Impact response of composites with an embedded battery

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Outlines

1) Motivation & background
2) Composites with embedded batteries
3) Manufacturing methods
4) Impact response
5) Risks to health and safety
6) Conclusion

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Motivation & Background

Integrating load-bearing composite structure and electrical energy storage devices leads to a reduction in empty mass (i.e. battery housing/casing). Hence, ***specific electrical energy capacity can be improved.***

Tesla Model S battery pack
https://qnovo.com/peek-inside-the-battery-of-a-tesla-model-s/
https://www.teslarati.com/tesla-model-s-weight/

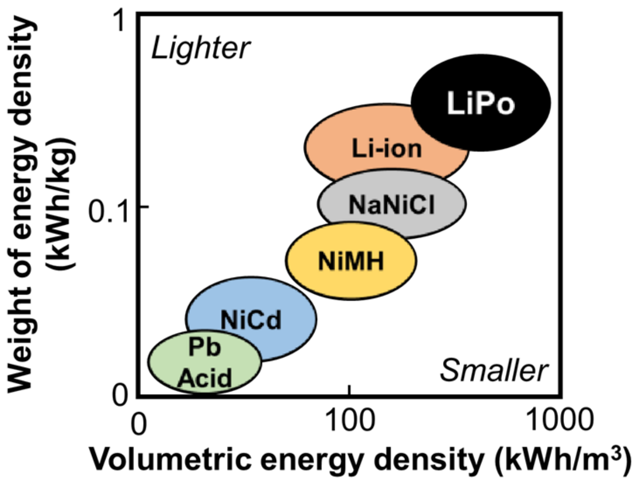
The total battery pack weight (~600 kg) corresponds to 30% of the overall vehicle mass.

Approaches to achieve multifunctional composites:

1) Composites with embedded batteries
2) Structural power composites

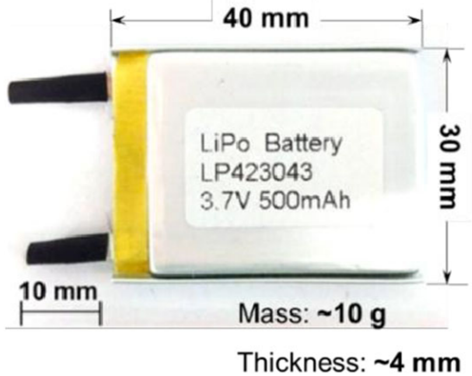
Composites with embedded batteries

Lithium-ion batteries are embedded into fibre reinforced composites to construct ***multifunctional energy storage composites***.



(a) Gravimetric and volumetric of various battery chemistries

Adapted from Manzetti et al., 2015



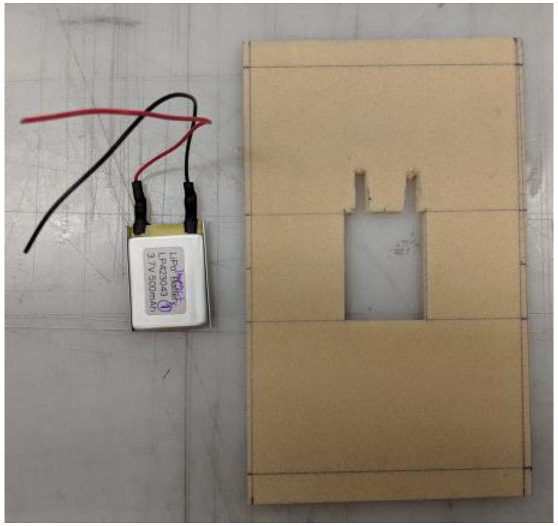
***(b)* Pouch batteries**

LiPol Battery Co. Ltd, China.

Manufacturing methods

1) CFRP laminates: Vacuum assisted resin infusion
2) CFRP/PVC foam sandwich composites: Wet hand lay-up + Vacuum bagging

