# Thin ply thermoplastic composites for damage tolerant monolithic mechanical hinges

## Deutscher Luft- und Raumfahrt Kongress 2022

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# Motivation: Morphing Trends – Morphing Applications & Materials

AIRBUS ETH zürich

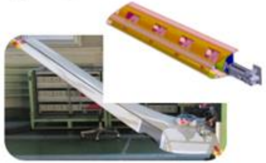
## SoA of AIRBUS internal

Material: GFRP

Smart LED @AIRBUS

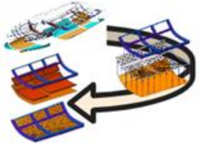
Material: Silicone & GFRP

Droop Nose & Winglet @AIRBUS



Material: Flexible Skin

Flexible Skin Belly Fairing @AIRBUS

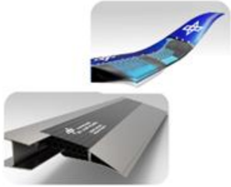


Material: M21E

FlexHinge Spoiler @AIRBUS

Material: CFRP

Pressure actuated cellular structure & Fluid Actuated Morphing Unit @DLR

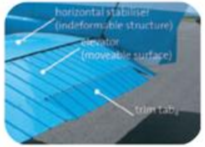


**Airbus UpNext**

EXTRA PERFORMANCE **WING**

with multifunctional trailing edges that dynamically change wing surface

**2008** **2010** **2012** **2014** **2016** **2018** **2018** **2021**

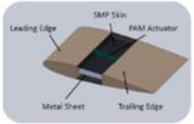


Morphing TE @Academia China;

Material: EAP

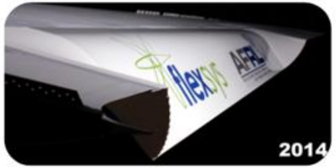
Morphing chevron @NASA

Material: SMA



Shock Control Bump @Academia China

Material: SMP



Morphing Trailing Edge @FlexSys/API (APF)

Material: unknown, CFRP supposed

Morphing Trailing Edge @Fraunhofer

Material: Hybrid Al & PDMDPS

Morphing wing @MIT & NASA (coop. XTCT 2018)

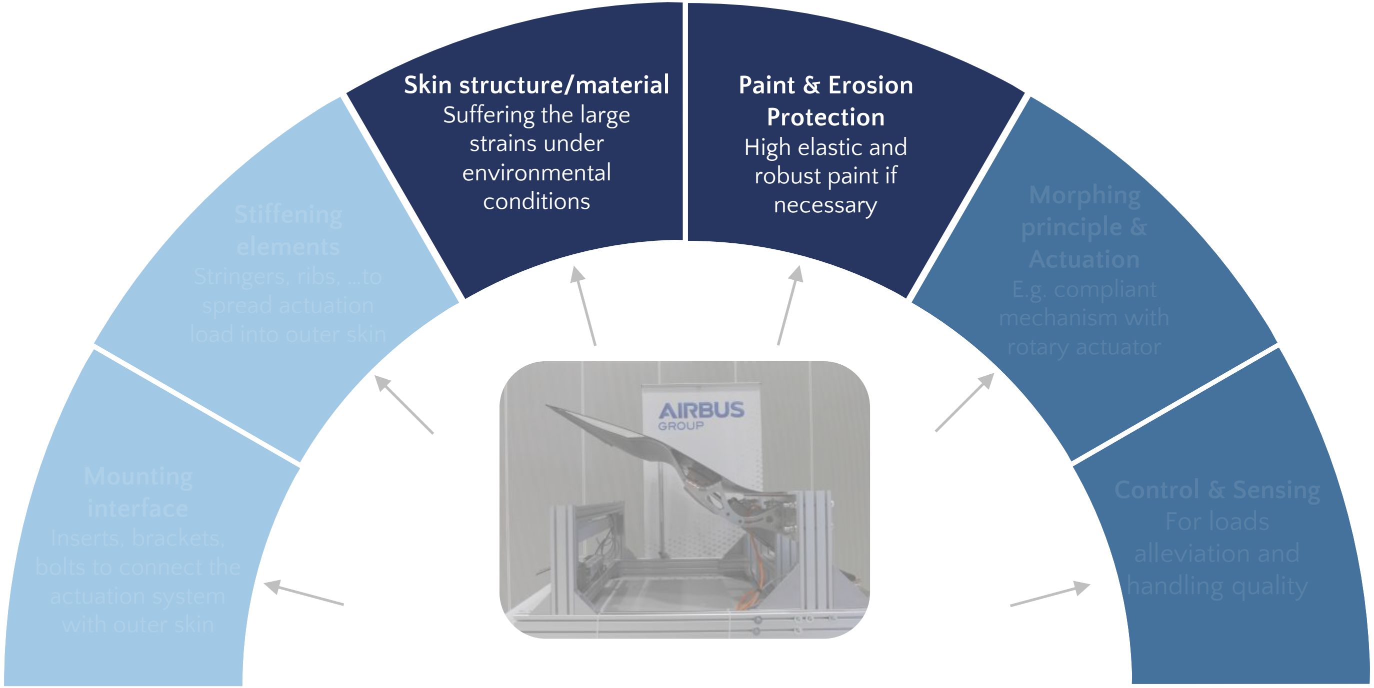
Material: CFRP cells

**FlexSys concept**

## SoA of AIRBUS external

# Motivation: Building blocks enabling adaptive structures

**ETH Zurich / Airbus CRT cooperation** is addressing one of the major technology building blocks, **Skin material.** which is an enabler for morphing and needs to be investigated in advance to the later applications



**Mounting interface**
Inserts, brackets, bolts to connect the actuation system with outer skin

**Stiffening elements**
Stringers, ribs, …to spread actuation load into outer skin

**Skin structure/material**
Suffering the large strains under environmental conditions

**Paint & Erosion Protection**
High elastic and robust paint if necessary

**Morphing principle & Actuation**
E.g. compliant mechanism with rotary actuator

**Control & Sensing**
For loads alleviation and handling quality

Building blocks for morphing application SoA

# Materials challenge for Airbus to enable adaptive structures

CRT functional demonstrator for spoiler with flexible hinge for laminar wing application

Enabling future aircraft structures which are largely bended (e.g. shown adaptive spoile) enabling gap and stepless connections:

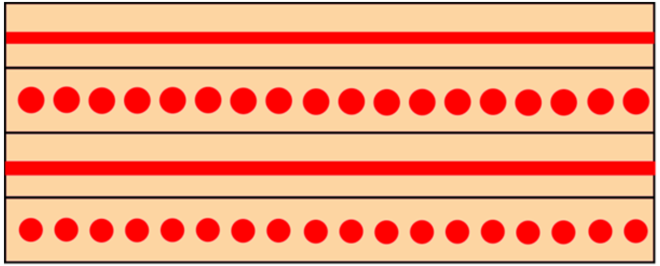
- Which material could comply with the **requirements** while providing the necessary performance?
- Sufficient **stiffness in cruise conditions** to comply with skin waviness requirements
- **Low actuation force** for bending for lightweight actuators
- How to provide **robustness/damage tolerance** to such kind of thin (monolithic) structures?
- **Design/stacking rules** for standard and non-standard laminates & thin skin thickness for CFRP

**Thin ply thermoplastic carbon fiber reinforced plastic (TP-CFRTP)** identified as **optimal solution** for such mechanical largely bended hinges.

