CleanSky2 SOLIFLY

Developing structural batteries towards aeronautic applications

Helmut KÜHNELT, Alexander BEUTL (AIT),
Frederic LAURIN (ONERA), Alexander BISMARCK (UNIVIE),
Sebastian WILLRODT (CCI), Michele GUIDA (UNINA), Fulvio ROMANO (CIRA)

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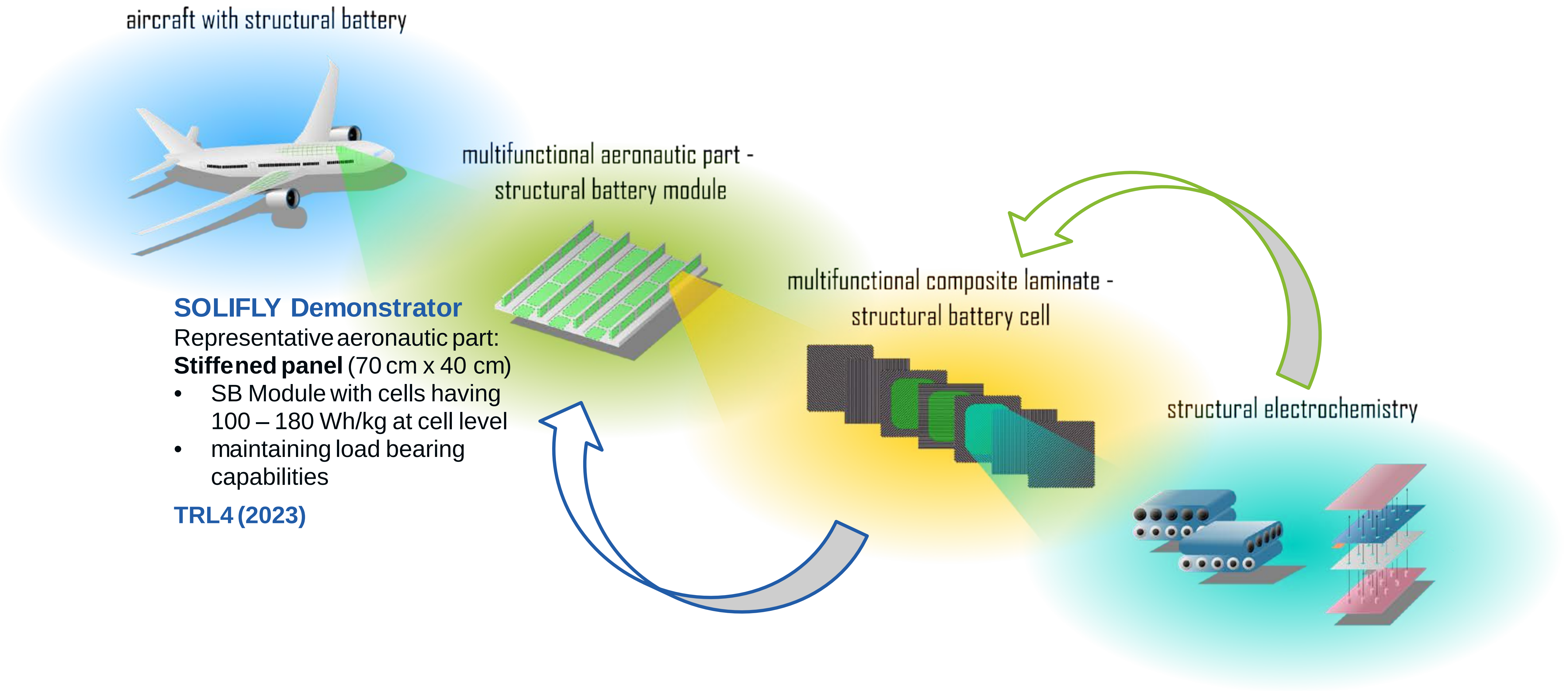
Project Overview

- **Full title:** Semi-**SO**lid-state **LI**-ion batteries **F**unctional**LY** integrated in composite structures for next generation hybrid electric airliner
- **Call ID:** JTI-CS2-2020-CFP11-THT-11
- **Duration:** 01/2021 – 12/2023
- **Budget:** 1.355 Mio €
- **Consortium:**
- **Industrial Advisory Board:**

Clean Sky 2

SOLIFLY

SOLIFLY Ambition



SOLIFLY Demonstrator

Representative aeronautic part:
Stiffened panel (70 cm x 40 cm)

- SB Module with cells having 100 – 180 Wh/kg at cell level
- maintaining load bearing capabilities

TRL4 (2023)

SOLIFLY Structure

WP1 - End-user requirements and specifications
(in-depth SotA review, AB workshop)

WP2 - Battery:
cell concepts, processing, performance, and prototype of the demo cells