(a) Cut-outs in the middle 18 plies of CFRP



(b) Cut-out in the foam core

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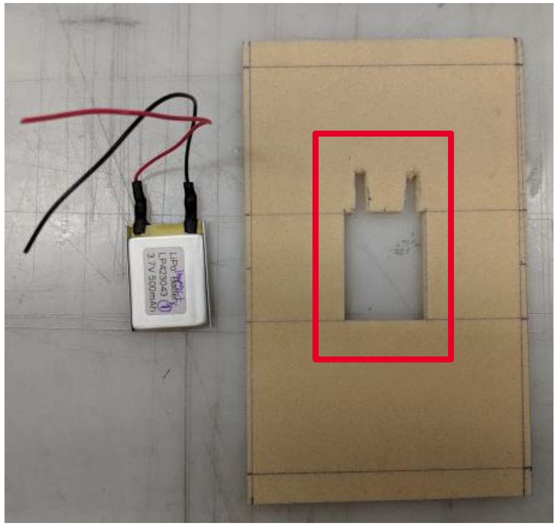
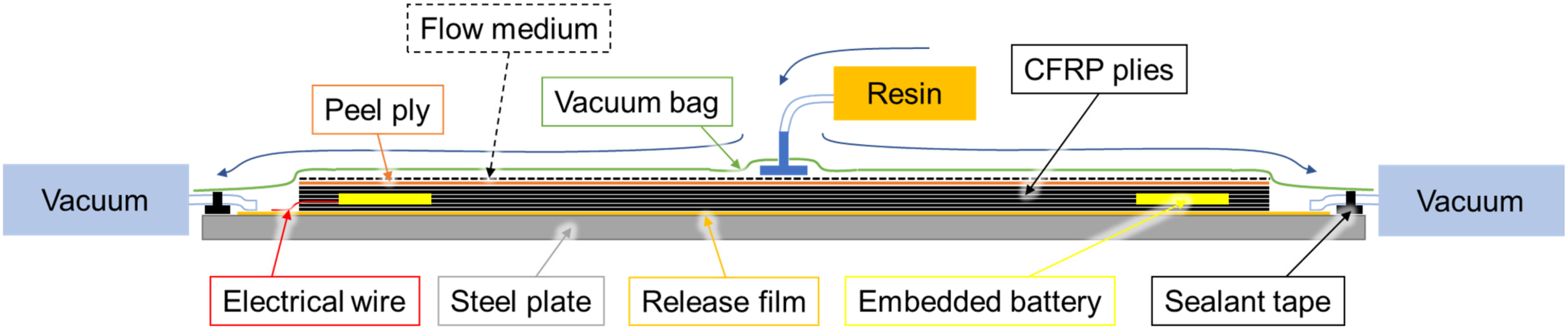


(b) Cut-out in the foam core

Manufacturing methods

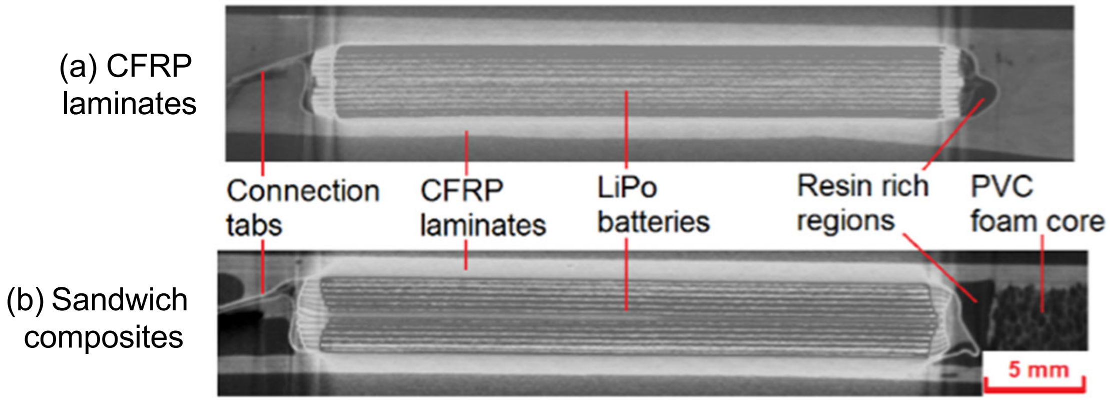
Both composites were cured under ***vacuum bag (~1 atm)*** and ***room temperature (~20 °C)*** for at least 24 hours. ***No post cure*** that usually applies excessive pressure and heat was conducted to avoid damaging the embedded batteries.



Schematic of vacuum assisted resin infusion process.

X-ray CT images

- Embedded battery adhered well to surrounding composites
- Embedded battery caused no damage to the surrounding composites
- Embedded battery was not damaged from the composites manufacturing methods



