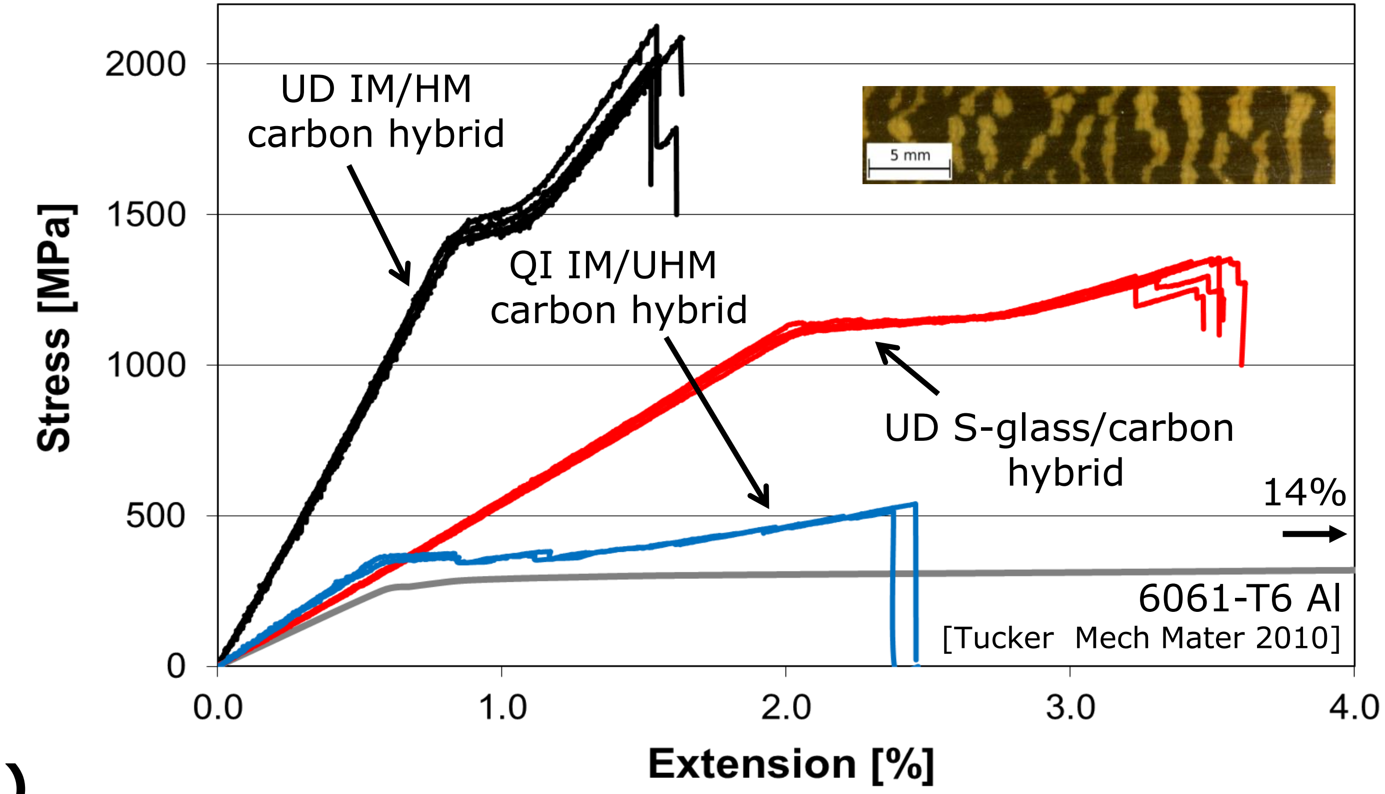


The concept is then extended to:

- **UD IM/HM carbon hybrids**
- **QI IM/UHM carbon hybrids**
- **Visible damage:**
  - **Overload indicator**

  (UK patent pending- no. GB2544792B)

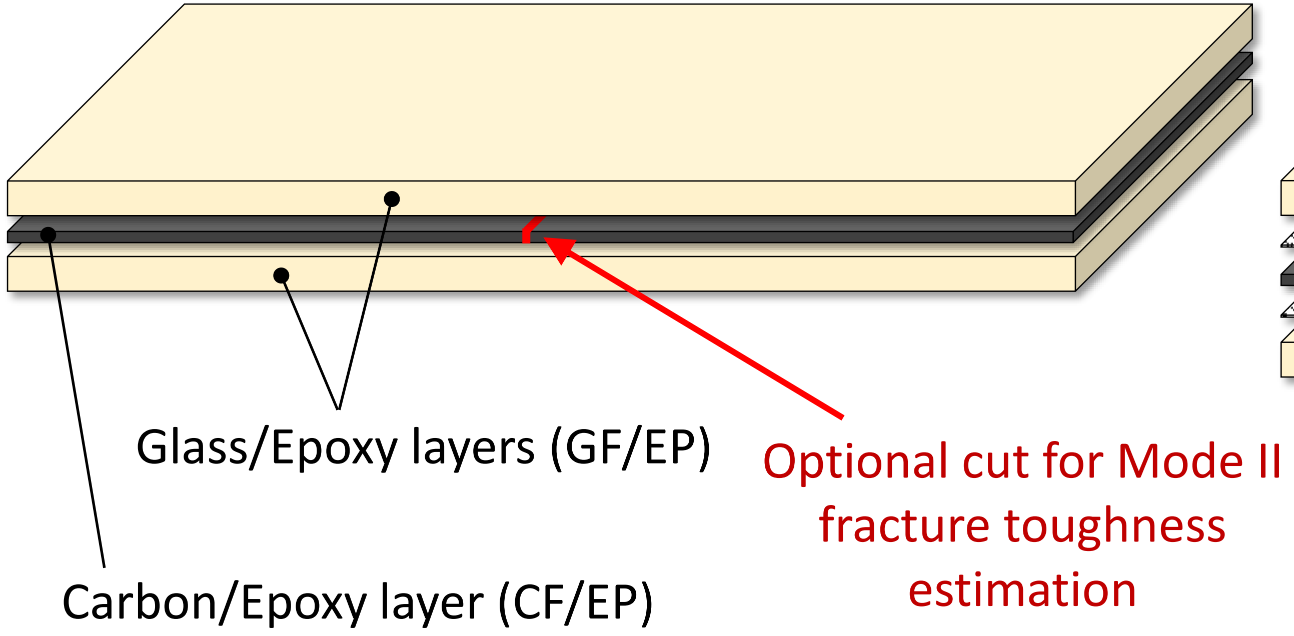
Key challenges

- To develop pseudo-ductile hybrid composites based on standard thickness plies
- Reduce cost by using cheaper normal CF/EP plies instead of thin-ply prepregs
- Improve performance by increasing the CF/EP to GF/EP ratio in the hybrid laminates while preserving pseudo-ductility

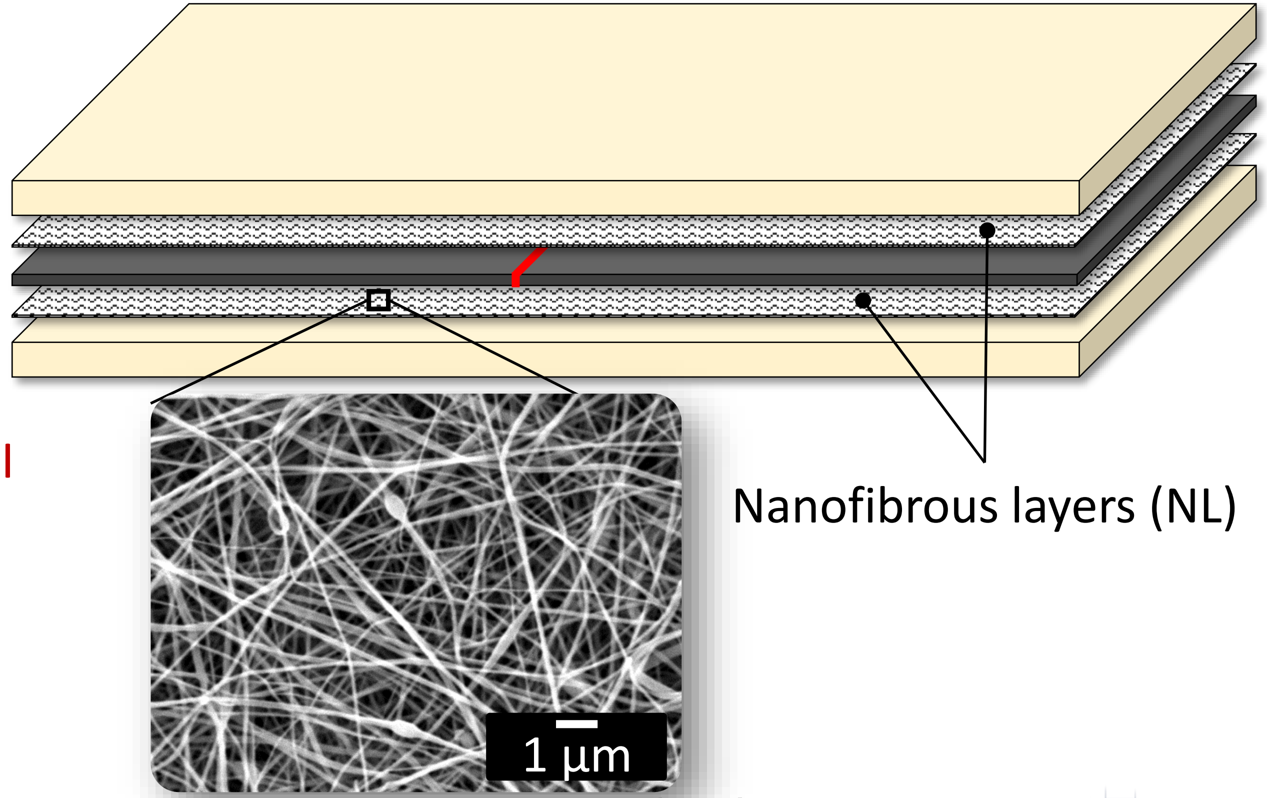
Concept, design

- Pseudo-ductility was demonstrated with thin, high strain CF/EP plies or normal thickness low strength (high modulus) CF/EP plies
- Increase the mode II fracture toughness by interleaving nanofibrous layers and use normal thickness high strain CF/EP

Baseline configuration - [G_3/C/G_3]



Interleaved configuration - [G_3/NL/C/NL/G_3]



Materials

Composite plies

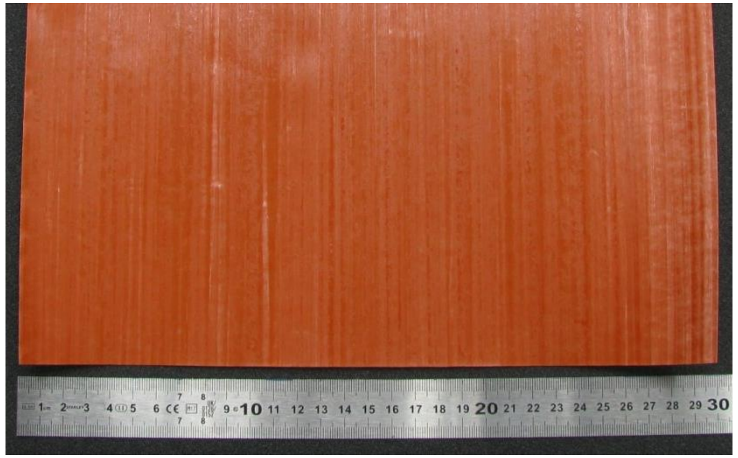
Prepregs	Nominal fibre areal density [g/m²]	Fibre volume fraction [-]	Cured ply thickness [µm]	Tensile strain to failure [%]	Tensile modulus [GPa]	Coefficient of thermal expansion [1/K]
AGY Y-110 S-2 glass/913 epoxy	190	0.49	153.8	3.7	45.6	$3.20 \cdot 10^{-6}$
Hexcel IM7 carbon/913 epoxy	100	0.58	95.8	1.6%	163.2	$-0.103 \cdot 10^{-6}$