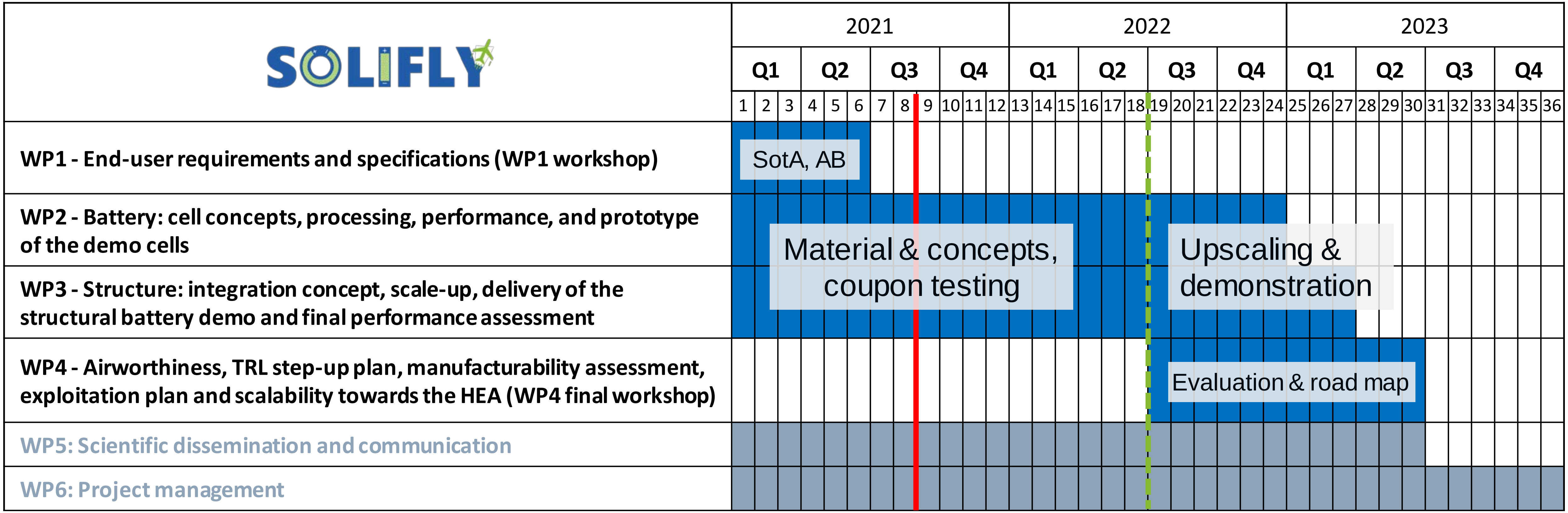
WP3 - Structure:
integration concept, scale-up, delivery of the structural battery demo and final performance assessment

WP4 - Airworthiness, TRL step-up plan, manufacturability assessment, exploitation plan and scalability towards the HEA (AB final workshop)

WP5 - Scientific dissemination and communication

WP6 - Project management

SOLIFLY Time line



SotA Review for Structural Batteries

- **Quantifying multifunctionality – metrics**

$$\eta_{mf} = \eta_e + \eta_s$$

$$\eta_e = \frac{E_{mf}}{E_e}$$

$$\eta_s = \frac{G_{mf}}{G_s}$$

η_e… e.g. ratio of the specific energy of the multifunctional material/structure (E_{mf}) and a non-structural reference system (E_e),

η_s… e.g. ratio of the specific moduli of the multifunctional material/structure (G_{mf}) and a purely structural reference system (G_s).

The structural battery yields a relative weight reduction only for $\eta_{mf} > 1$.

η_{mf}... overall efficiency of the structural battery

η_e ... electrochemical efficiency

η_s ... structural efficiency

SotA Review for Structural Batteries

- **Quantifying multifunctionality – KPIs**

Conventional **performance indicators**:

- Gravimetric energy density [$Whkg^{-1}$]
- Volumetric energy density [Whl^{-1}]
- Specific power [Wkg^{-1}]

(at certain charge/discharge rates)

Which reference?

- Materials level
- Cell level
- Structural level

Among the reported **mechanical properties** are:

- **elastic modulus**
- tensile strength
- tensile modulus
- bending modulus
- compression modulus
- shear modulus
- stiffness
- performance under compressive stress
- tensile stress
- …