X-ray CT images of embedded battery

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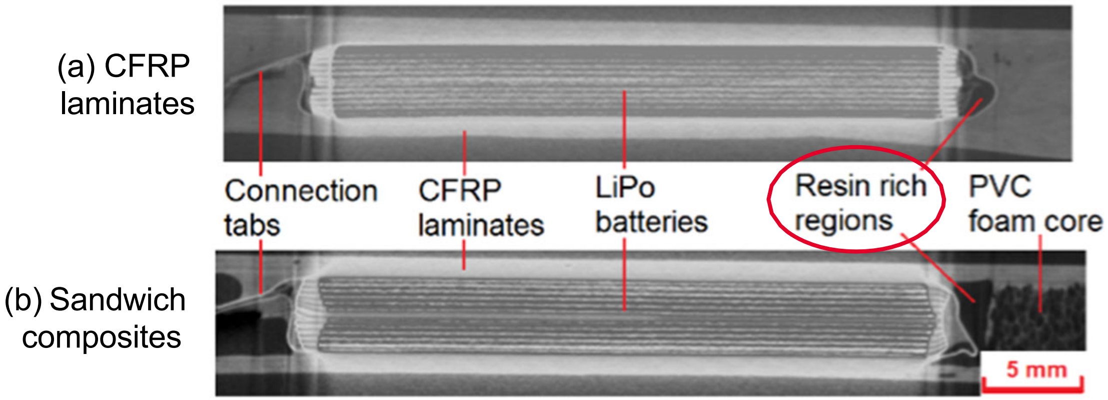

X-ray CT images of embedded battery

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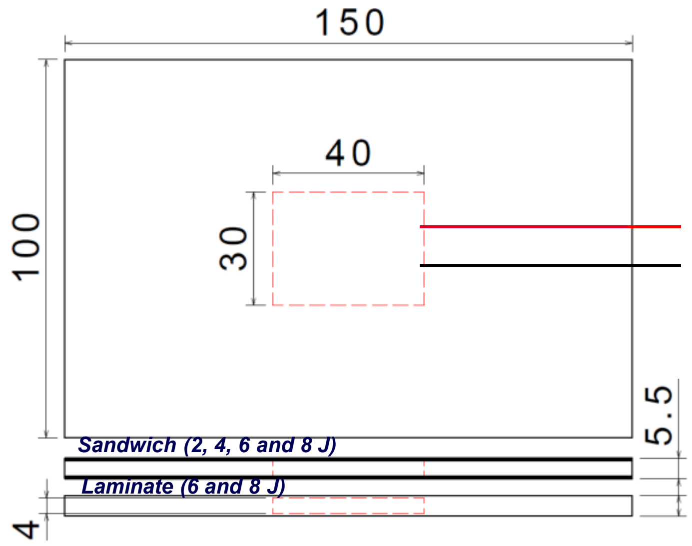
Impact samples

Standard test method for measuring the damage resistance of a fibre-reinforced polymer matrix composite to a drop-weight impact event (ASTM D7136) & Standard test method for compressive residual strength properties of damaged polymer matrix composite plates (ASTM D7137).

- A minimum of 5 samples for both specimen types



Top and side views of impact specimens

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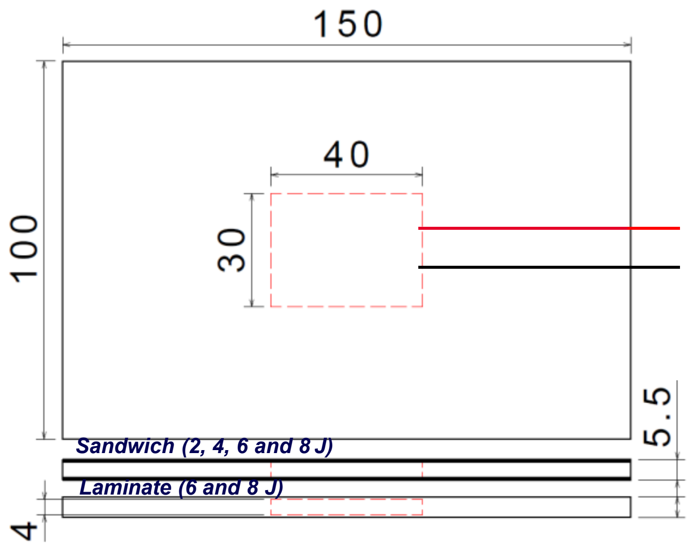
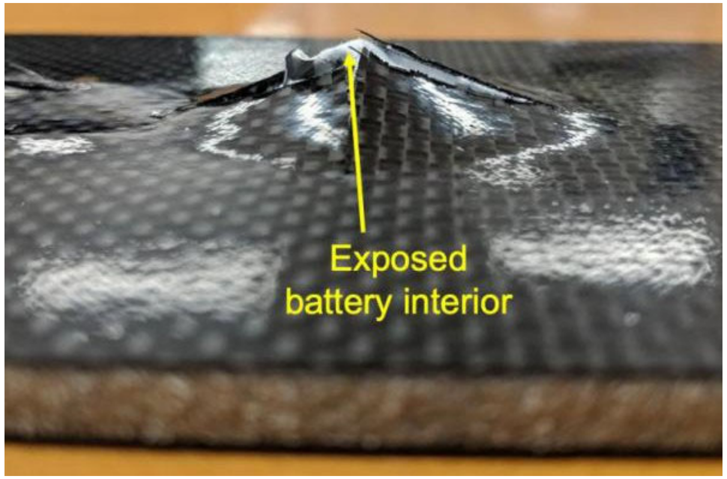