This **new material class** is **not commercially available**, hence **Airbus Central R&T** entered into a **collaboration** with **ETH-Zurich / CMAS** (Laboratory of Composite Materials and Adaptive Structures) which already has expertise in processing & lightweight design of TP-CFRTP.

# Advantages of thin ply composites

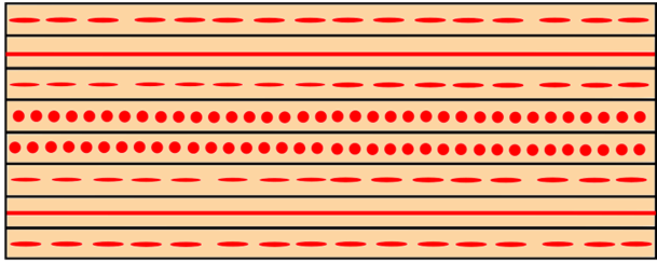
**Thick ply laminate shell**



$[0/90]_s$

160 g/m$^2$

**Thin ply laminate shell**

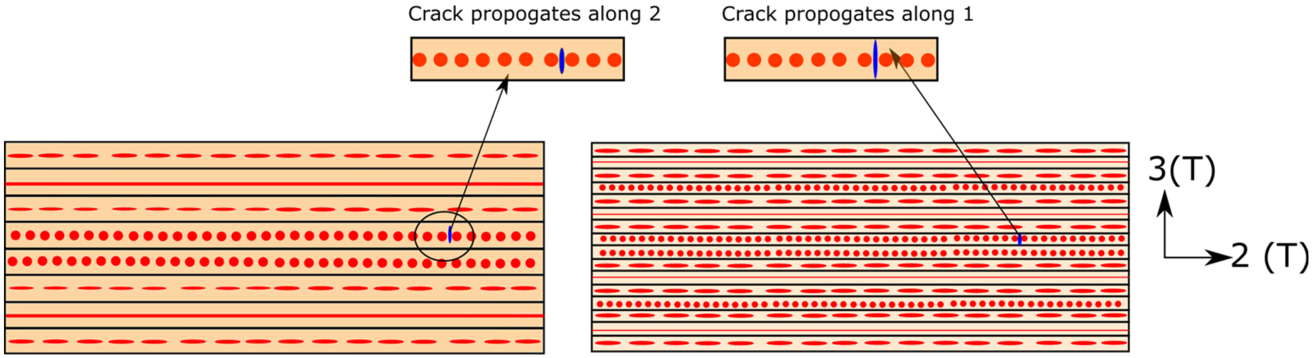


$[45/90/-45/0]_s$

80 g/m$^2$

- Expand the **design space** for same laminate thickness.

# Advantages of thin ply composites

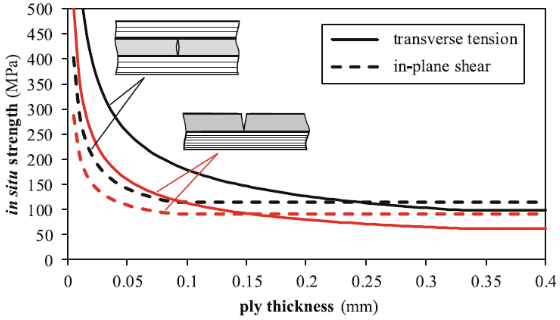


$[45/90/-45/0]_s$

200 g/m$^2$

$[45/90/-45/0]_{2s}$

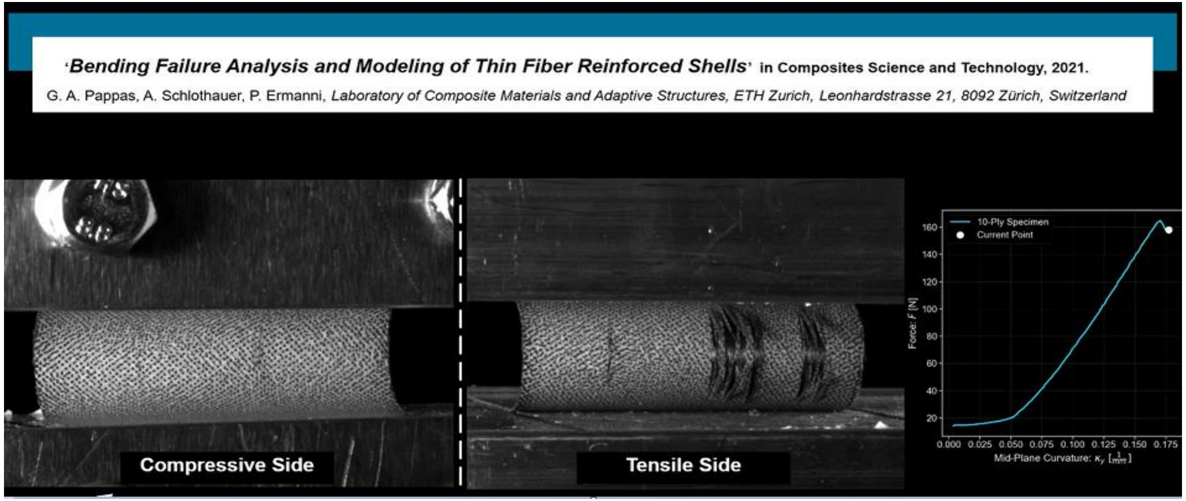
50 g/m$^2$



Camanho et al, *Compos Part A-Appl S, vol. 37, no. 2 (2006): 165-176.*

- Expand the **design space** for same laminate thickness.
- **In-situ transverse strength**: 200%⬆ for 50 gm$^2$ QI laminate vs 200 gm$^2$.

# Advantages of thin ply composites

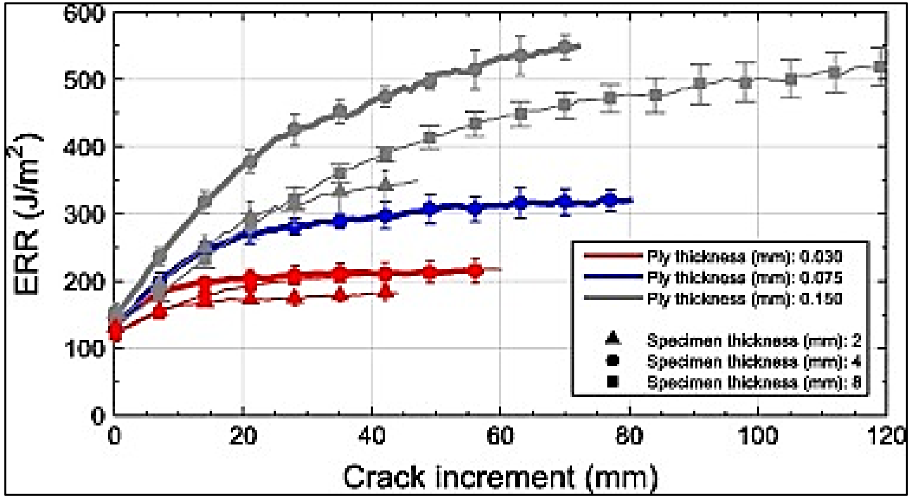


'*Bending Failure Analysis and Modeling of Thin Fiber Reinforced Shells*' in Composites Science and Technology, 2021.