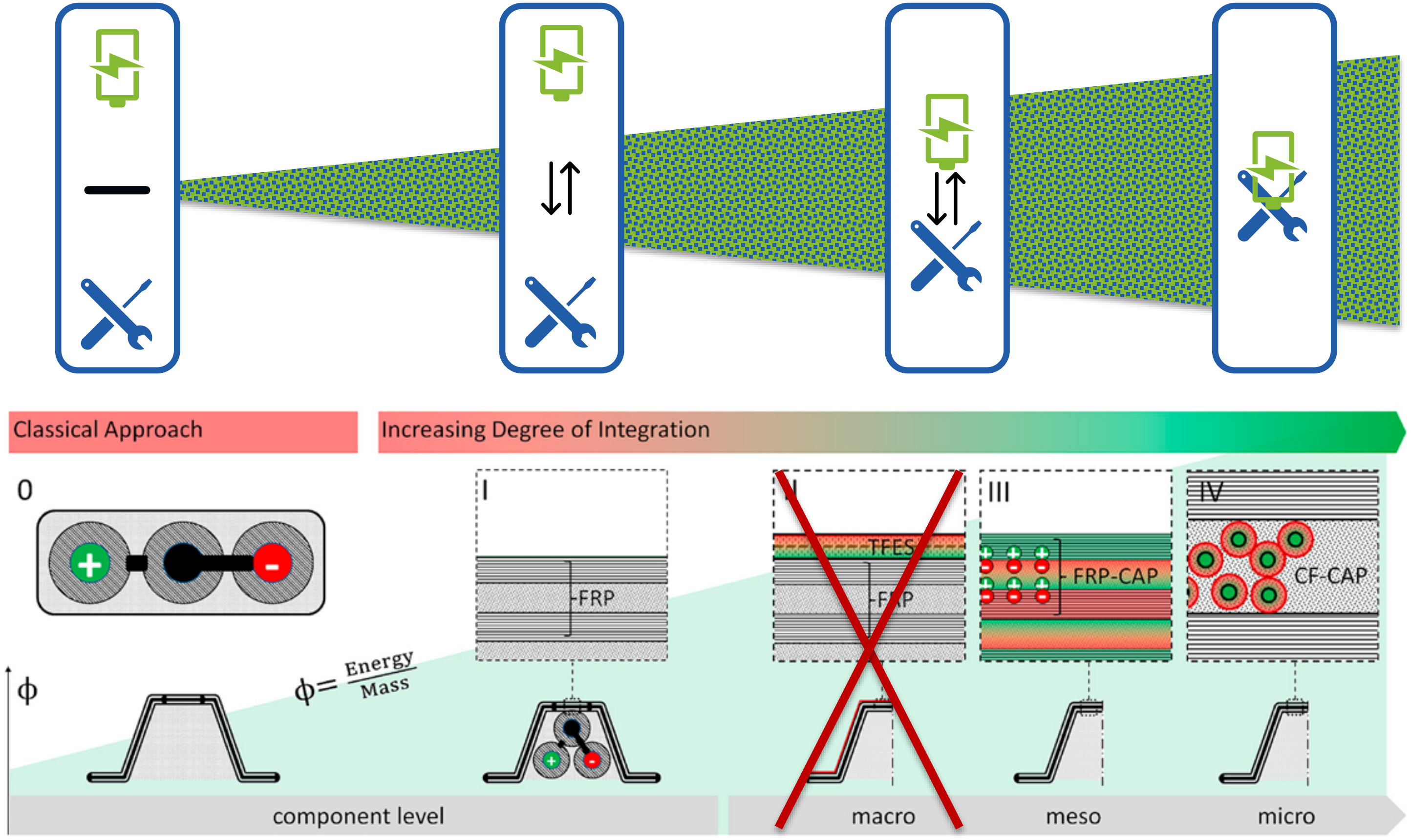
For aeronautic applications, not only elastic modulus but also other mechanical properties should be considered, e.g.

- onset of damage,
- strengths for different loadings such as bending or compression

SotA Review for Structural Batteries

- **Classification**

0	functional separation
I	integrated conventional storages
~~II~~	~~thin-film based approaches~~
III	single-ply functionalization
IV	constituent functionalization



Very low energy density

Adam et al. (2018) https://doi.org/10.3390/en11020335

Type 0 – Functional separation

energy storage

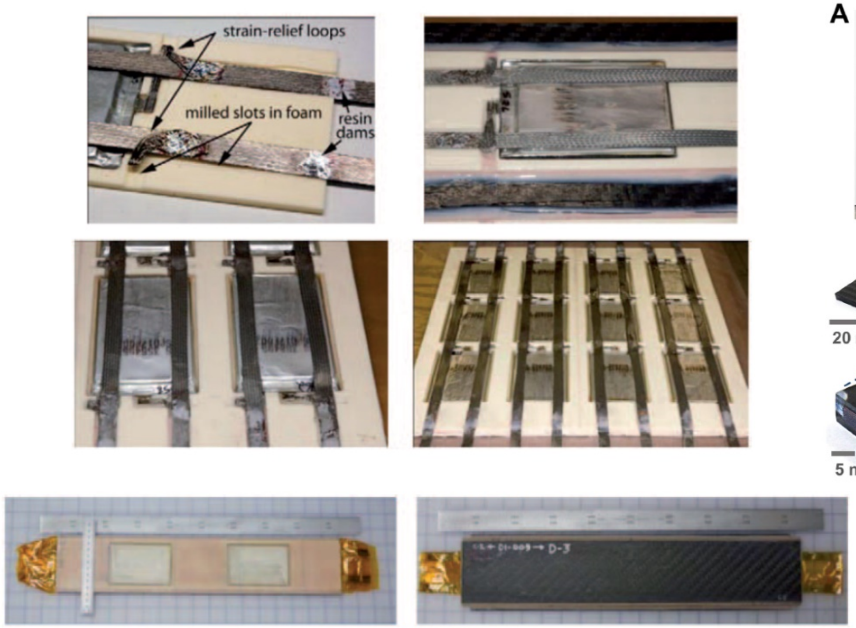
- e.g. Panasonic NCR18650B
- 260 $Whkg^{-1}$, 700 Whl^{-1}