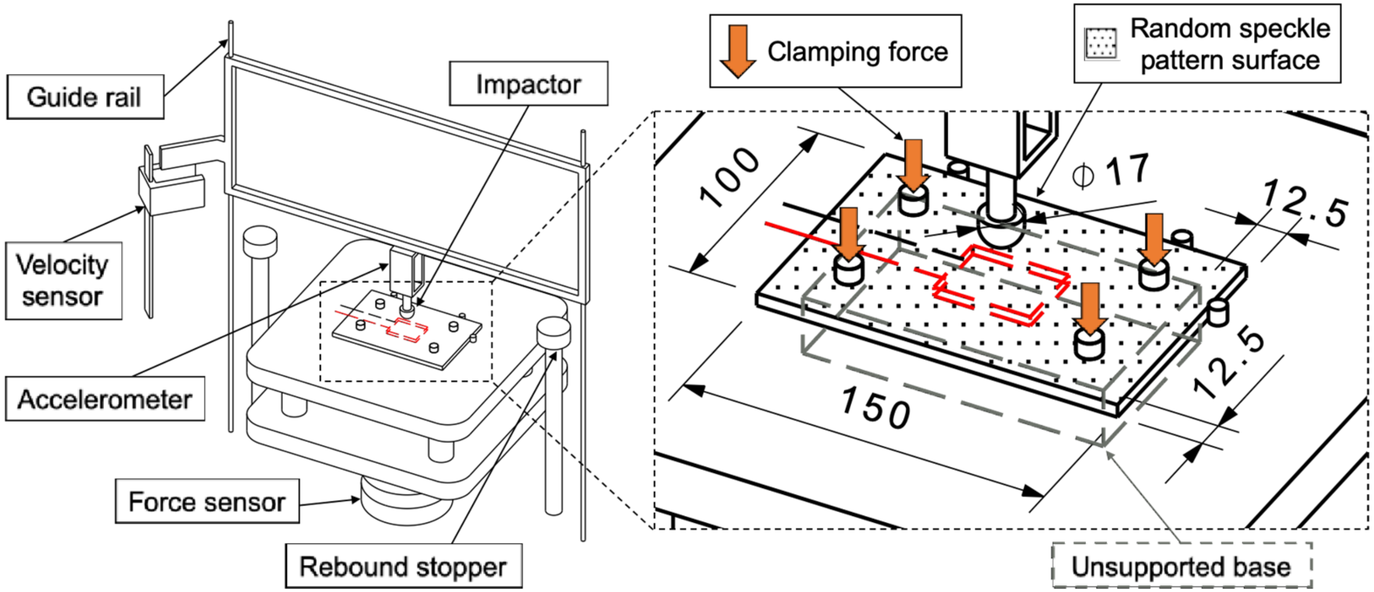
(a) Top and side views of impact specimens



(b) Impact damage of sandwich composites subjected to 10 J impact

Impact rig

Samples were impacted once and then compressed in out-of-plane direction.



Impact rig apparatus and Impact test setup

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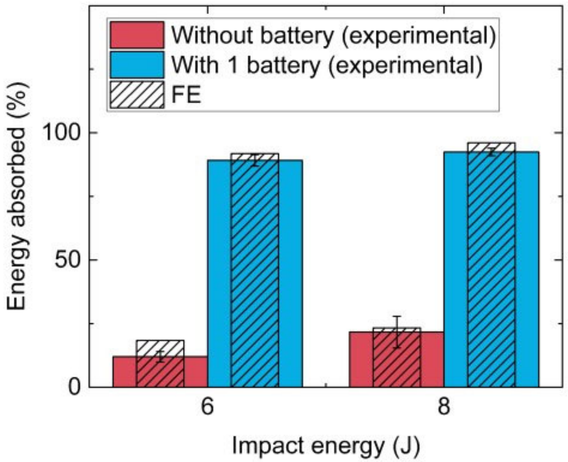
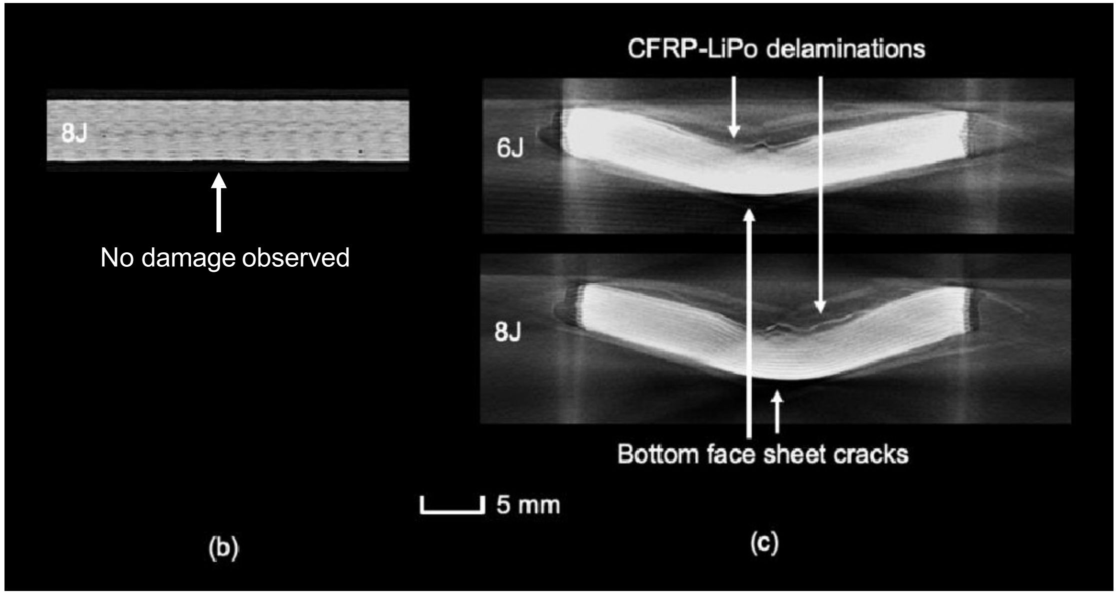
Energy absorbing capabilities & impact damages – CFRP laminates with an embedded battery