Nanofibrous layers

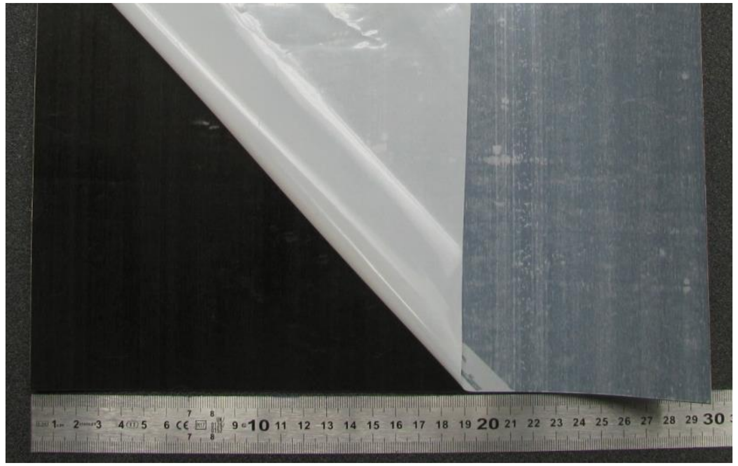
Targeted areal weight [g/m²]	*Electrospinning solution PA6 concentration: 8wt% (designation: 8PA6)*			*Electrospinning solution PA6 concentration: 15wt% (designation: 15PA6)*		
	Measured final areal weight [g/m²]	**Substrate speed [m/min]**	**Average fibre diameters [nm]**	**Measured final areal weight [g/m²]**	**Substrate speed [m/min]**	**Average fibre diameters [nm]**
2	2.3 (7.7)	0.20	108 (20.4)	2.44 (8.6)	0.80	267 (26.6)
5	5.26 (11.0)	0.12	103 (19.8)	5.68 (11.8)	0.36	243 (27.6)
10	10.92 (12.4)	0.05	121 (18.0)	10.66 (8.8)	0.22	280 (31.4)

Materials, manufacturing

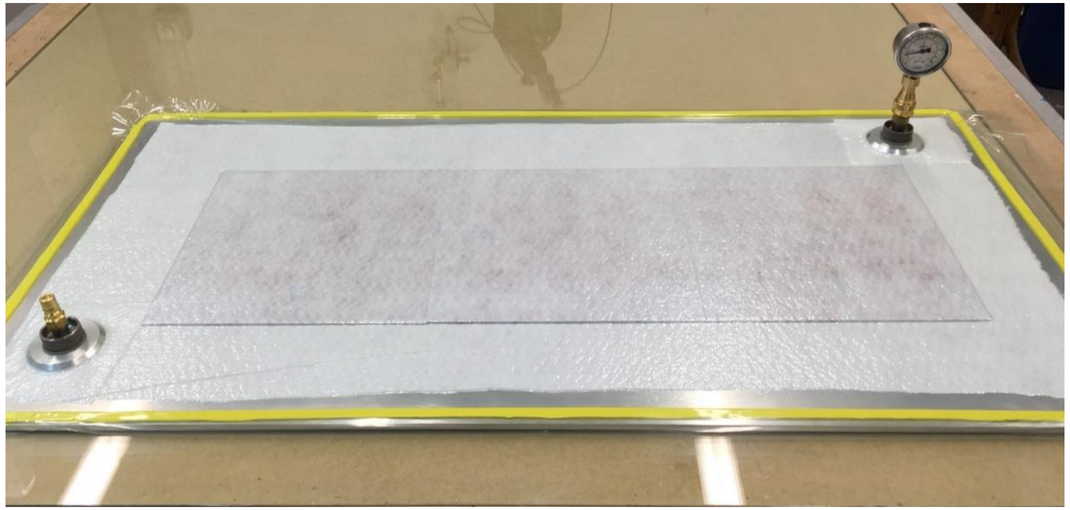
UD glass/epoxy prepreg

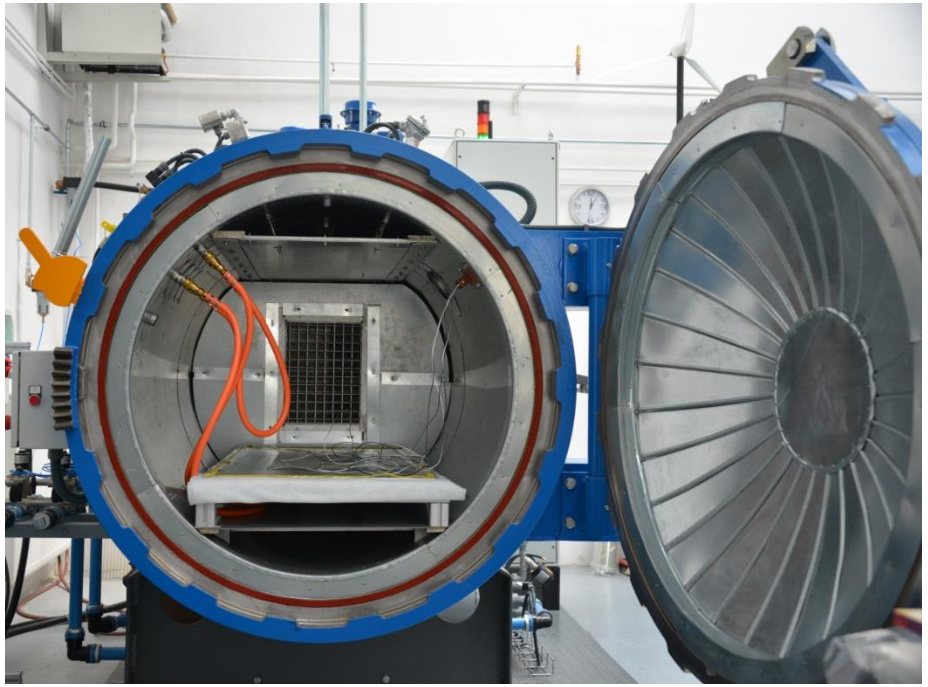


UD carbon/epoxy prepreg



- Manual lay-up of the composite prepreg plies
- Attaching dry nanofibrous layers to the prepregs
- Autoclave curing of the interleaved hybrid laminates at 125 °C and 7 bar