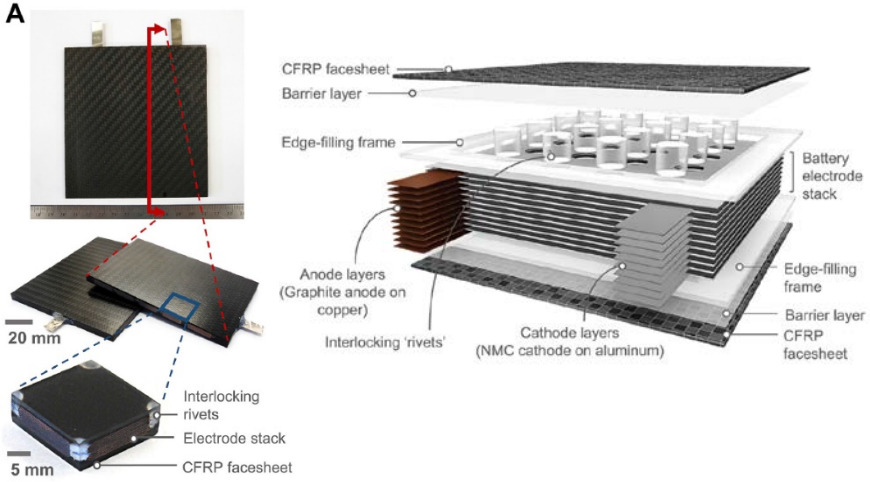
mechanical properties

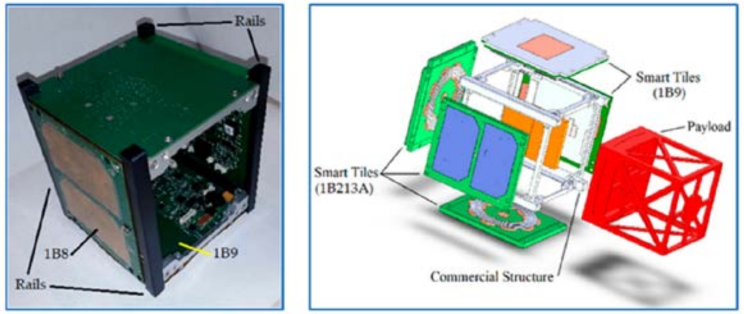
- e.g. CFRP
- which mechanical property most relevant (?)

Structural batteries need to compete against a classical functionally separate system of commercial batteries and conventional load-bearing elements.

Type I – Integrated conventional storages







- Integration of **commercial battery cells** into cut-outs or cavities of structural elements.

Thomas et al. (2012) https://doi.org/10.1177/0021998312460262
Ladpli et al. (2019) https://doi.org/10.1016/j.jpowsour.2018.12.051
Capovilla et al. (2020) https://doi.org/10.3390/aerospace7020017

Type I – Integrated conventional storages

+

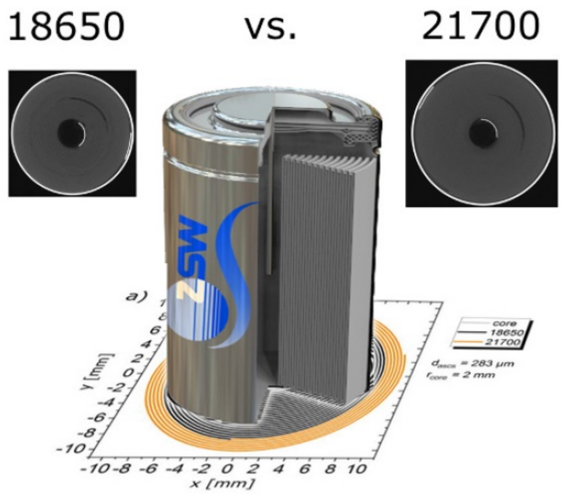
- cheap batteries
- straightforward integration

–

- limited weight reduction
- significant reduction in structural properties

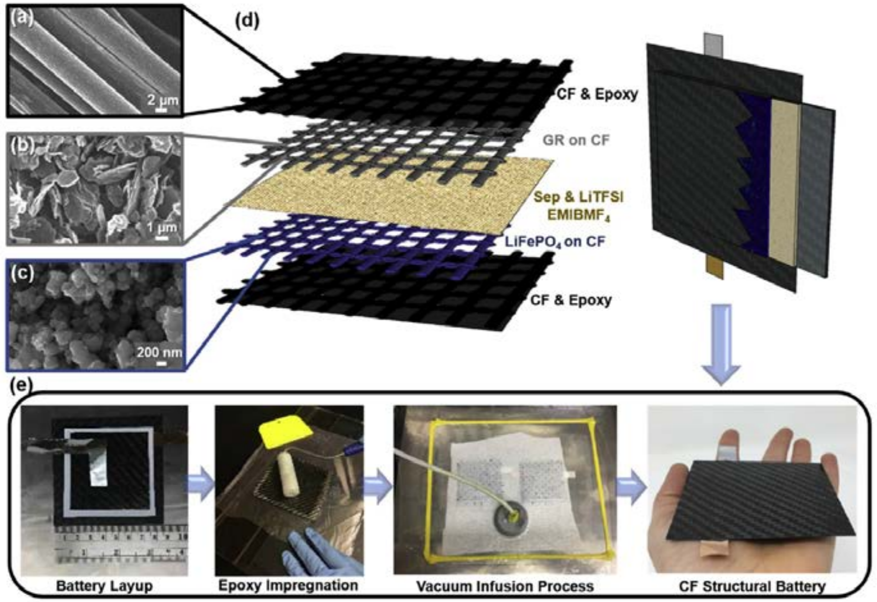
This approach becomes **less attractive** due to:

- **advancement of battery processing methods**
- **optimization of the cell design** (21700 vs. 18650 cell, cell-to-pack / cell-to-chassis).