Embedded battery significantly increase energy absorbing capabilities and change damage mechanisms of CFRP laminates.



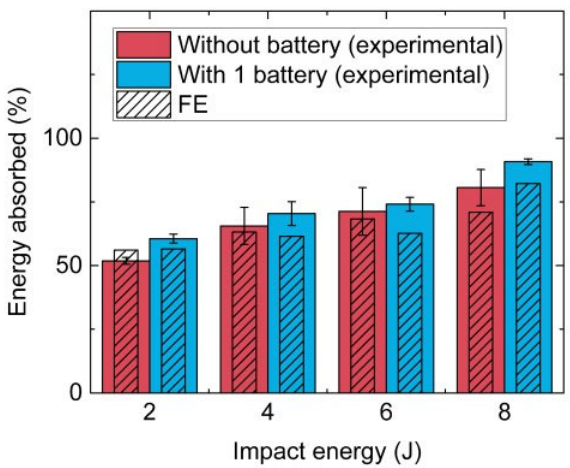
(a) Energy absorbing capabilities



X-ray CT images showing impact damages

Energy absorbing capabilities & impact damages – CFRP/PVC sandwich composites with an embedded battery

Embedded battery changed damage mechanisms of sandwich composites but did not significantly affect their energy absorbing capabilities.



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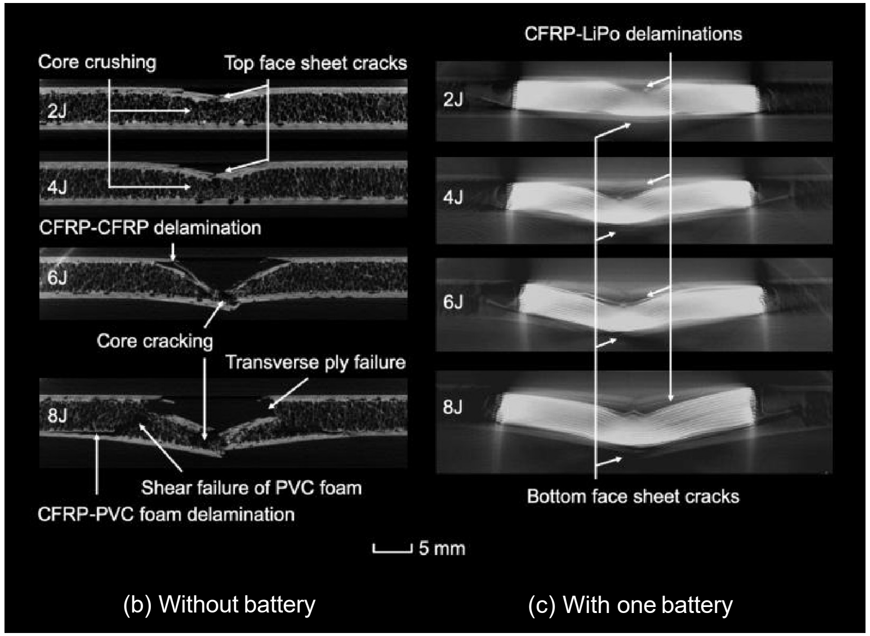
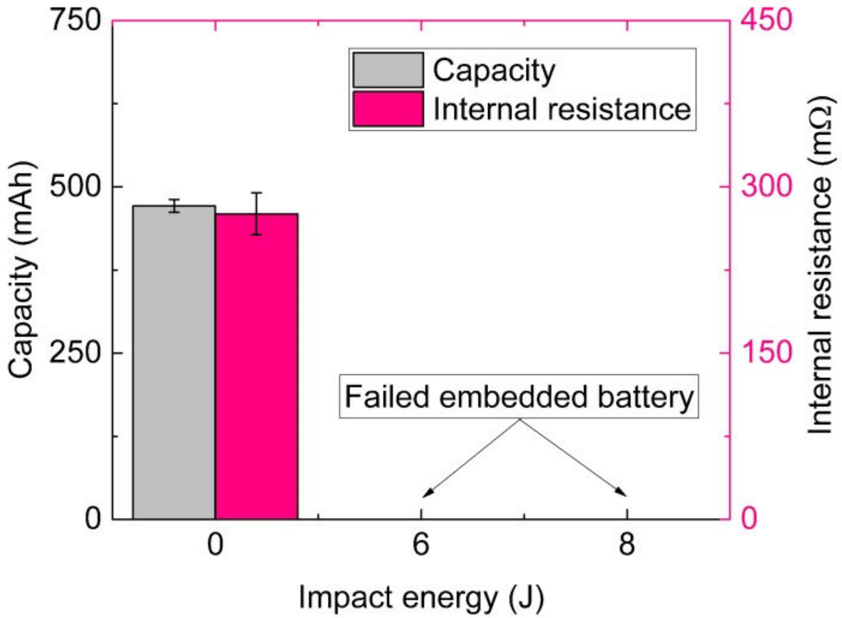