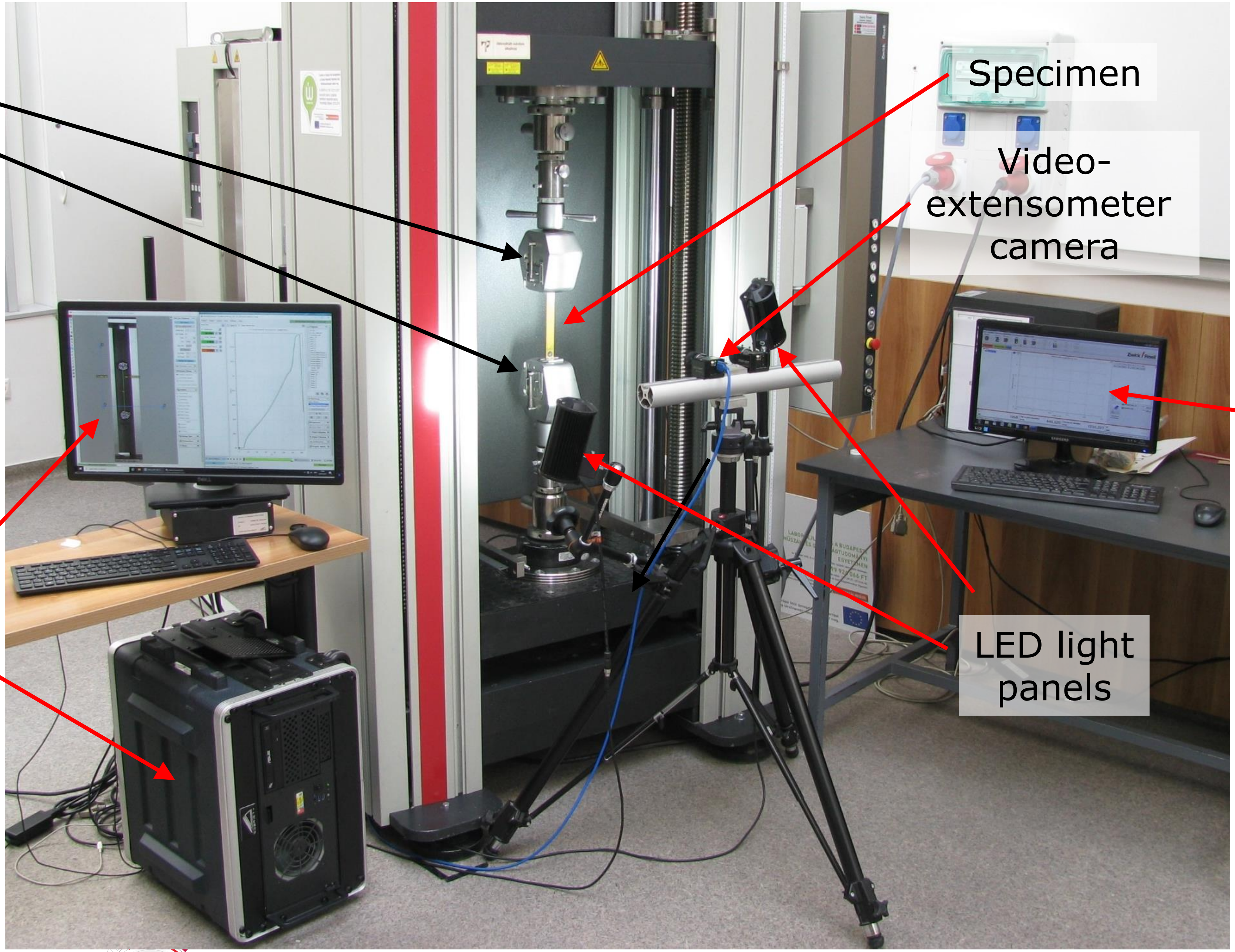


Tested hybrid laminate configurations

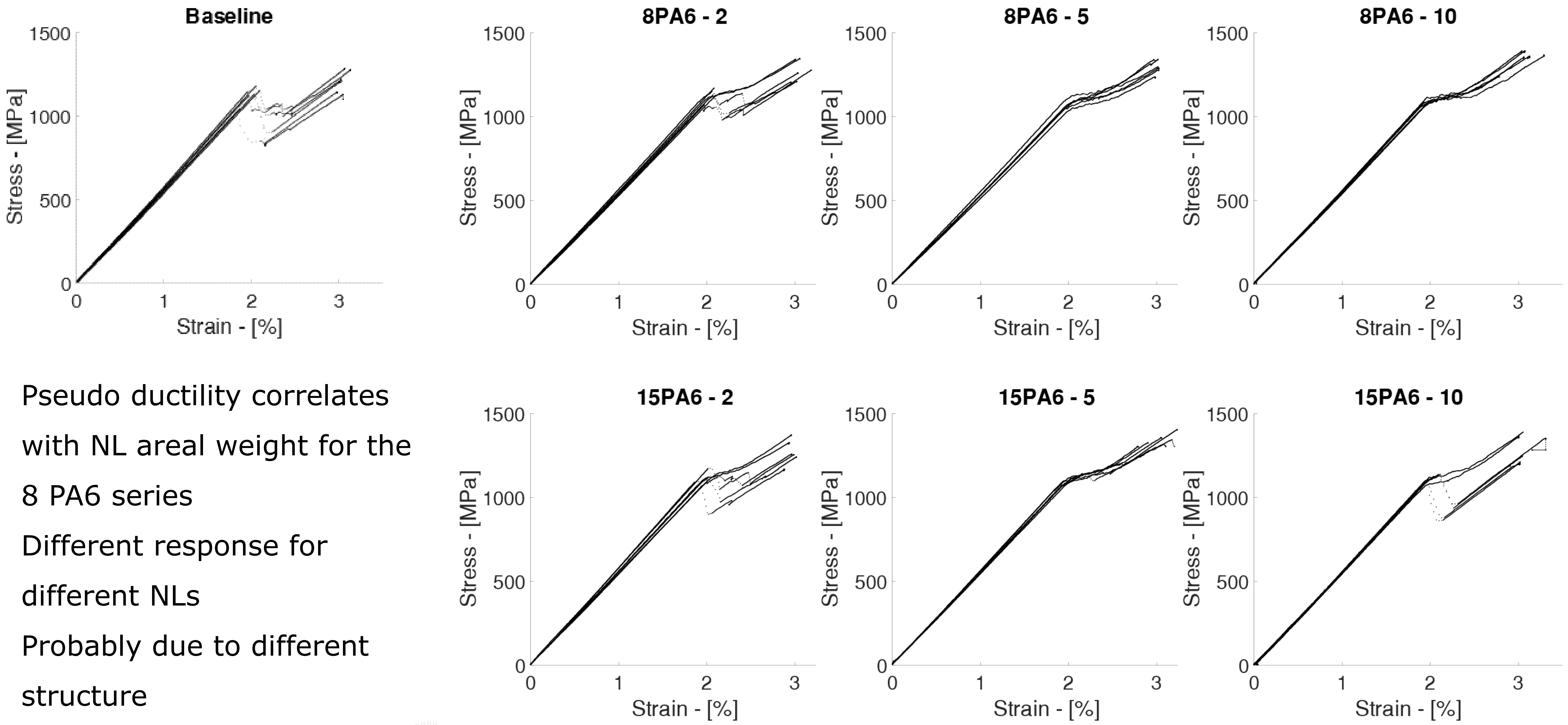
Configurations Lay-up sequence: $[G_3/NL/C/NL/G_3]$ Key: 8 PA6-2: 2 g/m² nanofibrous layer from a 8% PA6 solution	Fibre areal densities of the constituent plies [g/m²]	Measured thickness *h* [mm]
Baseline	$[190_3/0/100/0/190_3]$	1.08 (1.9)
8PA6-2	$[190_3/2/100/2/190_3]$	1.09 (2.1)
8PA6-2+RF	$[190_3/2+34/100/2+34/190_3]$	1.14 (2.1)
8PA6-5	$[190_3/5/100/5/190_3]$	1.11 (2.0)
8PA6-10	$[190_3/10/100/10/190_3]$	1.11 (1.9)
8PA6-5+5	$[190_3/5+5/100/5+5/190_3]$	1.07 (2.1)
8PA6-10+10	$[190_3/10+10/100/10+10/190_3]$	1.10 (2.8)
15PA6-2	$[190_3/2/100/2/190_3]$	1.09 (2.2)
15PA6-5	$[190_3/5/100/5/190_3]$	1.10 (2.2)
15PA6-10	$[190_3/10/100/10/190_3]$	1.10 (1.9)

NL- Nanofibrous layer
C- Carbon/epoxy
G- Glass/epoxy
RF- 34 g/m² epoxy film

Quasi-static uniaxial tensile test setup



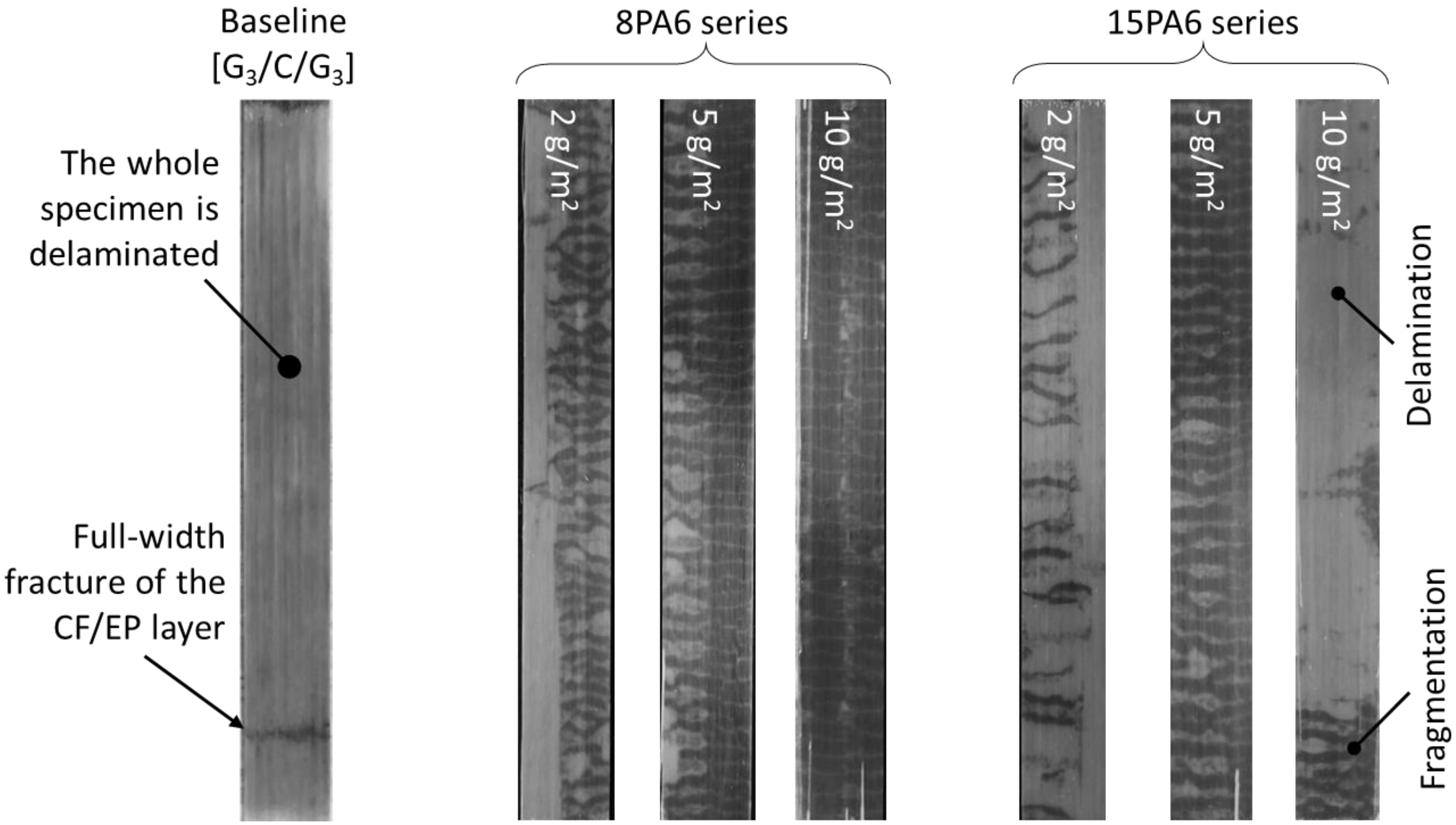
Test results- Stress-strain response



- Pseudo ductility correlates with NL areal weight for the 8 PA6 series
- Different response for different NLs
- Probably due to different structure

Test results- Damage modes

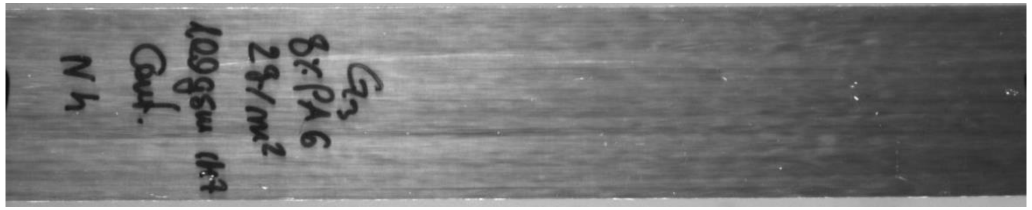
- All series performed much better than baseline
- Mixed delamination and fragmentation for the non-pseudo-ductile series
- Close to borderline



Test results- Damage sequence

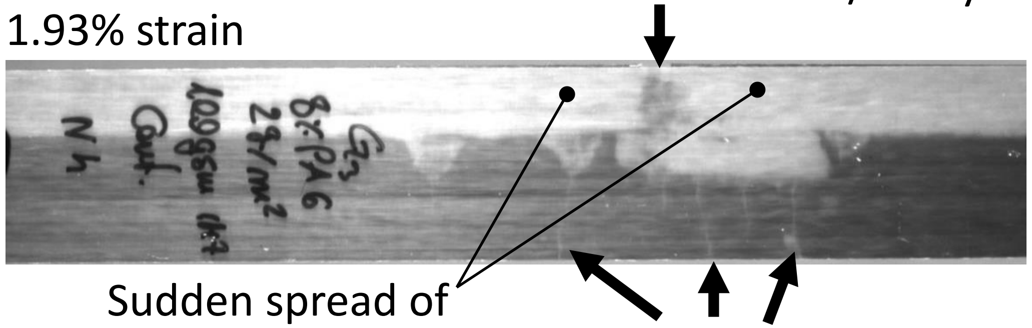
Delamination + fragmentation (8PA6-2)

1.92% strain (no damage)



First Fracture of the CF/EP layer

1.93% strain

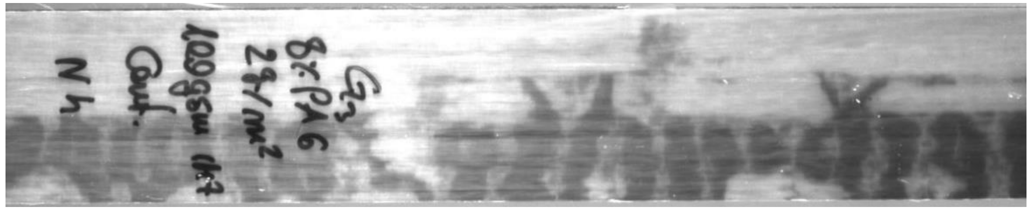


Sudden spread of delamination

Fragmentation

2.8% strain

Damage saturation

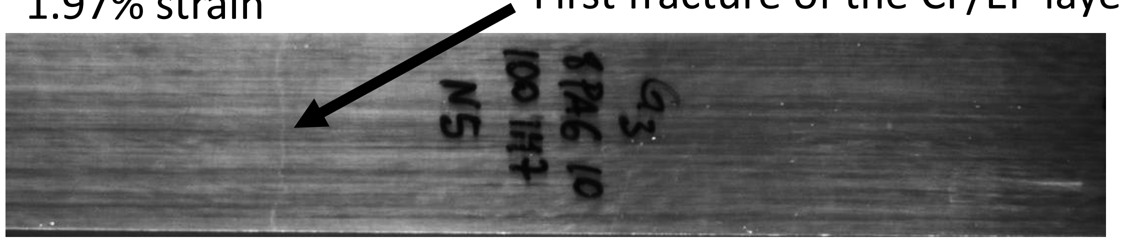


Delamination around fragments

Fragmentation (8PA6-10)