Waldmann et al. (2020) https://doi.org/10.1016/j.jpowsour.2020.228614

Type III – Single-Ply Functionalization

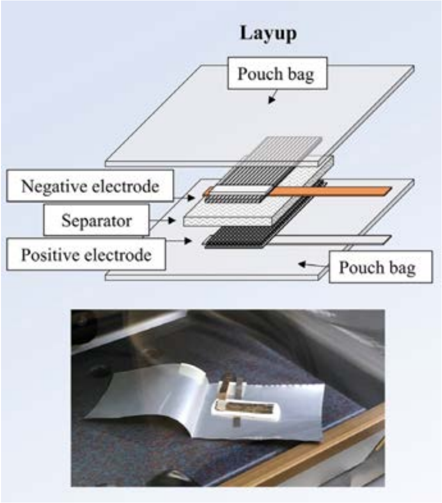


- All components of the energy storage system are substituted by **multifunctional materials** with **electrochemical and structural capabilities**.
- Often carbon fibers or fabrics are used as current collectors/ electrodes.
- **Lab-scale cells,** often a sandwich of woven carbon fabric and glass fiber separators.

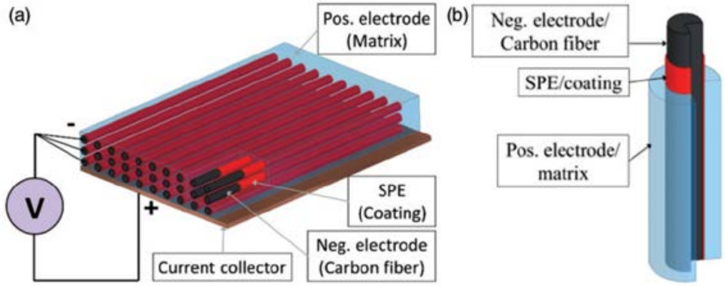
Moyer et al. (2020) https://doi.org/10.1016/j.ensm.2019.08.003