X-ray CT images showing impact damages

Electrical properties



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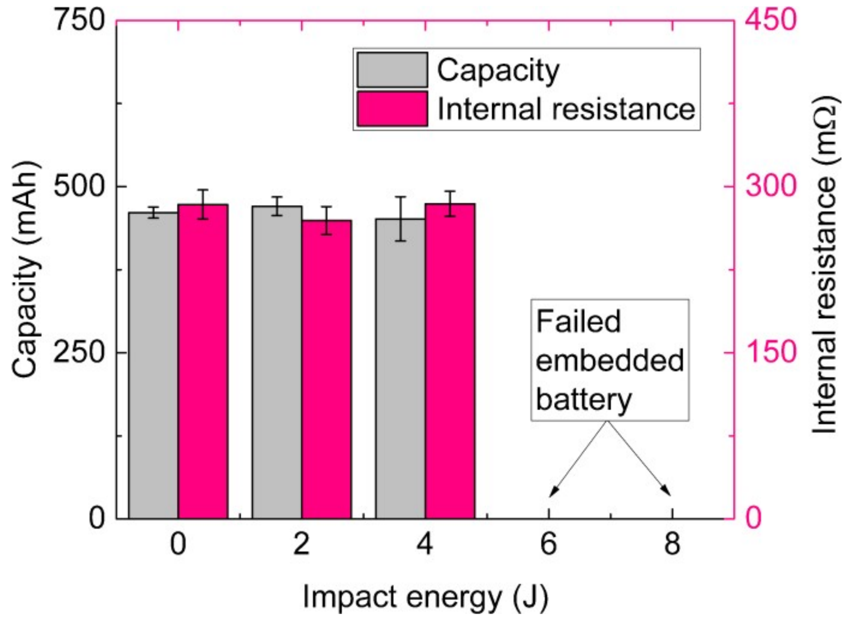

(b)

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Electrical properties of (a) CFRP laminates and (b) sandwich composites before and after impact event

Risks to health and safety

- Higher impact energy (> 8 J), could possibly cause sudden fire and explosion after the crash
- Fire would emit toxic gases such as Carbon Monoxide (CO) and carcinogenic Hydrogen Fluoride (HF)

Tesla Model S catches fire after crash
https://www.express.co.uk/life-style/cars/868374/Tesla-Model-S-fire-car-crash-electric-car

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Conclusion

- Composites with embedded batteries can be manufactured by composites manufacturing methods
- Embedded battery significantly changed CFRP laminates impact responses
- LiPo battery can be a potential energy absorbing material
- Impact energy of up to 8 J did not cause sudden fire and explosion
- Impact energy of higher than 8 J could possibly cause sudden fire and explosion which results in an emission of toxic gases such as CO and HF.