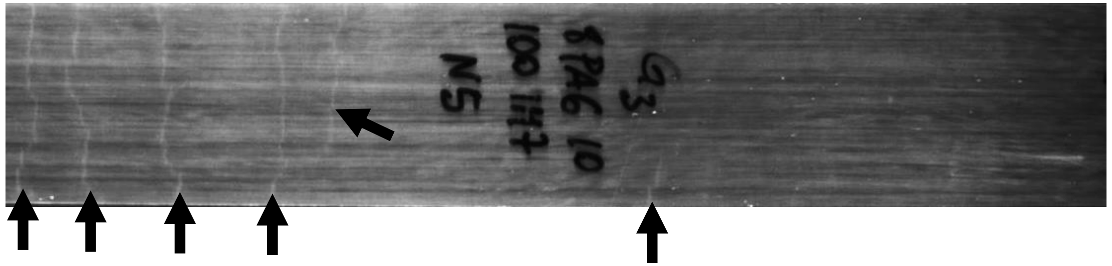
1.97% strain

First fracture of the CF/EP layer



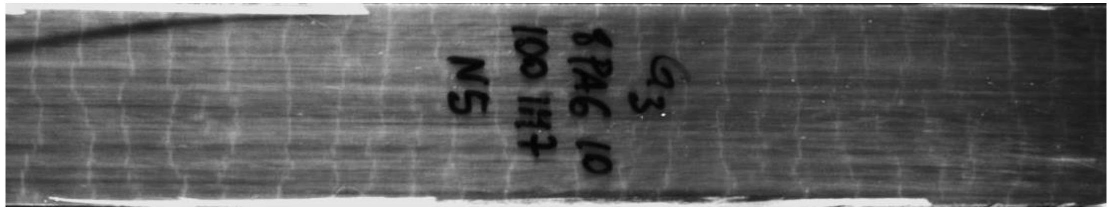
2.1% strain

Progression of fragmentation

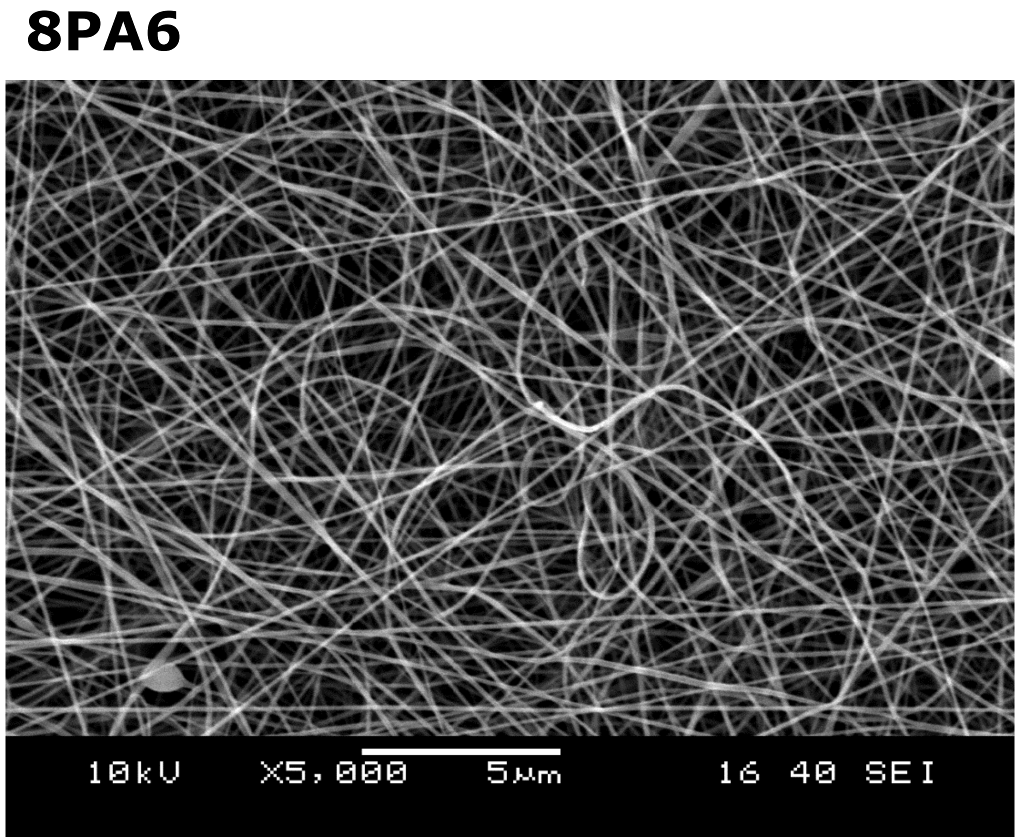


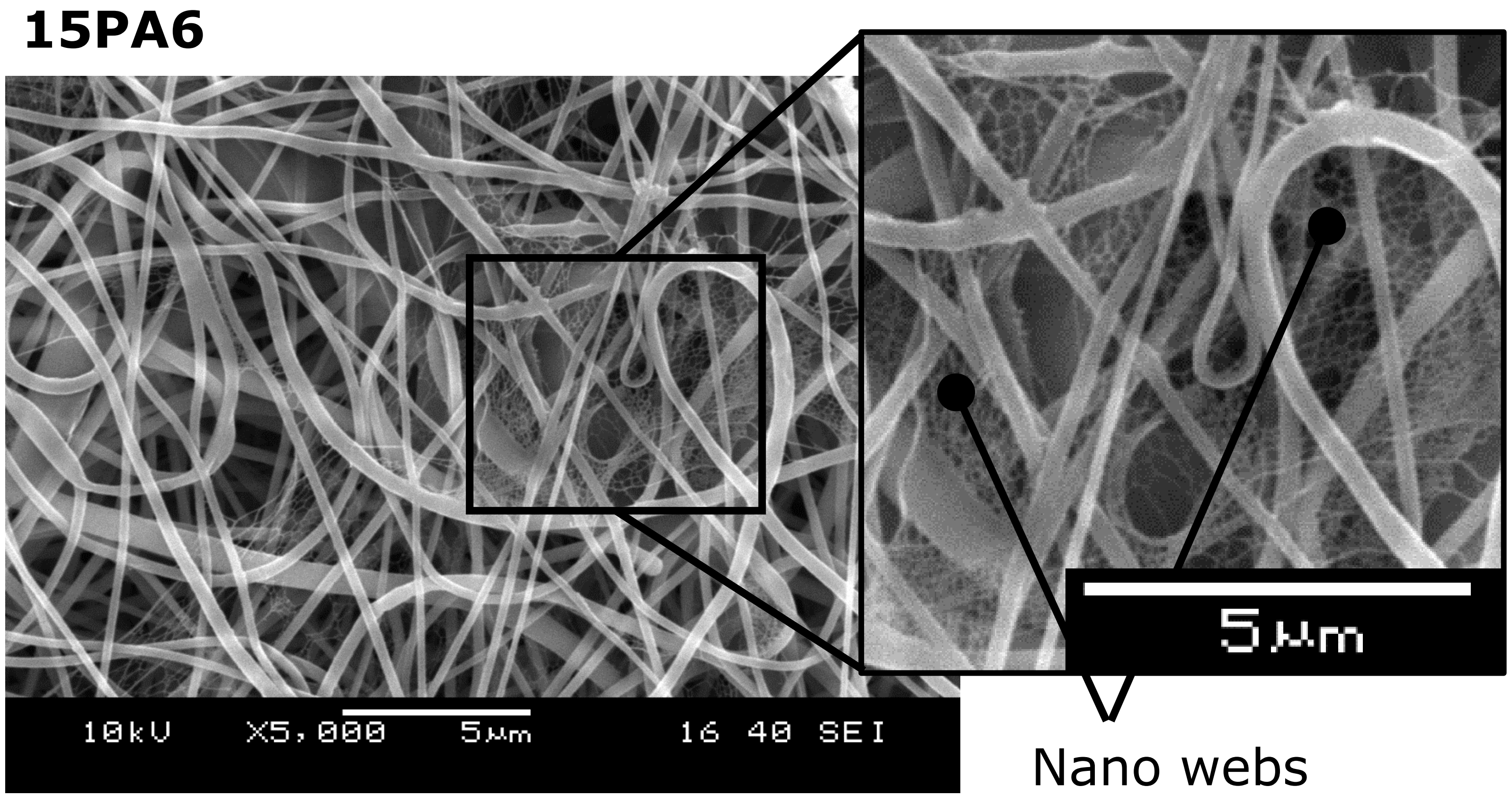
2.8% strain

Saturation of fragmentation



Test results- NL structure

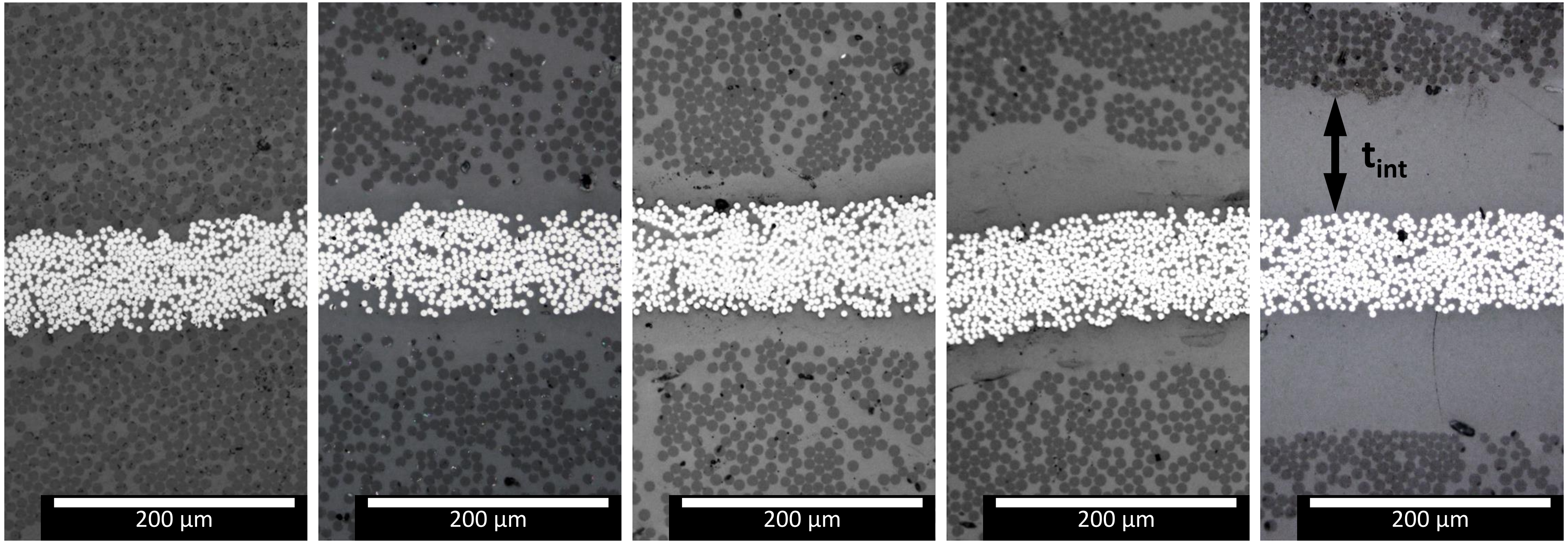




- Different diameters for different PA6 concentrations
- Nano webs for 15PA6
- Possibly different impregnation properties