Type IV – Constituent Functionalization

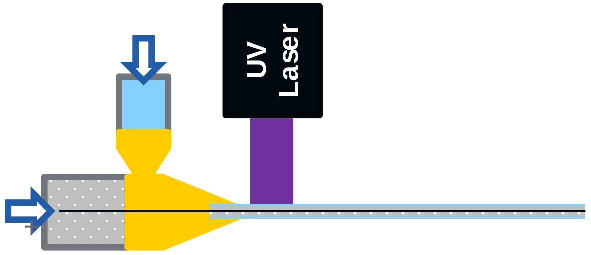
Carbon fibres anode



Coated carbon fibres



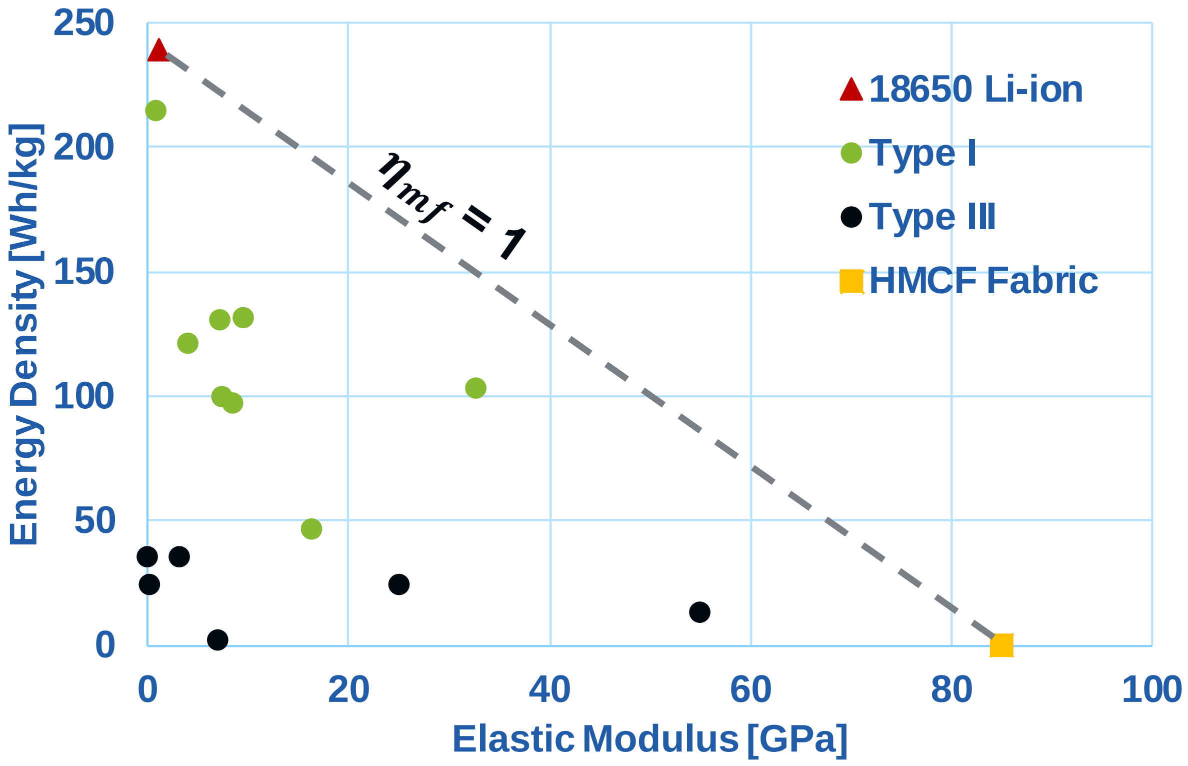
UV-assisted co-extrusion deposition



- Microscale approach for adding electrical energy storage capabilities to a structural material.
- Full structural integration of all battery components, e.g. coaxial integration, embedded carbon fibers, etc.
- Research mainly focusing on development and optimization of components.
- **No full system has been realized yet.**

Asp et al. (2021) https://doi.org/10.1002/aesr.202000093
Xu et al. (2020) https://doi.org/10.1177/0731684418760207
Thakur et al. (2020) https://doi.org/10.1016/j.mfglet.2020.02.001

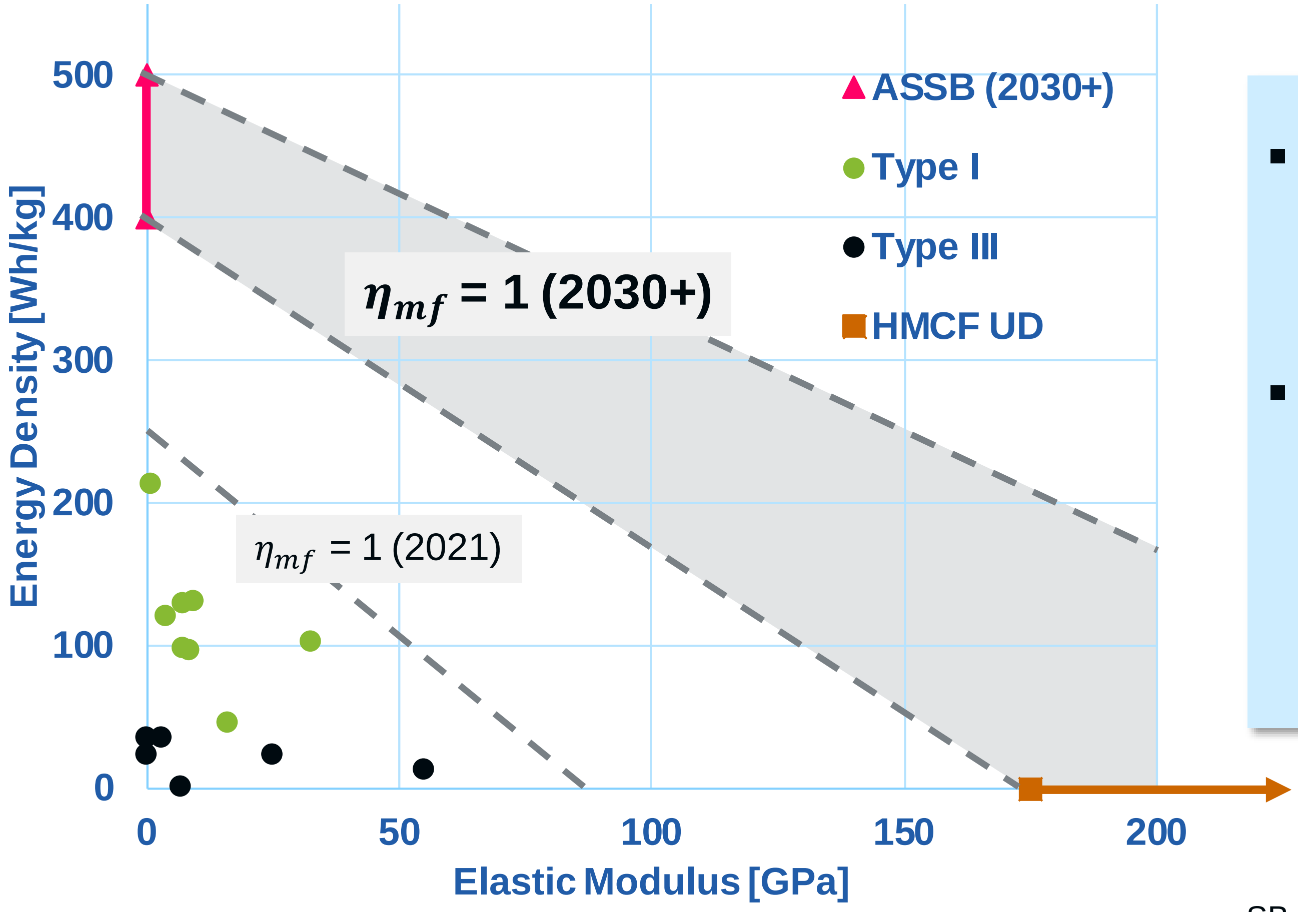
Comparison of SotA SB approaches



- Integrated storage (Type I) shows **higher multifunctionality** than single-ply functionalization (Type III).
- So far, **none of the concepts has demonstrated $\eta_{mf} > 1$** (against SotA base line).