Publications

- **K. Pattarakunnan**, J. Galos, and A. P. Mouritz, “A review of energy storage composite structures with embedded lithium-ion batteries,” *Proceedings of the 22nd International Conference on Composite Materials*, *Melbourne, Australia*, *11-16 August*, *2019*.
- **K. Pattarakunnan**, J. Galos, R. Das, and A. P. Mouritz, “Tensile properties of multifunctional composites embedded with lithium-ion polymer batteries,” *Composites Part A: Applied Science and Manufacturing,* p. 105966, 2020.

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Thank you

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Backup slides

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Specimens fabrication

- Material system
  - 200 g/m^2 plain woven T300 carbon fabric (AC220127 supplied by Colan Ltd.)
  - 4-mm H100 Divinycell PVC foam (100 kg/m^3)
  - 500 mAh and 3.7 V LiPo battery (LP423043 from LiPol Battery Co. Ltd, China)
  - Low-temperature cure bisphenol-A epoxy resin (West system)
    - One-part 206 slow hardener
    - Five-part 105 resin
  - Araldite 420 A/B adhesive
  - Plain woven glass fibre
- Wet hand layup for sandwich specimens
- Resin infusion for laminate specimens

Impact modelling

- Sandwich composite (150mm x 100mm x 5.5mm)
  - CFRP facesheets (Colan 198gsm woven plain weave)
  - Foam core (H100 Divinycell PVC foam)
  - Epoxy (West system 105 Resin + 206 Slow hardener)
  - Battery (LiPol 500mAh LiPo battery)
- Steel impactor

CFRP modelling approach (1/2)

- Each ply is modelled individually as continuum shell (SC8R)
- Built-in VUMAT for woven fabric reinforced composites (ABQ_PLY_FABRIC) is selected to introduce plasticity and damage
  - Applicable for only shell, plane stress, and membrane elements

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CFRP modelling approach (2/2)

26 user material constants must be specified for this subroutine

- Young's moduli in fiber 1- and 2-directions
  - $E_{1+/-}$, $E_{2+/-}$
- Poisson's ratio
  - ν_{12+}, ν_{12-}
- Shear modulus
  - G_{12}
- Shear stress at the onset of shear damage
  - S
- Tensile and compressive strength along fiber directions
  - $X_{1+/-}$, $X_{2+/-}$
- Shear equation parameters
  - α^{12}, $d^{12}{}_{max}$
- Energy per unit area for tensile and compressive fracture along fiber directions
  - $G_f^{1+/-}$, $G_f^{2+/-}$
- Shear plasticity coefficients
  - σ_{y0}, C, p
- Controls for material point failure
  - `lDelFlag`, d_{max}, $\varepsilon^{pl}{}_{max}$, ε_{max}, ε_{min}

Foam modelling approach

- A foam core is modelled as 3D solid element (C3D8R)
- Crushable foam plasticity + Crushable foam hardening is used to introduce plasticity
  - Isotropic material must only be used in this criteria

Epoxy modelling approach (1/2)

- Epoxy is modelled as cohesive interaction between each of the CFRP plies and between CFRP plies and foam core
  - Damage initiation criteria: Quadratic stress criterion >> Damage is assumed to initiate when a sum of ratio in below formula reaches 1

$$\left(\frac{\langle t_n \rangle}{t_n^{\max}}\right)^2 + \left(\frac{t_s}{t_s^{\max}}\right)^2 + \left(\frac{t_t}{t_t^{\max}}\right)^2 = 1$$

- *tn*: normal contact stress in the pure normal mode
- *ts*: shear contact stress along the first shear direction
- *tt*: shear contact stress along the second shear direction

Epoxy modelling approach (2/2)

– The damage evolution is governed by fracture energy from Benzeggagh-Kenane (BK) criteria as presented below