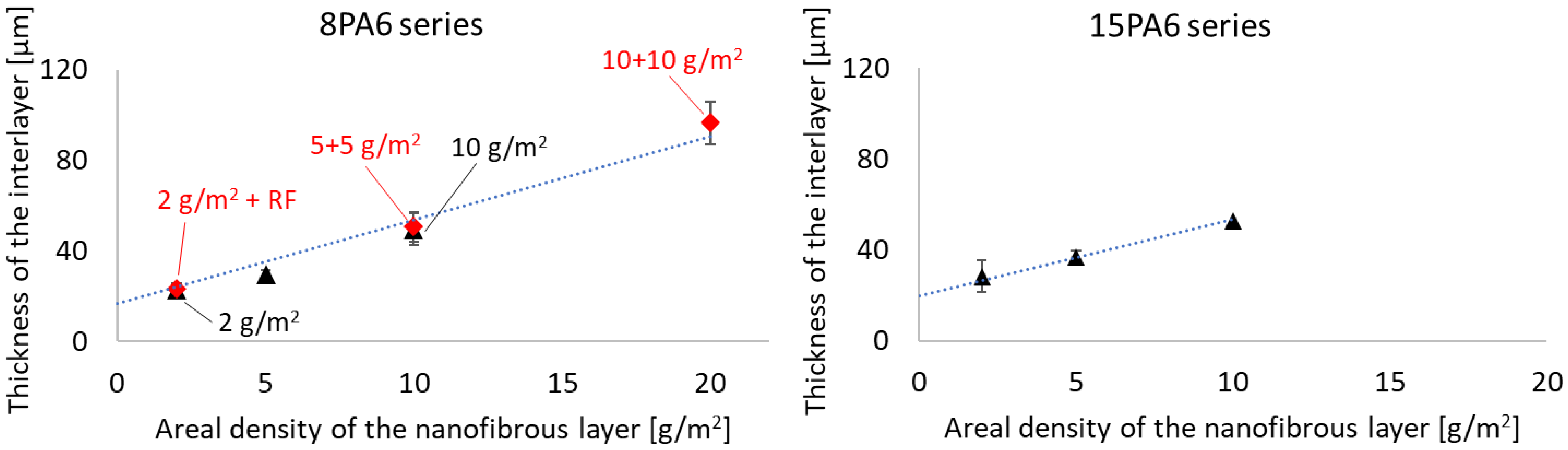
Test results- Thickness of the interlayer

Baseline **8PA6-2** **8PA6-5** **8PA6-10** **8PA6-10+10**

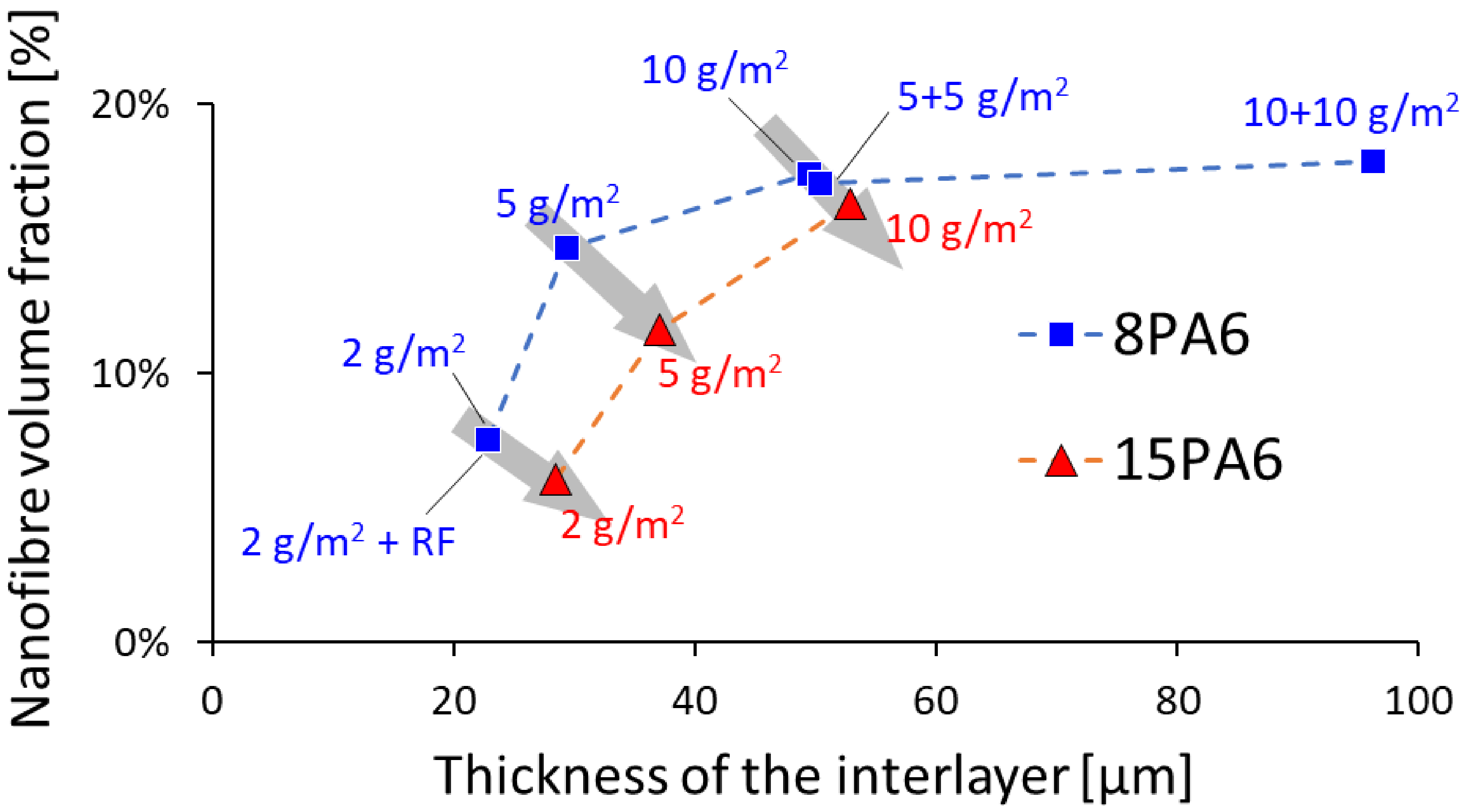


Average t_{int} = 23 µm | Average t_{int} = 29 µm | Average t_{int} = 49 µm | Average t_{int} = 96 µm

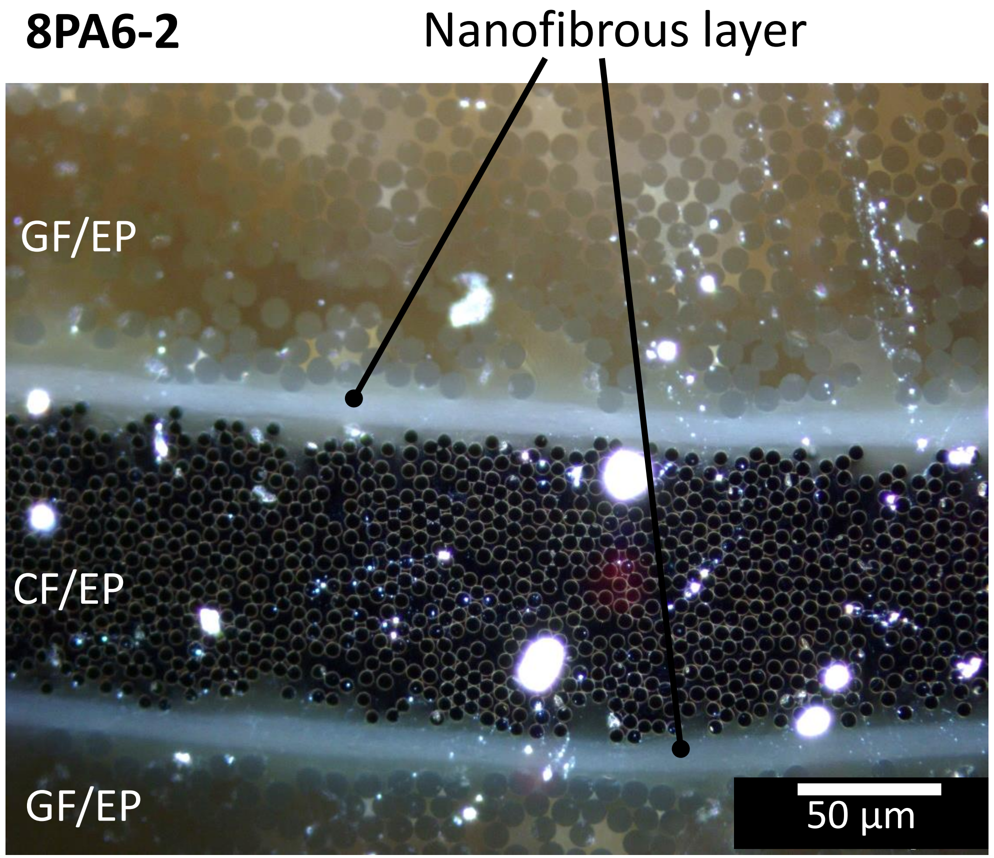
Test results- Thickness of the interlayer