SB Data compiled from
Hopkins et al. (2020) https://doi.org/10.1016/j.joule.2020.07.027,
Asp et al. (2021) https://doi.org/10.1002/aesr.202000093,
Chen et al (2021) https://doi.org/10.1016/j.compscitech.2021.108787

SB target setting – aeronautic applications, 2030+



- **Energy storage:**
  - Safe, high energy, long cycle life
    - All-solid-state battery technology
- **Structural performance**:
  - High performance UD composite materials
  - SB integration into aeronautically compliant composite layups
  - **From materials to aeronautic structures**

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Concept

Materials

Energy dense semi-solid-state Li-ion battery formulation

- LFP | C (100 Wh/kg);
  NMC111 | graphite (380 Wh/kg)
- BCE: Epoxy matrix + organic liquid electrolyte (flammable)

- NMC622 | BCE | Si/C
  (500 Wh/kg at material level)
- BCE: Epoxy matrix + ionic liquid (non-flammable)
- Towards all-solid-state battery

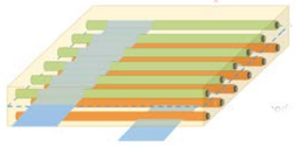
Concept

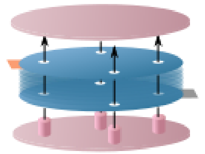
Materials

Cell concepts

Energy dense semi-solid-state Li-ion battery formulation

#1: Coated Carbon Fibres





#2: (Reinforced) Multilayer Stack

- ➢ Constituent functionalization (Type IV)
- ➢ CF as current collectors, coated with active materials, embedded into BCE

– not realized as full cell so far

- ➢ Laminate battery cell (Type I)
- ➢ Active materials coated on metal current collectors + BCE

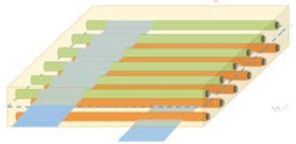
– Liquid organic (non-structural) electrolyte

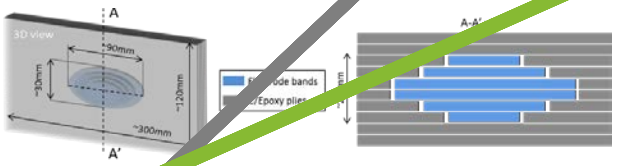
Concept

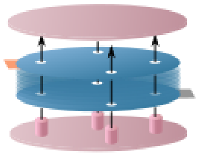
Materials → **Cell concepts** → **Structural integration & Optimisation**

Energy dense semi-solid-state Li-ion battery formulation

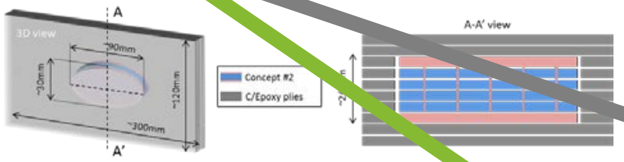
#1: Coated Carbon Fibres







#2: (Reinforced) Multilayer Stack



- No work to optimize shape, size and position of cell in a structure.
- Only one work studies damage state around the cell after the manufacturing

- ➢ Integration concepts for CCF and RMS (cell shape, size, position in structure)
- ➢ Develop understanding of structure-battery interaction / damage

- 2D woven or UD cross-ply laminates [0º/90º] composites
- Mainly twill or satin architectures (automotive applications) – easy manufacturing of complex shapes
- Vacuum bag, curing between RT up to 150ºC, with post-curing

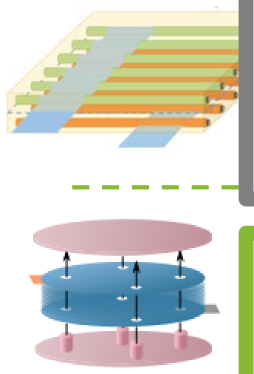
- ➢ **Unidirectional plies** for higher compressive strength
- ➢ Accepted aeronautic ply stacking sequences
- ➢ Evaluate **autoclave process**

Concept

Materials → **Cell concepts** → **Structural integration & Optimisation** → **Scale up to aeronautic relevant part, characterisation of performance**