G. A. Pappas, A. Schlothauer, P. Ermanni, *Laboratory of Composite Materials and Adaptive Structures, ETH Zurich, Leonhardstrasse 21, 8092 Zürich, Switzerland*

- Expand the **design space** for same laminate thickness.
- **In-situ transverse strength**: 200%⬆ for 50 gm$^2$ QI laminate vs 200 gm$^2$.
- For very low thickness (<250 microns) shells, we achieve highly **resilient** structures.

# Key challenges of thin ply thermoset composites

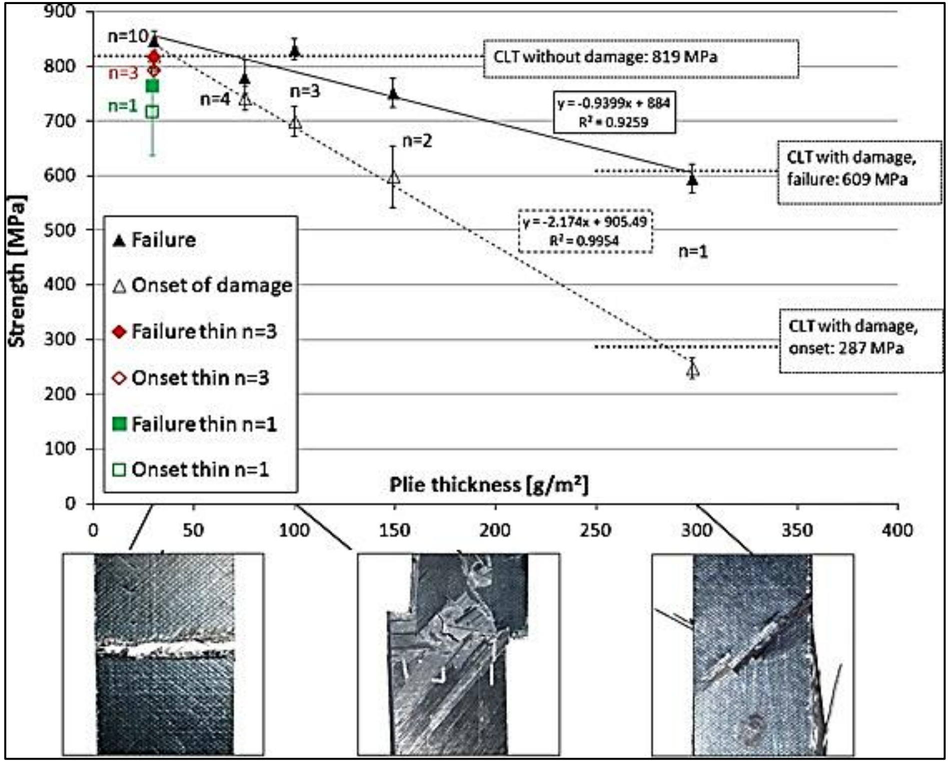


Mode I interlaminar crack propagation of CF/Epoxy system

Frossard et al, *Compos Part A-Appl S*, 91 (2016): 1-8

- Resistance to crack propagation **dependent** on ply thickness.
- Attributed due to effect of ply thickness on **microstructure**.

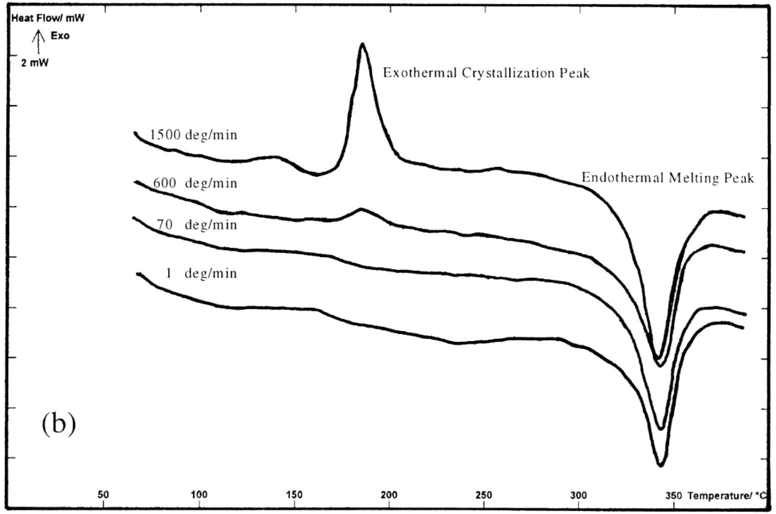
**Problem:** As ply thickness decreases, **damage tolerance decreases.**



Ultimate failure and onset of damage as function of ply thickness

Amacher et al, *Compos Sci Technol*, 101 (2014): 121-132

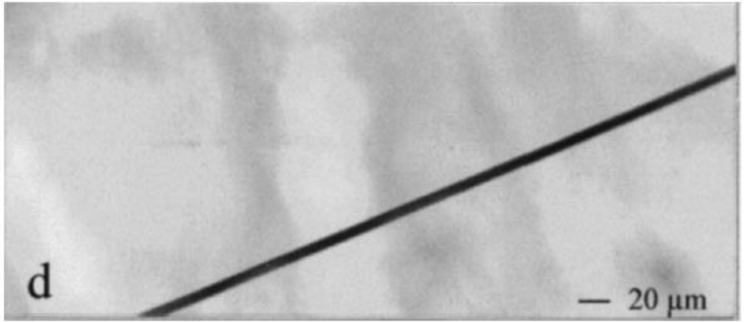
# High-end Thermoplastics: Polyether-ether Ketone (PEEK)



DSC thermograms for CF/PEEK composites at different cooling rate

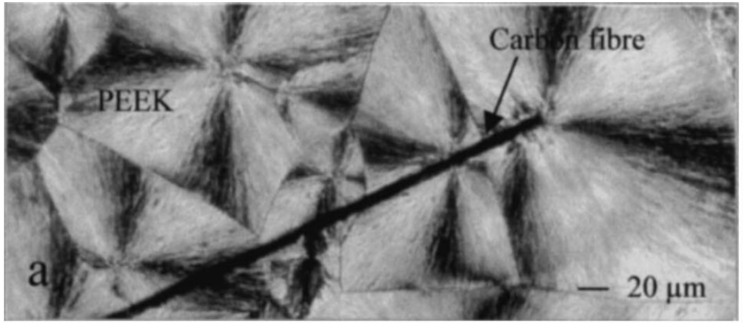
- **High toughness** & **Interface strength.**
- **PEEK crystallinity** could be controlled using cooling rate (in ˚ C/min).
- Mechanical properties is **dependent** on PEEK crystallinity.