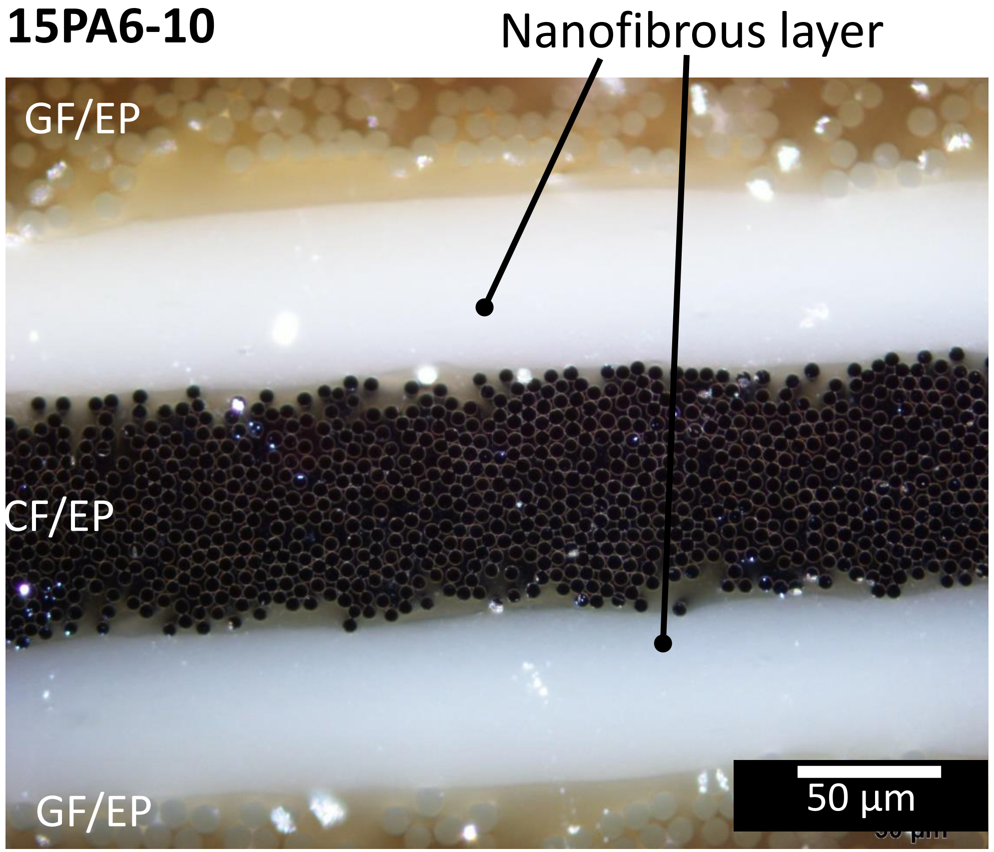


Test results- Nanofibre volume fraction in the interlayer



Results- Cross section microscopy

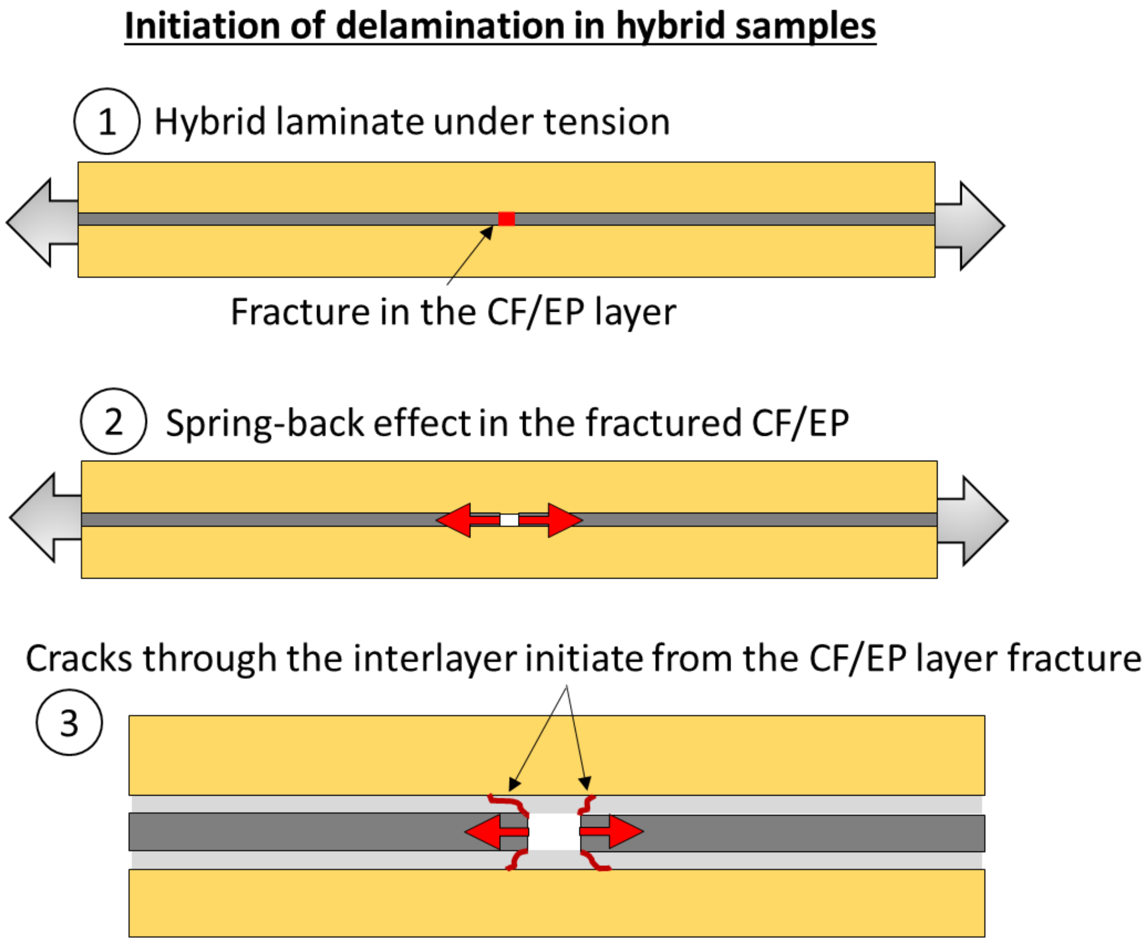


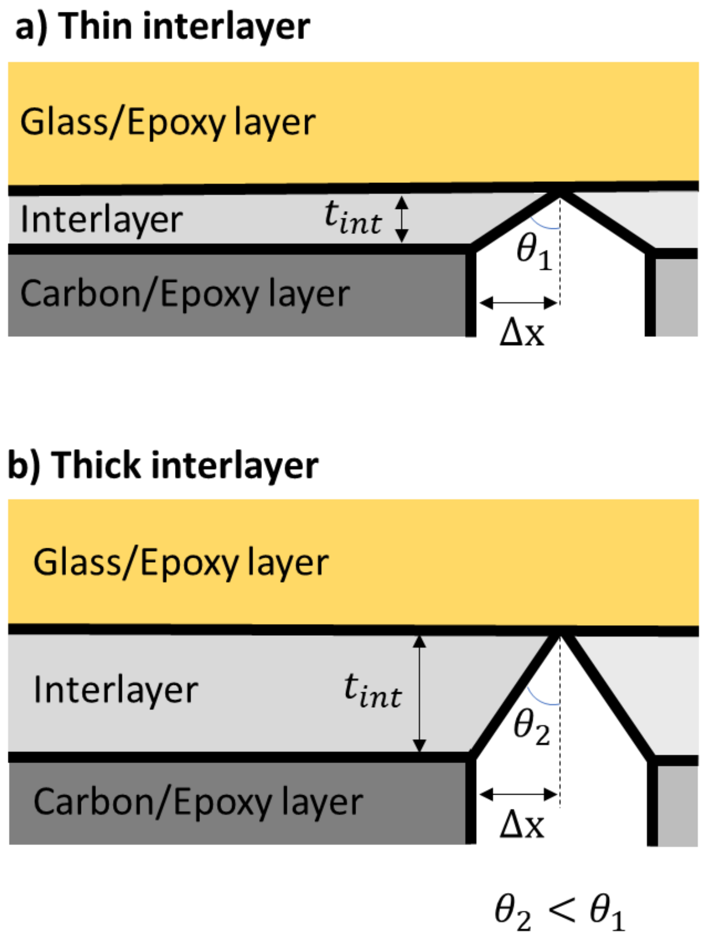


- NLs are well infiltrated with epoxy and form interlayers between the composite layers
- Interlayer thickness is well controlled by the NL areal weight

Anticipated toughening mechanism

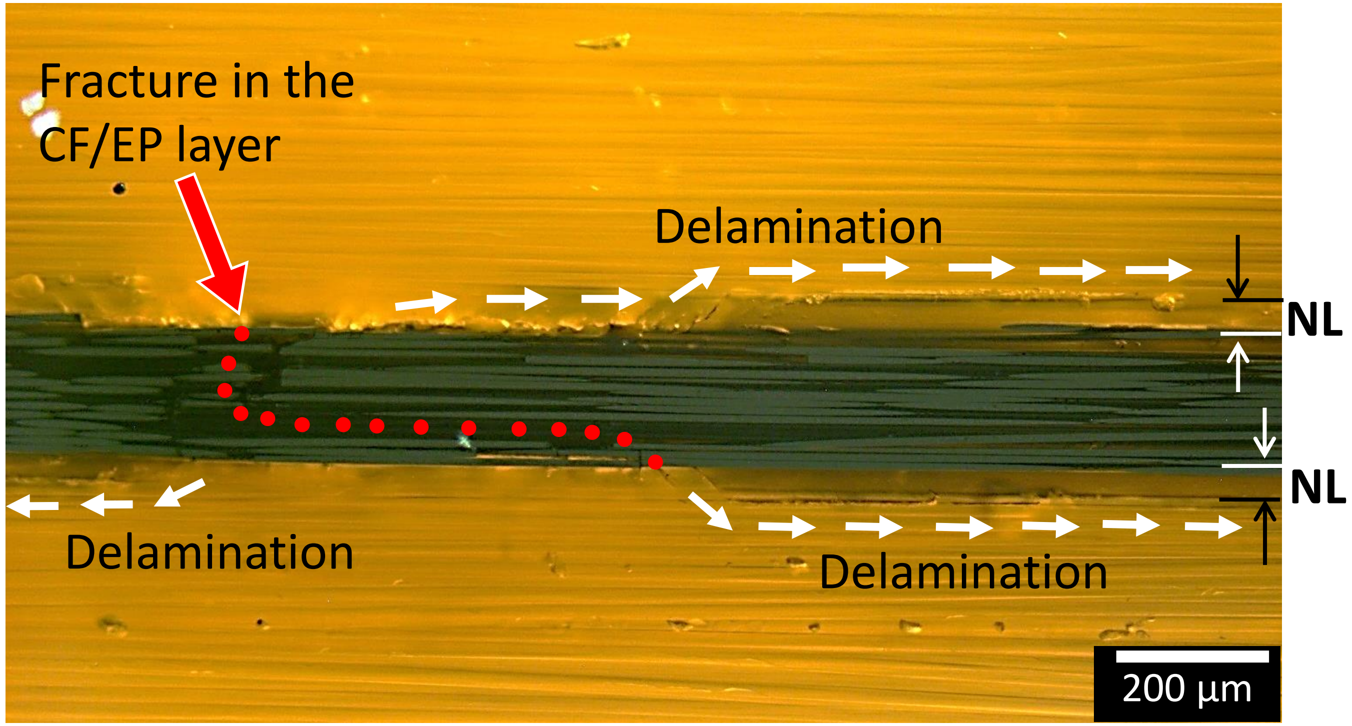
- Thick interlayer goes under proportionally lower shear strain
- Can accommodate higher displacements across the interface
- Can extend the damage process zone
- Expected to knock down singular shear stress at the delamination crack tip