Energy dense semi-solid-state Li-ion battery formulation

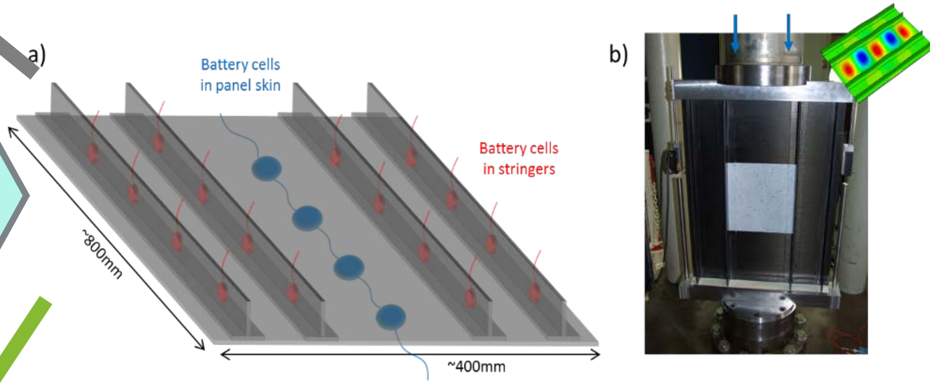
#1: Coated Carbon Fibres



#2: (Reinforc Multilayer St

- Mainly small size, plain coupons
- No integration strategy to minimize the degradation of the mechanical properties considering embedded battery cells
- No test on post-buckled structure

- First SB module integrated into aeronautic stiffened panel with optimized cell placement
- Test with multi-instrumented bench
- Test on post-buckled structure

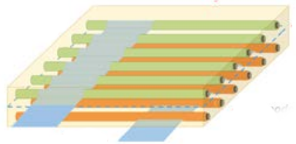


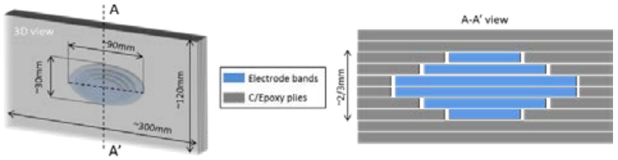
Concept

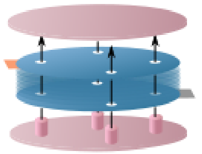
Materials → Cell concepts → Structural integration & Optimisation → Scale up to aeronautic relevant part, characterisation of performance

Energy dense semi-solid-state Li-ion battery formulation

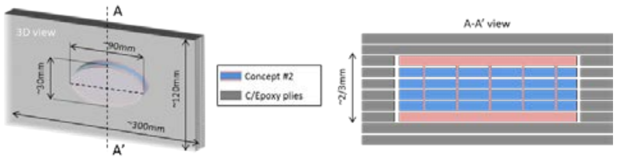
#1: Coated Carbon Fibres

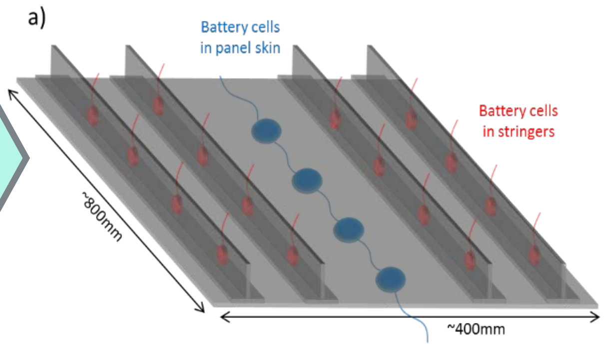


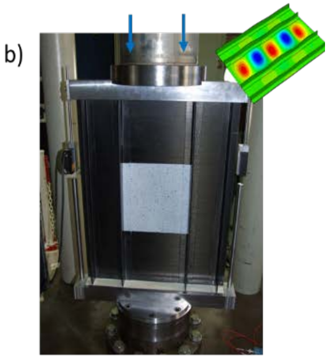




#2: (Reinforced) Multilayer Stack







Aeronautic requirements (industrial advisory board) → Airworthiness & manufacturability → Technology roadmap & TRL scale-up strategy

Outcome of other WP1 activities

- Advisory Board – Expectations for structural batteries:
  - PAI, PIP (OEMs) – Propulsive and secondary (e.g. e-taxiing) applications for hybrid electric commuter aircraft
  - FACC (TIER) – Decentralized electrification in the cabin: hatrack, infotainment, …
  - Initial recommendations for potential integration in aircraft, but **technology needs to mature**
- Manufacturability aspects – initial assessment of SOLIFLY approaches
  - No show stoppers (in principle)
    - CCF concept – scalable electrophoretic fibre deposition
    - RMS concept – close to conventional battery cell manufacturing
- Airworthiness certification aspects
  - Structure: well established
  - Propulsive batteries: now in low kWh range, large propulsive battery systems to be expected soon
    - certification route needs to be fully established
  - **Multifunctional structure with integrated batteries: many open questions, too early**

Conclusion and Outlook

- In-depth SotA analysis has confirmed the SOLIFLY concept
- Many **gaps for technology maturation** identified for:
  - Structural electrochemistry and cell processing
  - Structural integration and manufacturing
    - maintain load bearing when integrating batteries
    - aeronautically compliant manufacturing
  - Certification for multifunctional structures to be established
- WP1 outcome currently prepared for journal submission
- EASN 2022 – more on technological development

SOLIFLY

developing structural batteries towards aeronautic applications

Thank you for your attention!

Acknowledgments:

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