**Scope**: i) Produce **thin-ply thermoplastic-based composites ($TP^2C$)**
ii) Assess their **properties** vs. CF/Epoxy counterparts & identify **optimization potential**



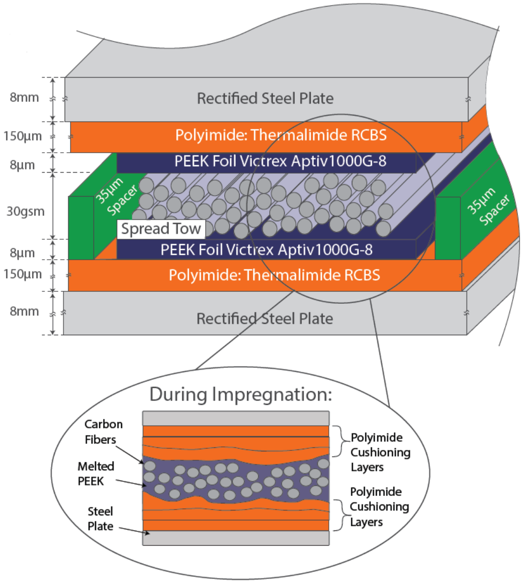
Micrograph of CF/PEEK composites for 2000˚C/min

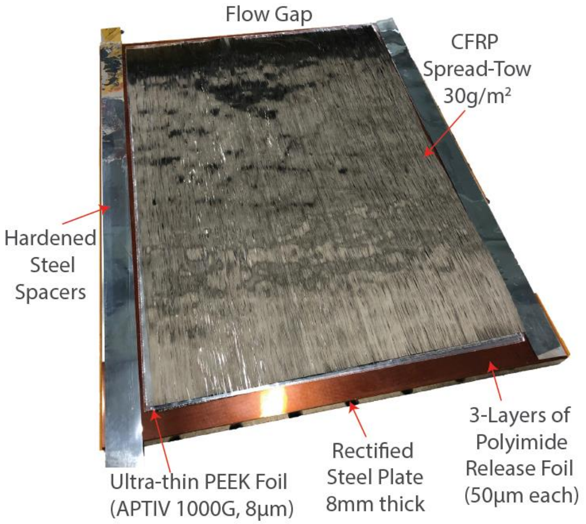
Gao,Kim, *Compos Part A-Appl S, vol.* 31, no. 6 (2000): 517-530 *&* 32, no. 6 (2001): 763-774

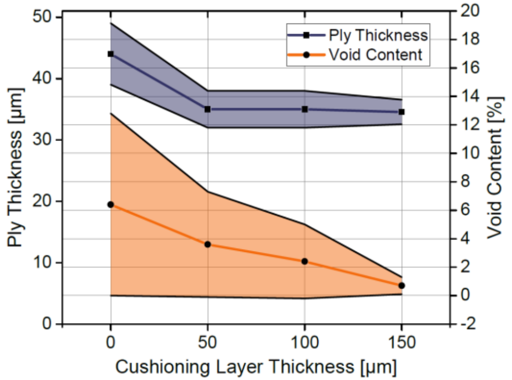


Micrograph of CF/PEEK composites for 1˚C/min

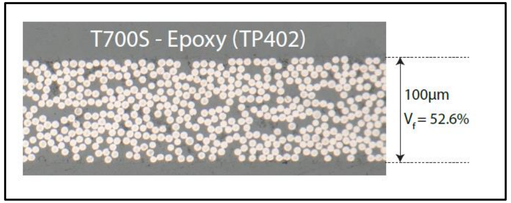
# Thin-ply Thermoplastics: CMASLab in-house processing technique



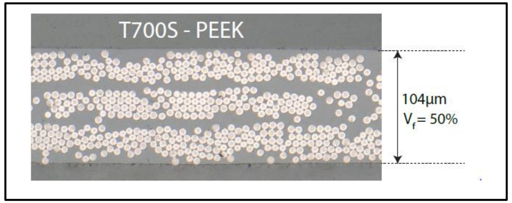




- **Advanced film stacking** methodology.
- Aerospace grade **low void** content.
- Different **microstructure**.