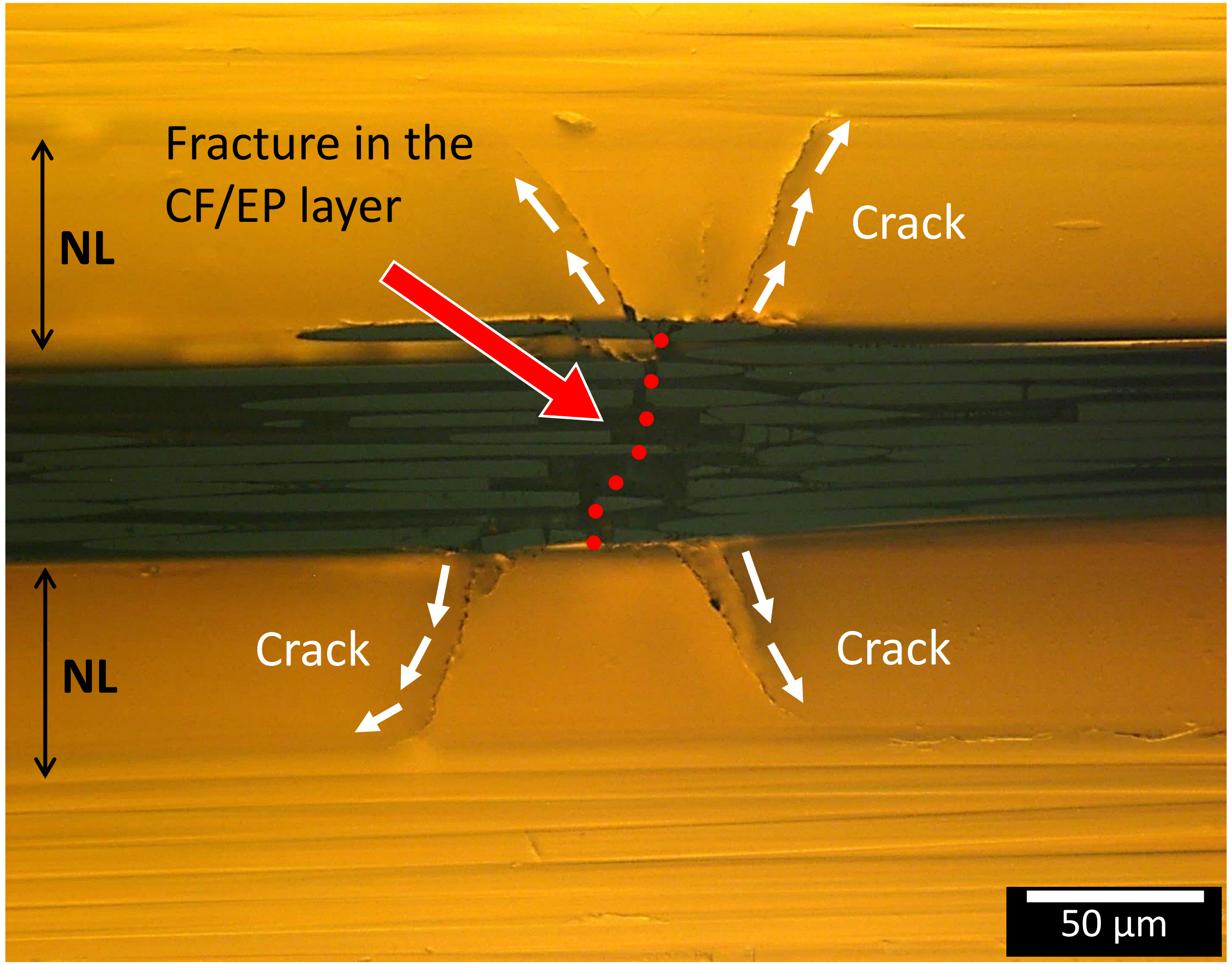


Results- Longitudinal section microscopy

8PA6-2

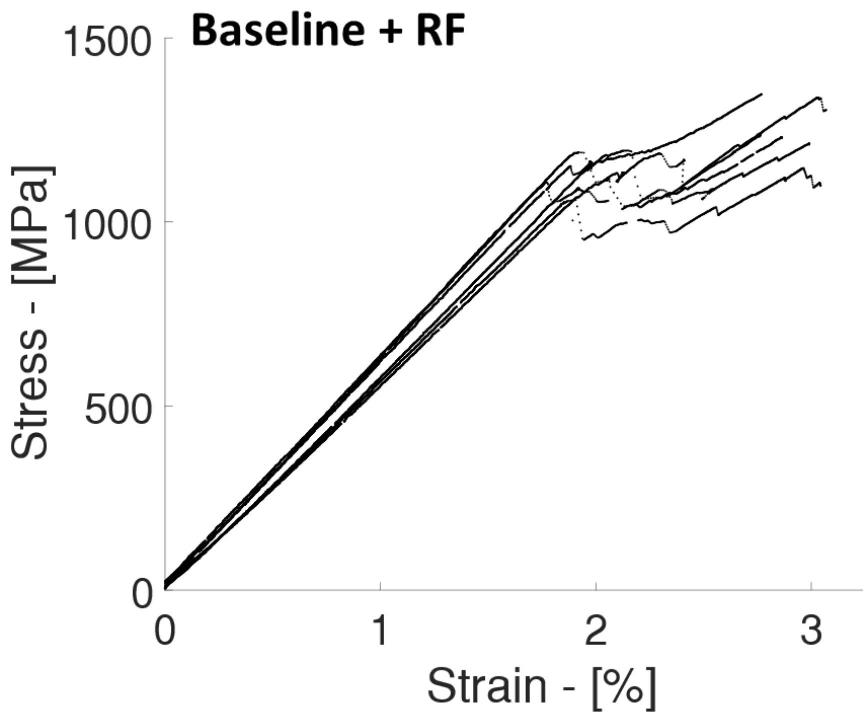


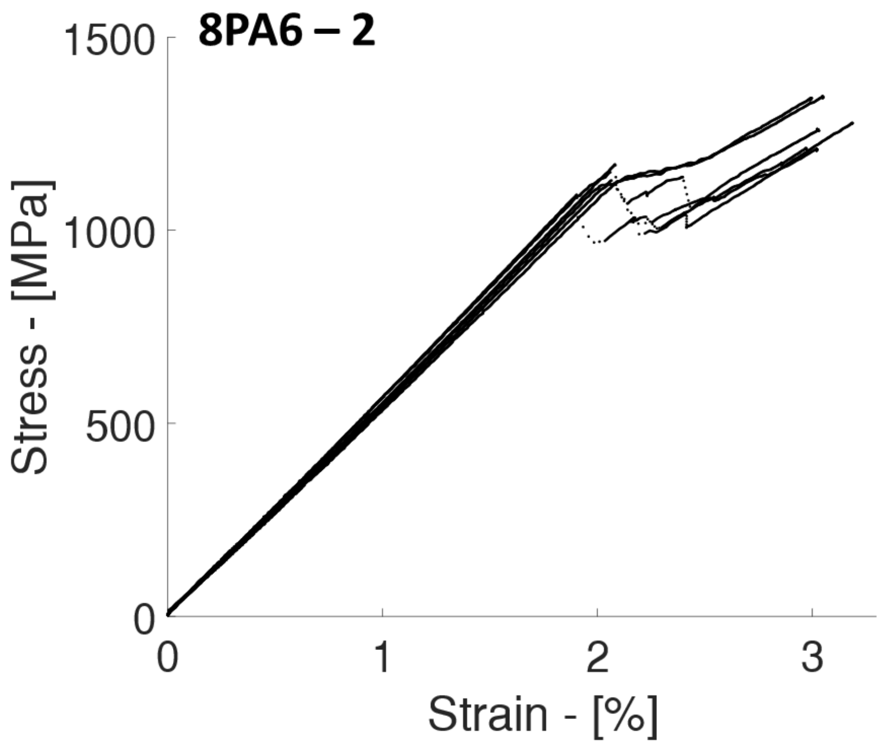
8PA6-10

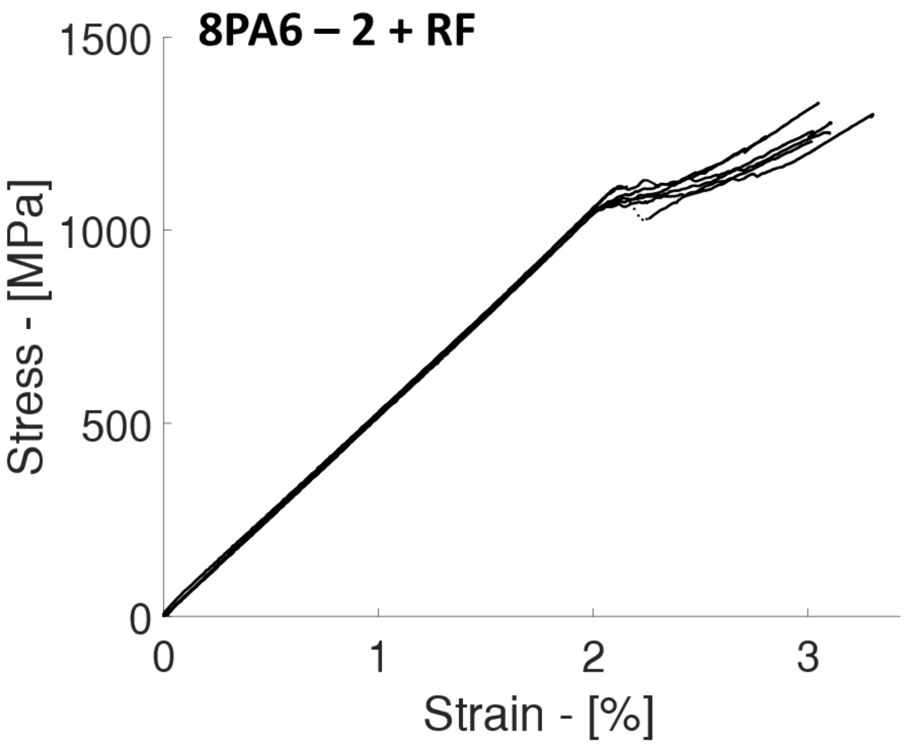


- Thin interlayer cannot suppress delamination completely
- Thick interlayer arrests delamination cracks