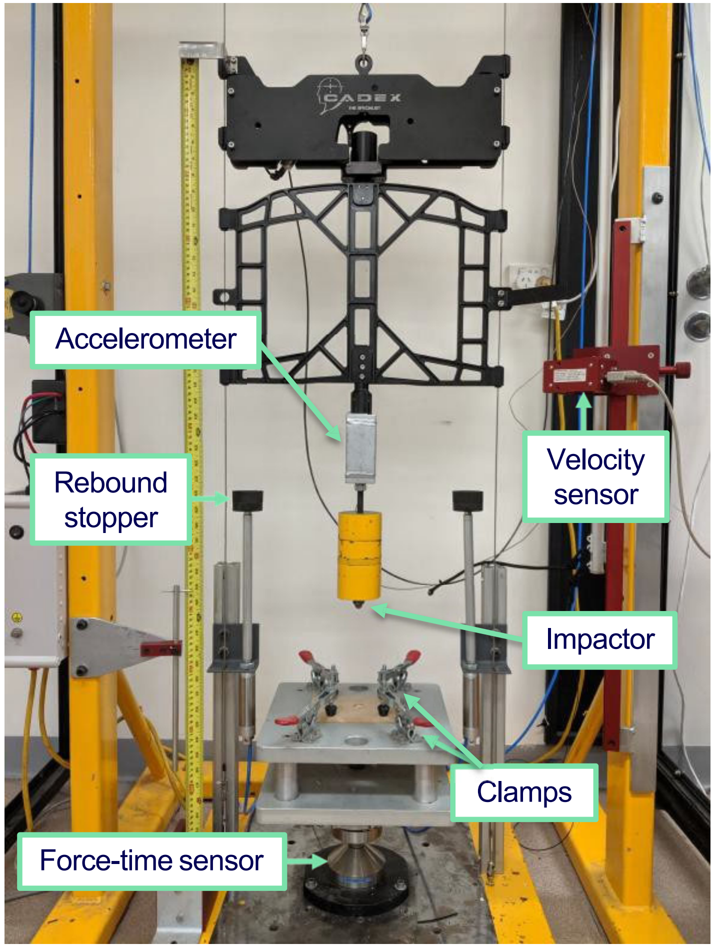
$$G_{IC} + \left(G_{IIC} - G_{IC}\right)\left(\frac{G_{shear}}{G_T}\right)^{\eta} = G_{TC}$$

where $G_{shear} = G_{II} + G_{III}$

$$G_T = G_I + G_{shear}$$

Contact algorithm

- General contact (explicit) is used
  - Specify hard contact to prevent elements penetration
  - Specify coefficient of friction to be 0.2
  - Specify contacts between plies and plies, and plies and core as cohesive interaction



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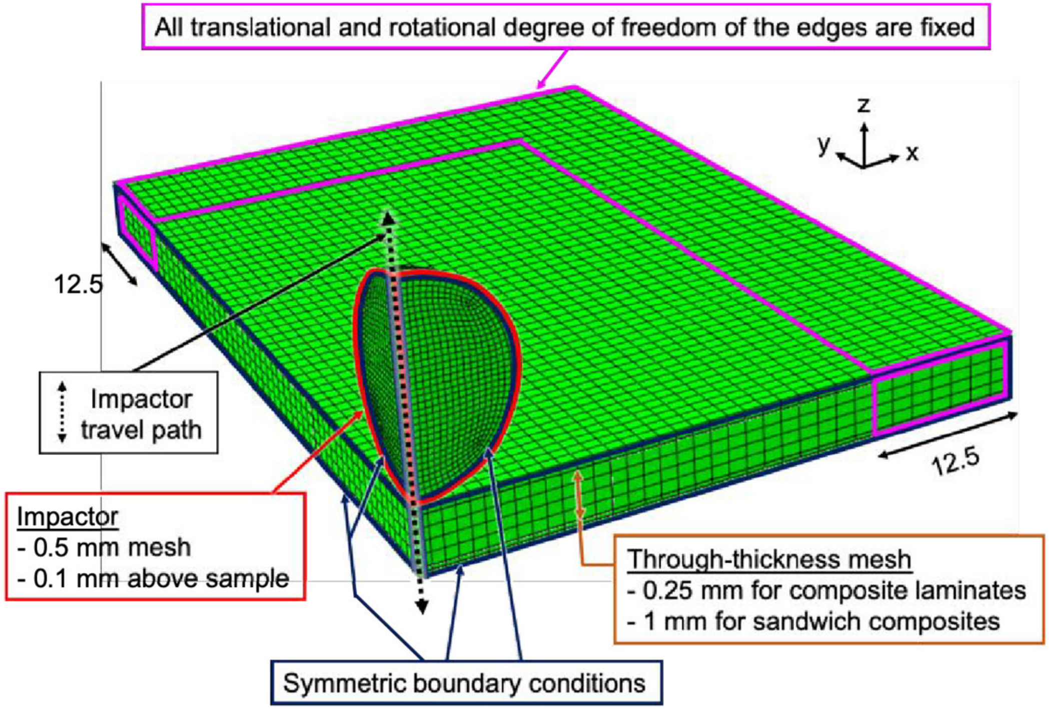
FE model – Impact test



FE model of the impact test showing meshing strategy and boundary condition

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Electrical properties before and after impact

Electrical properties of embedded batteries subjected to impact loading

Impact energy (J)	Capacity (mAh)	Internal resistance (mΩ)
CFRP laminate		
0	471.3 ± 9.6	275.6 ± 19.0
6	~ 0	α
8	~ 0	α
Sandwich composite		
0	460.8 ± 8.4	283.8 ± 13.1
2	470.3 ± 14.0	269.3 ± 12.6
4	451.0 ± 33.4	284.5 ± 11.3
6	~ 0	α
8	~ 0	α