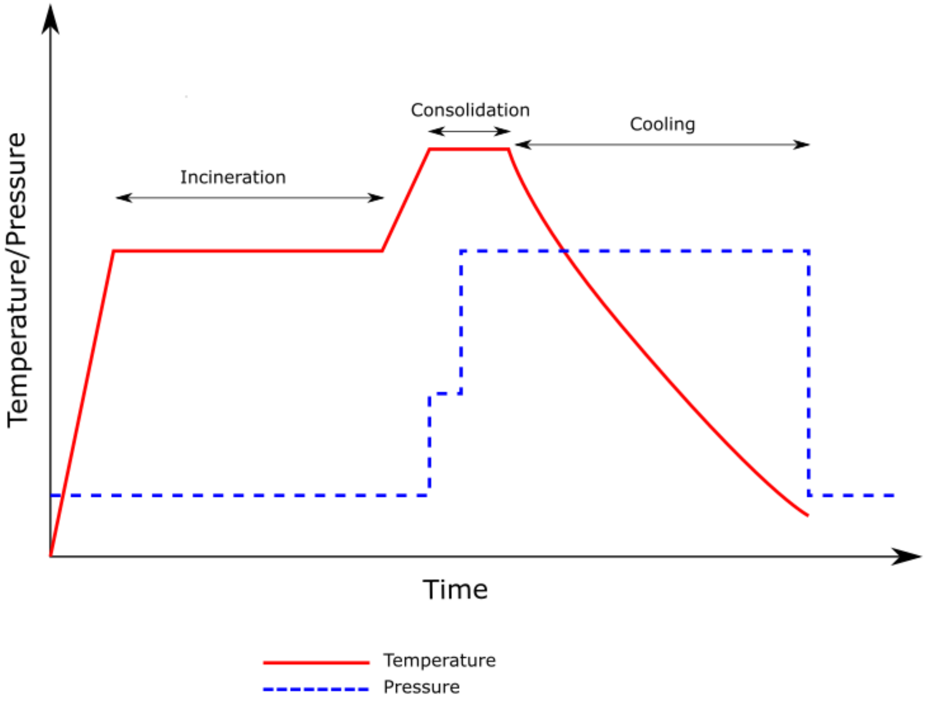


VS



Schlothauer et al, *pre-print, arXiv:2204.00671v1*, 2022

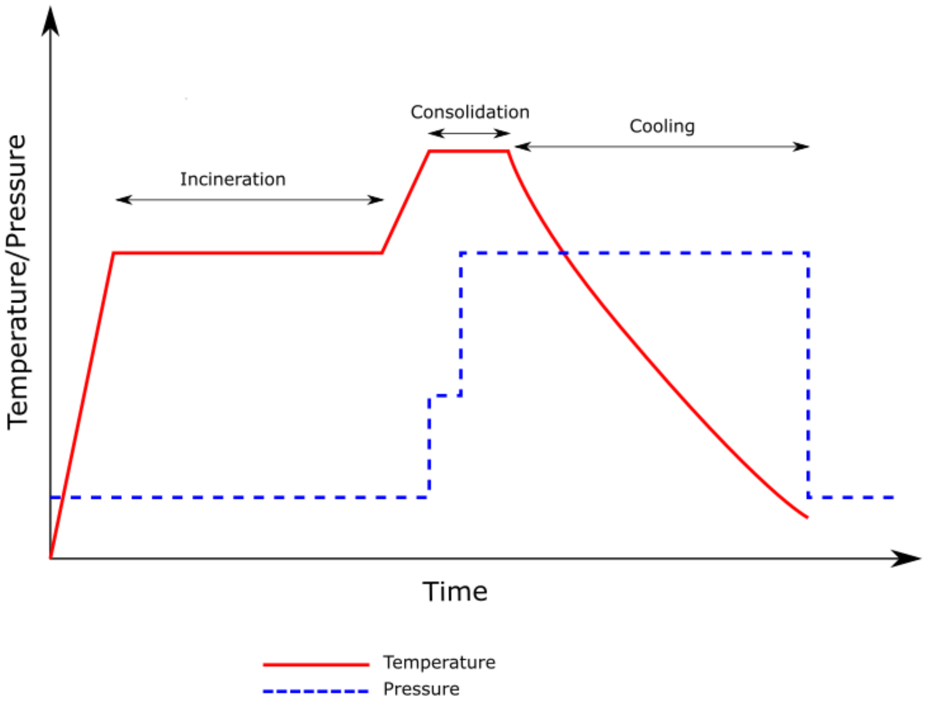
# Processing



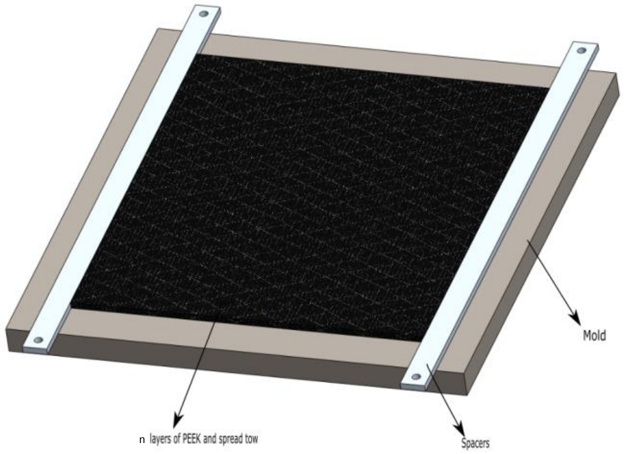
## Material

| Constituents | Value |
|---|---|
| Zoltek$^{TM}$ PX35 50K Spread tow (CF) | 50 g/m$^2$ |
| Victrex Aptiv® 1000 series PEEK film | 25 µm |
| Cured ply thickness | 50 µm |
| Target Fiber volume fraction | 52% |
| Bleeding (w.r.t matrix volume) | 7% |