Test results- Effect of extra epoxy film

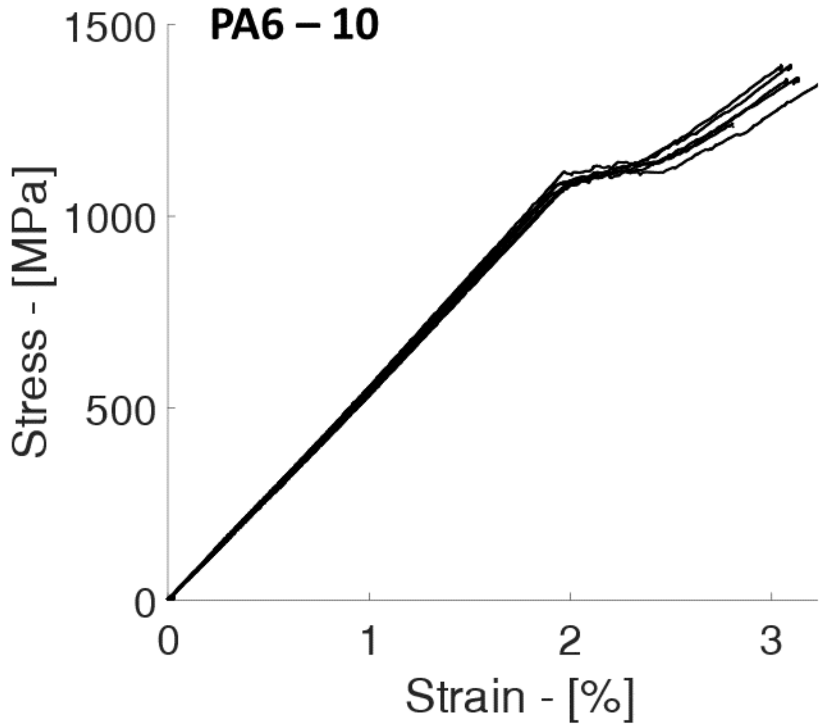


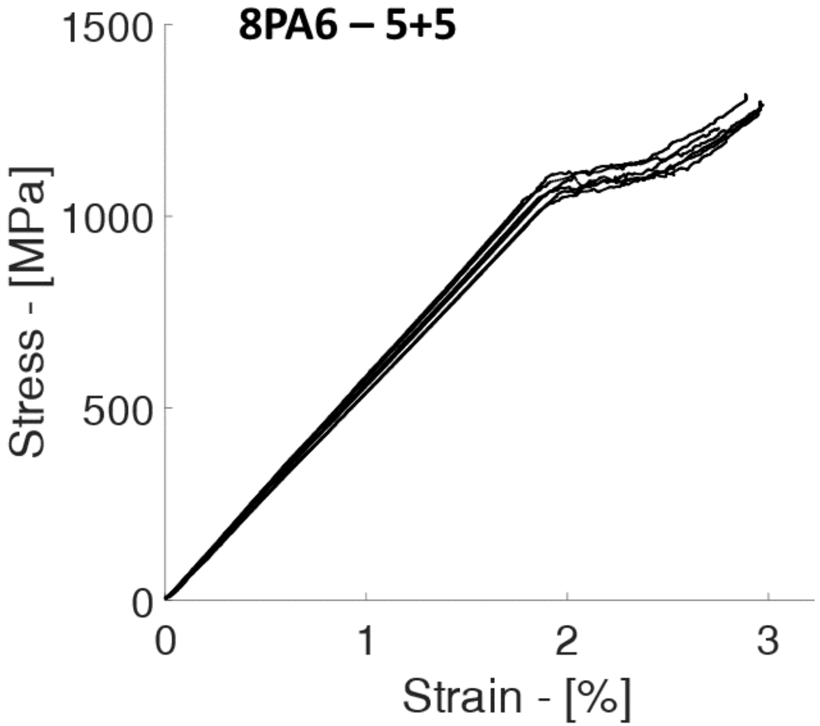


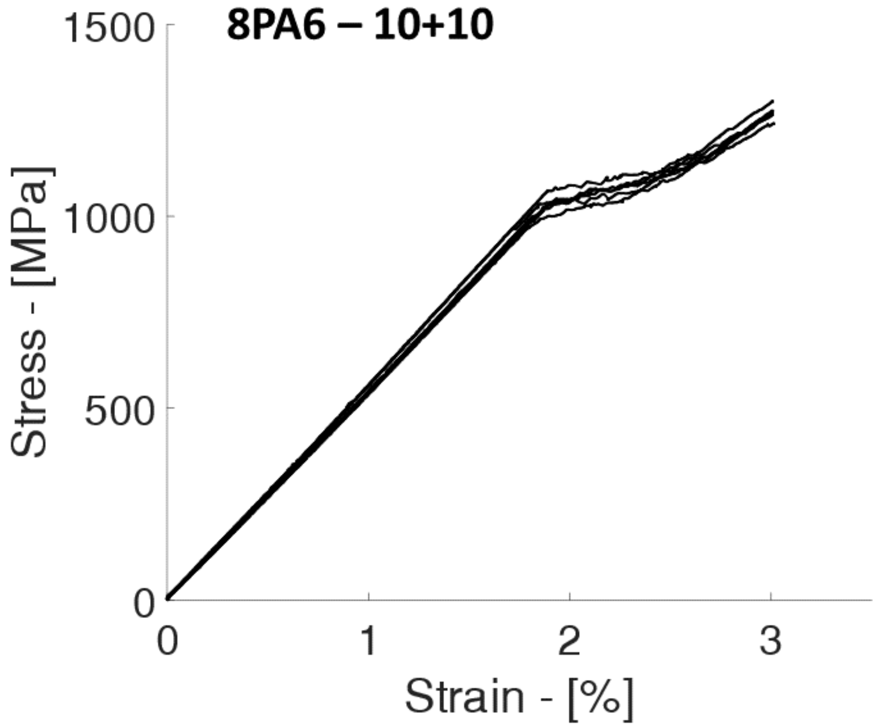


- Possible synergy between NL and epoxy film stabilising borderline response

Test results- Effect of stacking multiple NLs

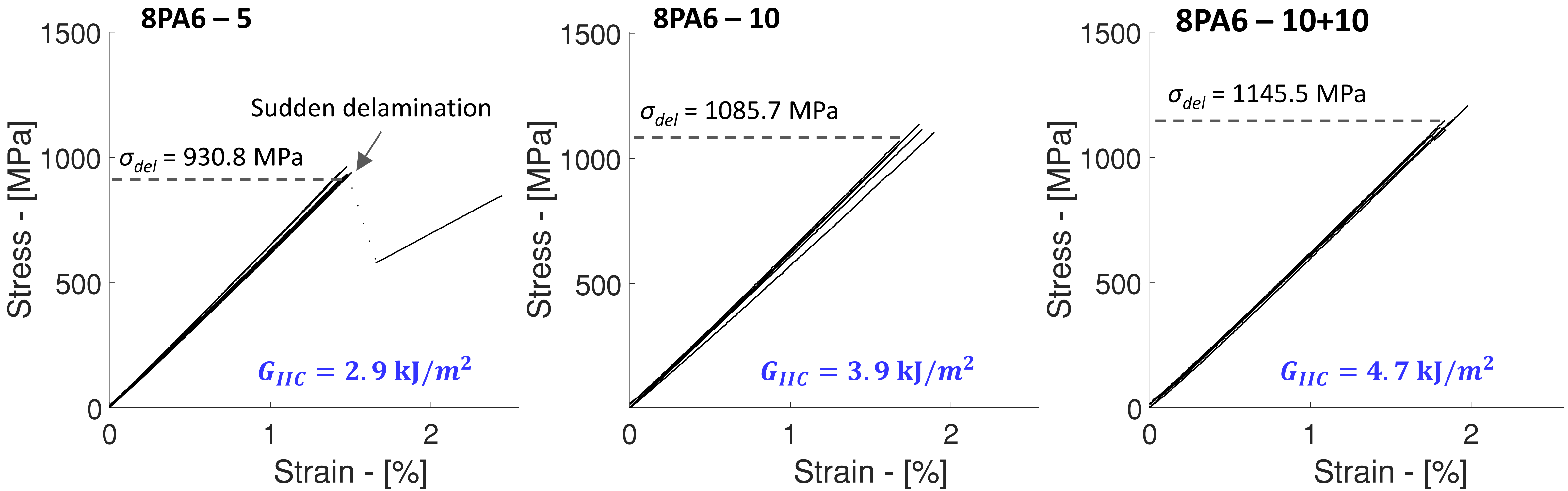






- Stacked NLs with the same areal weight perform similarly
- Thicker NL stack improves pseudo-ductility and mode II fracture toughness

Test results- Mode II fracture toughness improvement



- Significant improvement of G_{IIC} from 1.8 kJ/m^2 (baseline) up to 4.7 kJ/m^2
- Saturation is expected above 10+10 g/m^2 NL areal weight

Results summary- 8PA6 series

Configuration	Baseline	Interleaved configurations [G_3/NL/C/NL/G_3] (NL refers to the Nanofibrous Layer)					
		8PA6-2	8PA6-2+RF	8PA6-5	8PA6-10	8PA6-5+5	8PA6-10+10
Measured thickness [mm]	1.08 (1.9)	1.09 (2.1)	1.14 (2.1)	1.11 (2.0)	1.11 (1.9)	1.07 (2.1)	1.10 (2.8)
Elastic modulus [GPa]	58.0 (2.7)	56.6 (2.6)	54.5 (2.0)	55.7 (3.8)	56.8 (1.5)	56.5 (4.1)	54.8 (4.2)
Knee-point stress [MPa]	1134[(a)] (3.7)	1124 (3.0)	1070 (2.9)	1099 (3.9)	1096 (2.1)	1074 (3.9)	1014 (4.1)
Knee-point strain [%]	1.99[(a)] (3.4)	2.02 (3.3)	2.02 (3.4)	2.02 (2.7)	1.97 (1.3)	1.93 (1.9)	1.87 (2.2)
Strain energy release rate @knee-point [kJ/m²]	2.4 (9.3)	2.5 (8.3)	2.4 (6.9)	2.4 (10.2)	2.4 (6.4)	2.1 (11.1)	2.0 (11.9)
Mode II interlaminar fracture toughness[(b)] [kJ/m²]	1.8 (7.4)	- -	- -	2.9 (8.1)	3.9 (6.6)	- -	4.7 (7.8)

(a) Evaluated from the load drop in the stress-strain curves of this configuration.

(b) Measured on [G_3/NL/C_2/NL/G_3] laminates with a cut in the middle of the CF/EP layer.

Results summary- 15PA6 series

Configuration	Baseline	Interleaved configurations [G_3/NL/C/NL/G_3] (NL refers to the Nanofibrous Layer)		
		15PA6-2	15PA6-5	15PA6-10
Measured thickness [mm]	1.08 (1.9)	1.09 (2.2)	1.10 (2.2)	1.10 (1.9)
Elastic modulus [GPa]	58.0 (2.7)	56.8 (3.1)	57.0 (2.7)	57.3 (1.5)
Knee-point stress [MPa]	1134 (3.7)	1122 (2.8)	1113 (2.3)	1108 (2.2)
Knee-point strain [%]	1.99[a] (3.4)	1.97 (4.0)	1.96 (2.2)	1.96 (1.6)
Strain energy release rate @knee-point [kJ/m2]	2.4 (9.3)	2.4 (8.0)	2.4 (6.0)	2.4 (6.9)

[a] Evaluated from the load drop in the stress-strain curves of this configuration.

Conclusions

- Pseudo-ductility was achieved in a range of interlayer hybrid configurations by inserting nanofibrous layers (NL) between the GF/EP and CF/EP composite layers.
- Nanofibres electrospun from 8% PA6 concentration solutions performed better than the 15% version.
- The thickness of the interlayers between the composite layers were precisely controlled by the areal weight of the NLs.
- Thick interlayers between the composite plies suppressed delamination because of lower shear strains experienced at given displacements across the interface. Interlaminar cracks were arrested in case of NLs with 5 g/m^2 areal weight and above. Saturation is expected at NL areal weights higher than 20 g/m^2.
- The G_{IIC} was significantly increasing with the areal density of the nanofibrous interleaves in the case of 8PA6 NLs, i.e. from 1.8 kJ/m^2 (baseline) up to 4.7 kJ/m^2 for the 8PA6-10+10 configuration containing NLs with a total areal density of 20 g/m^2.

Further details:

Marino S. G., Kuželová Košťáková E. , Czél G. : Development of pseudo-ductile interlayer hybrid composites of standard thickness plies by interleaving polyamide 6 nanofibrous layers. Composites Science and Technology, **234**, 109924/1-109924/14 (2023)
10.1016/j.compscitech.2023.109924

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Hungarian Academy of Sciences

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Thank you for your attention!

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Department of Polymer Engineering

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