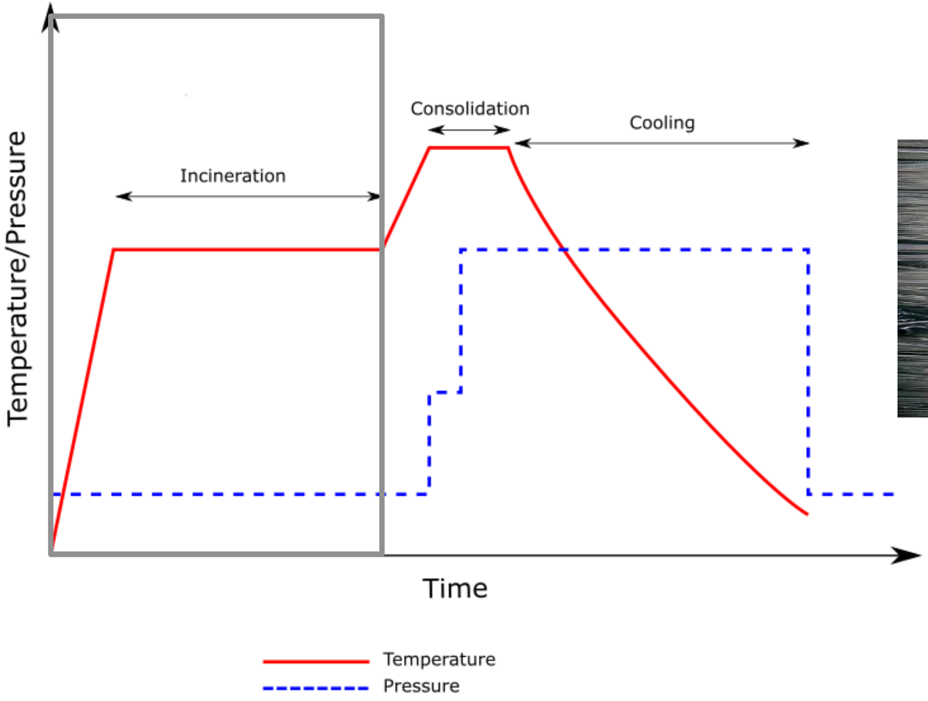
# Processing

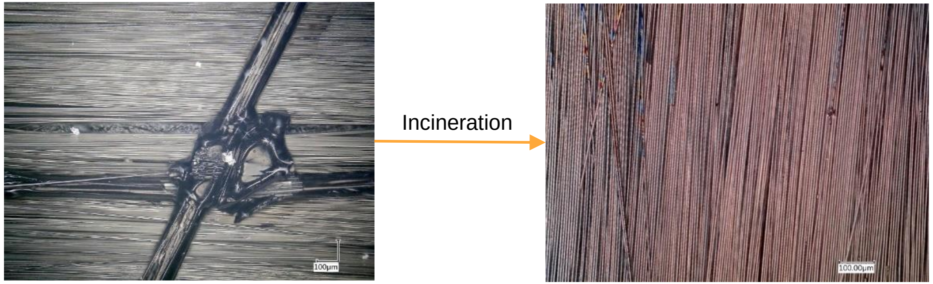


## Advanced Film Stacking

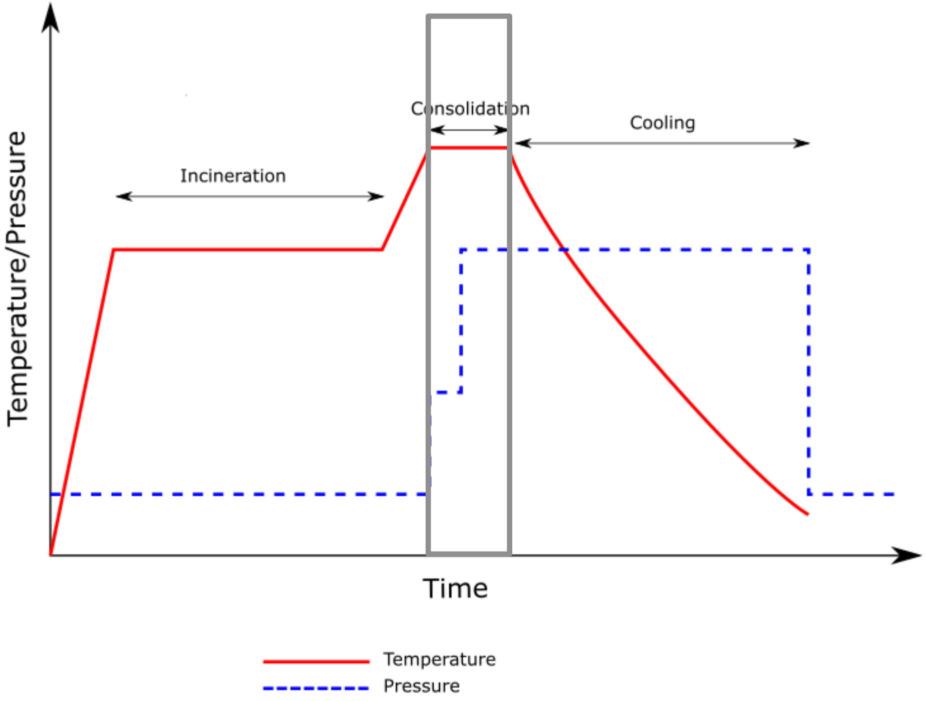


# Processing


Temperature/Pressure
Time
Incineration
Consolidation
Cooling
Temperature
Pressure

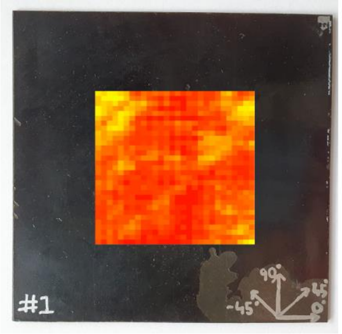

Before
After
Incineration
100µm
100.00µm

# Processing



Void free laminate

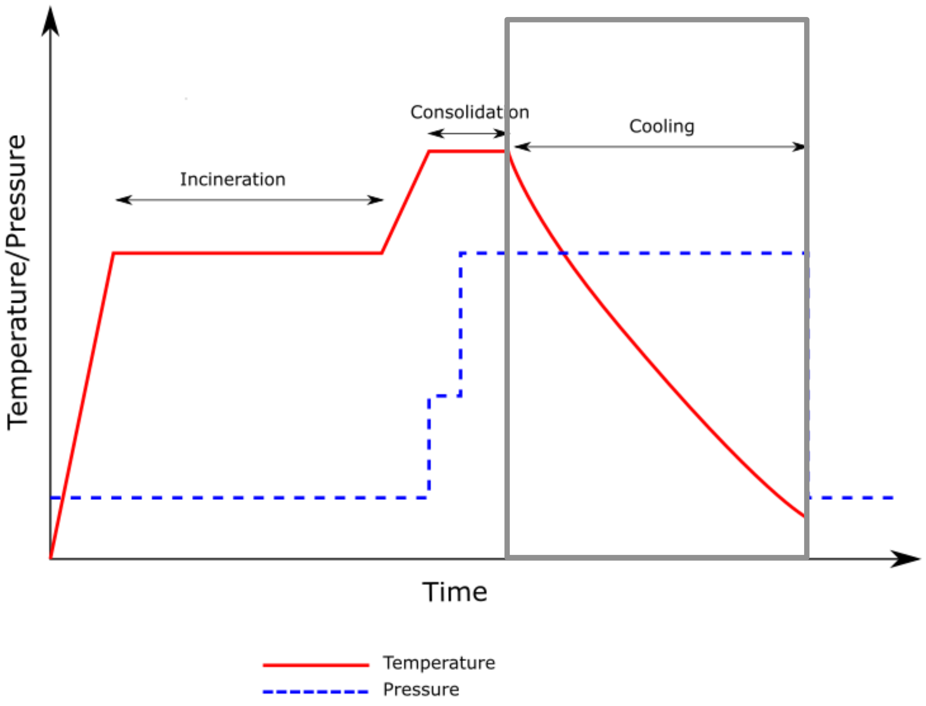
Optical Micrograph



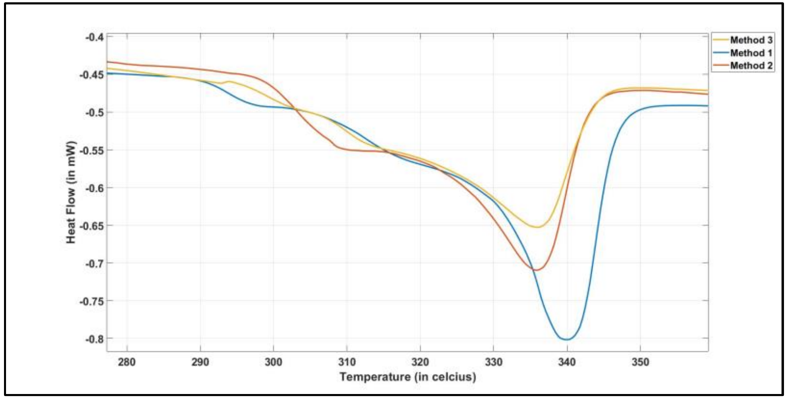
US Scan

CT Scan

# Processing



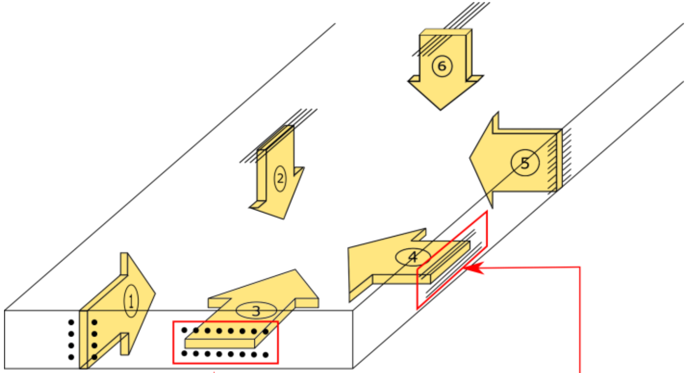
Different crystallinities could be realized by controlling the cooling rate!



Control of crystallinity with cooling rate

# Mechanical characterization

## Fracture properties

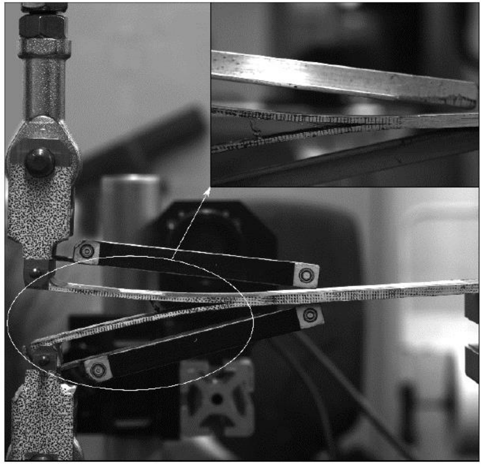


Intralaminar cracks: 1 and 2

**Interlaminar cracks: 3 and 4**

Fiber breaking: 5 and 6

## Fracture testing

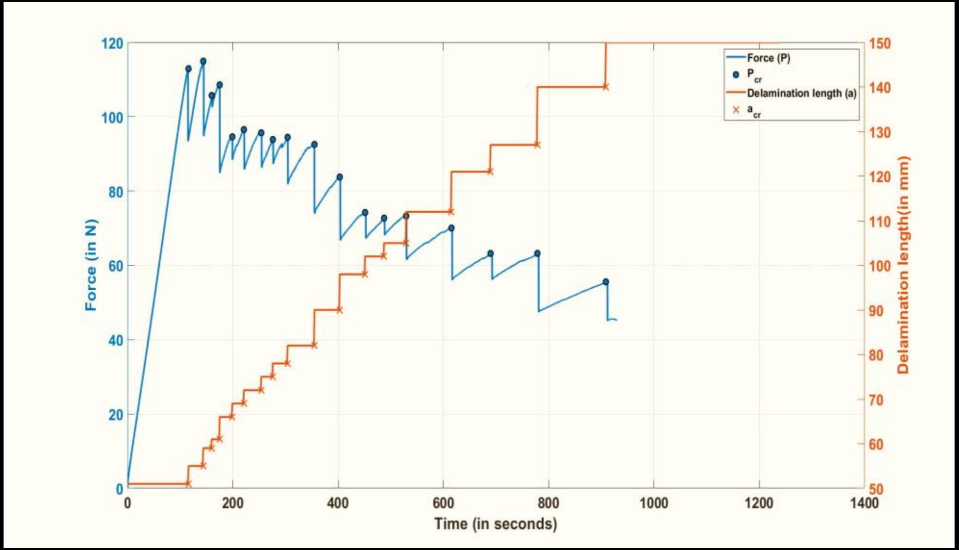


- **Material:** Nominal FVF of 52.5% and crystallinity of 32.7%.
- **Interlaminar fracture properties** were obtained according to ASTM D5528.
- Additional **transverse tensile experiments** conducted according to ASTM D3039.

$$G_I = \frac{3P^2C^{2/3}}{2A_1bh}$$

# Mode I interlaminar fracture testing

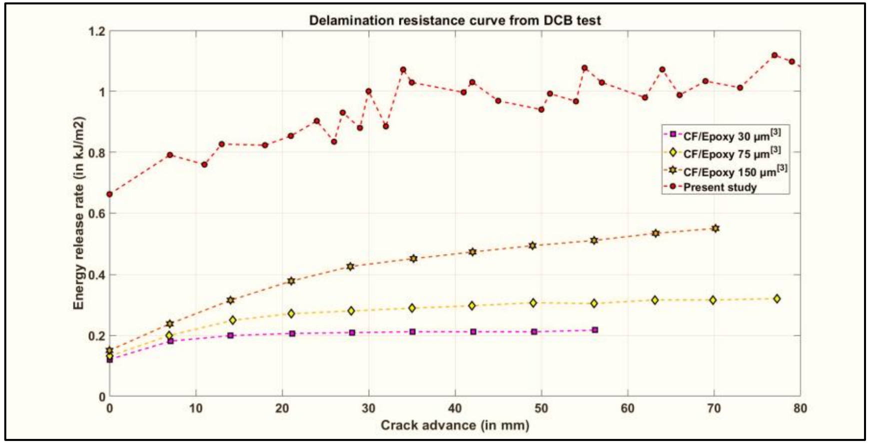
AIRBUS ETH zürich



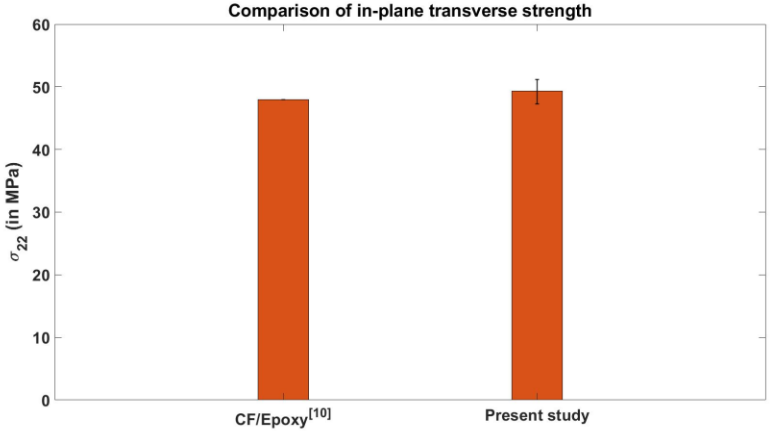
Time history of load and crack length

Crack opening

# Results: Summary



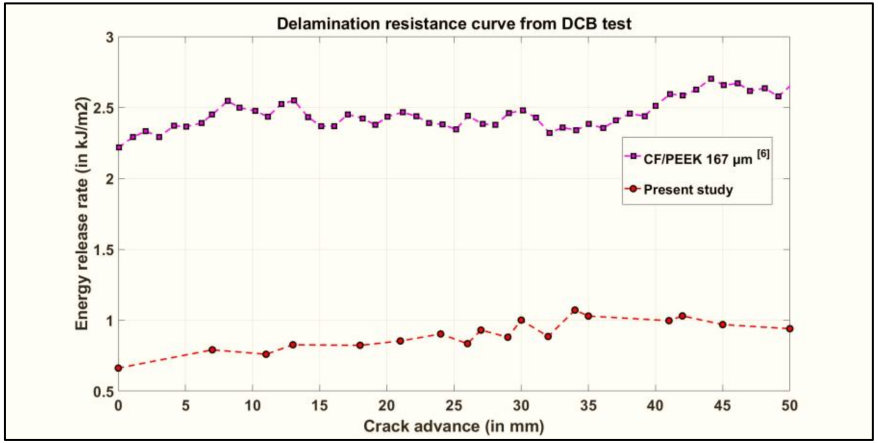
Effect of ply thickness on fracture toughness of CF/PEEK



Thermoplastic matrices doesn’t compromise transverse strength

- More than **4 times** the initiation fracture toughness vs CF/Epoxy.
- More than **3 times** the propagation fracture toughness vs thin ply CF/Epoxy.
- About **1.8 times** the propagation fracture toughness vs thick ply CF/Epoxy.
- **No change** in intralaminar transverse strength.

# Results: Summary



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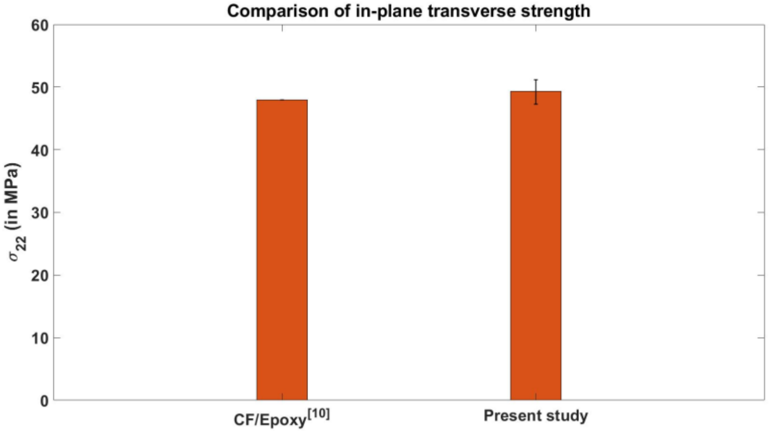

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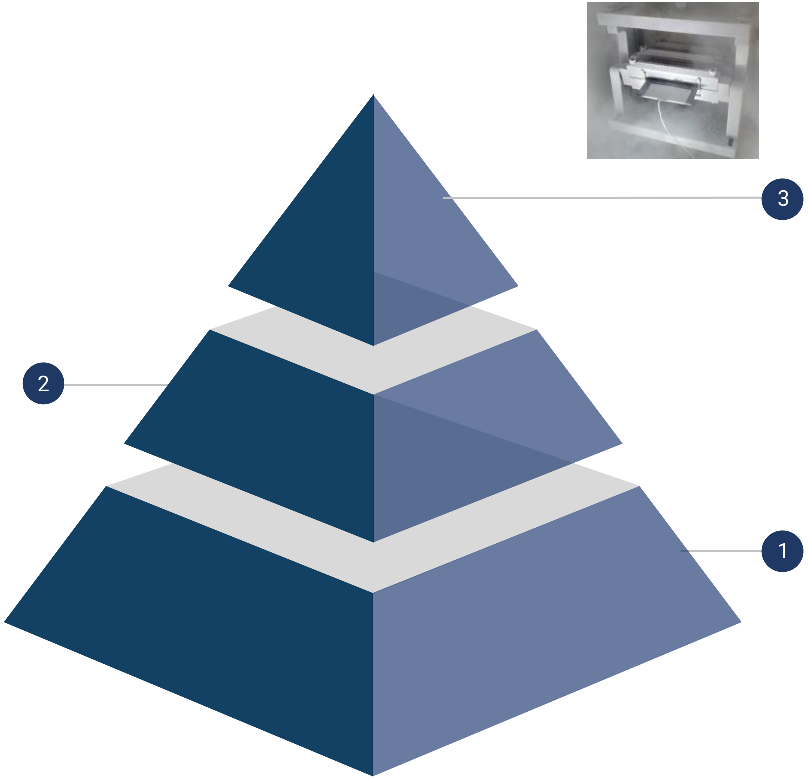
- About **1.8 times** the propagation fracture toughness vs thick ply CF/Epoxy.
- **No change** in intralaminar transverse strength.
- **Less durable** than thick CF/PEEK plies.

# Next steps of collaboration ETH Zurich / Airbus for ThinPly CFRTP

AIRBUS ETH zürich



## 3rd phase

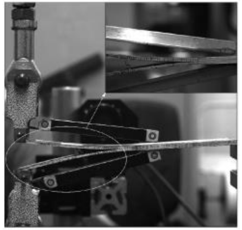
Impact tests and cyclic 4 point large bending for damage tolerance

- Comparison thin ply CFRTP with SoA TP and TS CFRP
- Stacking optimization and use case for bending materials

## 2nd phase

Static testing

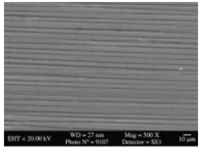
- ✓ Transverse Tensile
- ✓ Interlaminar (mode I) fracture toughness DCB

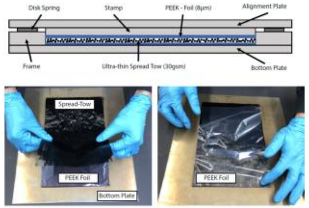


## 1st phase

Basic investigations on the raw thin ply tapes and on the processing/consolidation

- ✓ Tape morphology,
- ✓ DSC, DMA, rheology
- ✓ Laminates consolidation & associated quality expertises
- Process upscaling





# Thank you for your attention

Wolfgang Machunze[1], Georgios Pappas[2], Akshay Ramachandran[2], Brian Bautz[1], Patrice Lefebure[3] and Paolo Ermanni[2]

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*[2] Laboratory of Composite Materials and Adaptive Structures, ETH Zurich Leonhardstrasse 21, 8092, Zürich, Switzerland*
*[3] Airbus Central R&T Materials, Airbus Defence and Space GmbH, Allée du chaffault, 44340 Bouguenais, Nantes, France*

# References

1. Camanho, Pedro P., Carlos G. Dávila, Silvestre T. Pinho, Lorenzo Iannucci, and Paul Robinson. "*Prediction of in situ strengths and matrix cracking in composites under transverse tension and in-plane shear.*" Composites Part A: Applied Science and Manufacturing 37, no. 2 (2006): 165-176.
2. Pappas, Georgios A., Arthur Schlothauer, and Paolo Ermanni. "*Bending failure analysis and modeling of thin fiber reinforced shells.*" Composites Science and Technology 216 (2021): 108979.
3. Frossard, G., J. Cugnoni, T. Gmür, and J. Botsis. "Mode I interlaminar fracture of carbon epoxy laminates: Effects of ply thickness." Composites Part A: Applied Science and Manufacturing 91 (2016): 1-8.
4. Amacher, R., J. Cugnoni, J. Botsis, L. Sorensen, W. Smith, and C. Dransfeld. "*Thin ply composites: Experimental characterization and modeling of size-effects.*" Composites Science and Technology 101 (2014): 121-132.
5. Gao, Shang-Lin, and Jang-Kyo Kim. "*Cooling rate influences in carbon fibre/PEEK composites. Part 1. Crystallinity and interface adhesion.*" Composites Part A: Applied science and manufacturing 31, no. 6 (2000): 517-530.
6. Gao, Shang-Lin, and Jang-Kyo Kim. "*Cooling rate influences in carbon fibre/PEEK composites. Part II: interlaminar fracture toughness.*" Composites Part A: Applied science and manufacturing 32, no. 6 (2001): 763-774.
7. Arthur Schlothauer, Georgios A. Pappas, Paolo Ermanni, "*Thin-ply thermoplastic composites: from weak to robust transverse performance through microstructural and morphological tuning.*", pre-print, arXiv:2204.00671v1, 2022.
8. Pierreux Brecht, "*Investigation on damage tolerance of thin ply thermoplastic composites.*", Semester Project Report, CMASLab, ETH Zurich.
9. "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." ASTM D3039.
10. Dvorak, George J., and Norman Laws. "*Analysis of progressive matrix cracking in composite laminates II. First ply failure.*" Journal of Composite Materials 21, no. 4 (1987): 309-329.
11. "Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites.", ASTM D5528-13.