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IMPACT RESPONSE OF TOUGHENED COMPOSITE SANDWICH STRUCTURES

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Introduction

- Composite sandwich structure
  - Stiff carbon fibre reinforced epoxy skins
  - Lightweight epoxy foam core.
- Applications include
  - Marine hulls and superstructure

https://www.naval-technology.com/projects/visby/

- Properties include
  - High specific strength and stiffness
  - Corrosion resistance
  - Brittle → high safety factors
- Critical loading types due to brittleness :
  - Blast loading
  - Impact loading

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Introduction

- **What is required?**
  - Damage resistance
    - Increased energy absorption
- **Impact loading damage types**
  - Skin damage:
    - Fibre fracture
    - Delamination
  - Core cracking and crushing
  - Skin/core debonding
- **Can we increase energy absorption associated with these damage types?**
  - Everything made in-house, complete control over constituent parts
  - Systematically “toughen” individual components and interfaces of the sandwich

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Toughen sandwich components

Skin

- Toughen bulk epoxy with CSR
- Transfer to carbon epoxy laminate
- Transfer to skins of sandwich
- Silica recovers stiffness lost by rubber addition

Skin/core bond

- Toughen interface
- Grooved foam cores
- Toughen through crack deflection and arrest

Core

- Toughen core
- Short fibre reinforced cores
- Toughen through fibre pull-out
- Crack deflection and arrest

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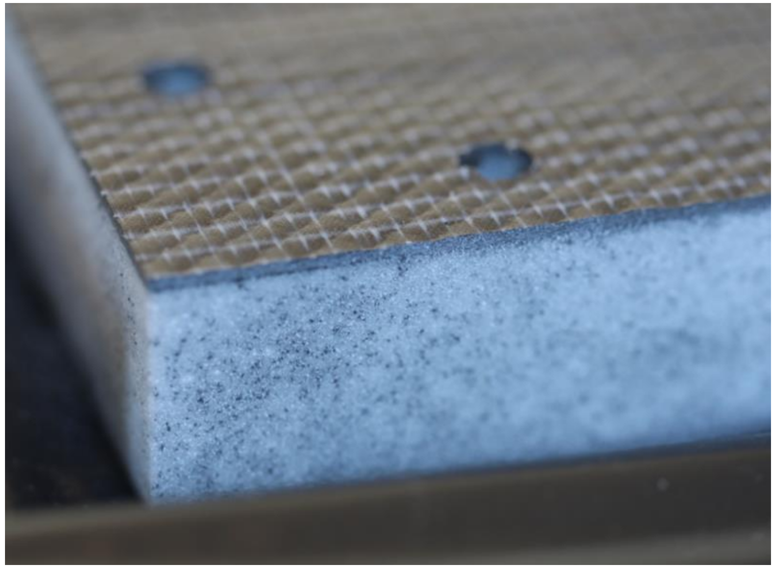
Materials

- Epoxy resin: Diglycidyl ether of bisphenol-A (DGEBA)
- Amine hardener: Jeffamine D230

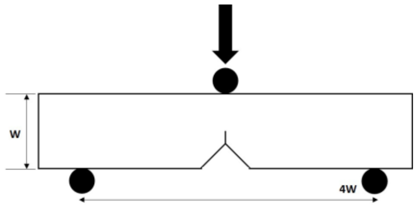
- Nano particles:
  - Polysiloxane core shell rubber (CSR)
  - Silicon dioxide SiO_2
  - Both pre-dispersed at 40 wt % in DGEBA

- Foam: Epoxy Foam, ρ = 170 kg/m^3
- Carbon fibre: 385 gsm 0/90 non-crimp fabric
- Short cut aramid fibres 0.75 mm

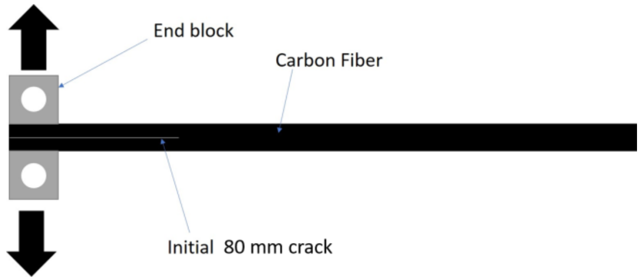


Coupon Testing

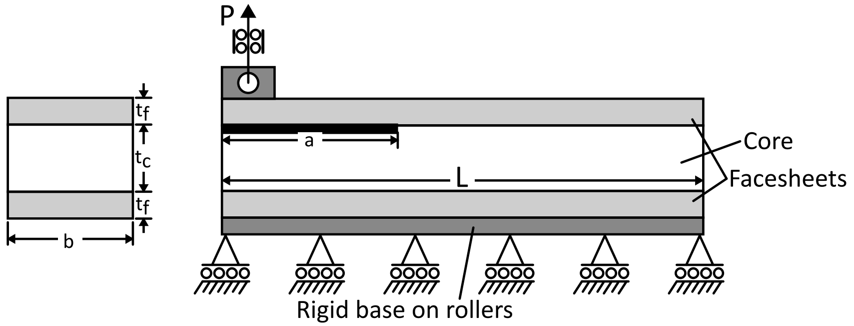
- Bulk polymer plates
  - Modulus and strength: Tensile
  - Fracture properties: Single-edge notch bend (SENB)



- Laminate interlaminar fracture properties: Double cantilever beam (DCB)



- Skin/core bond: Single cantilever beam (SCB)



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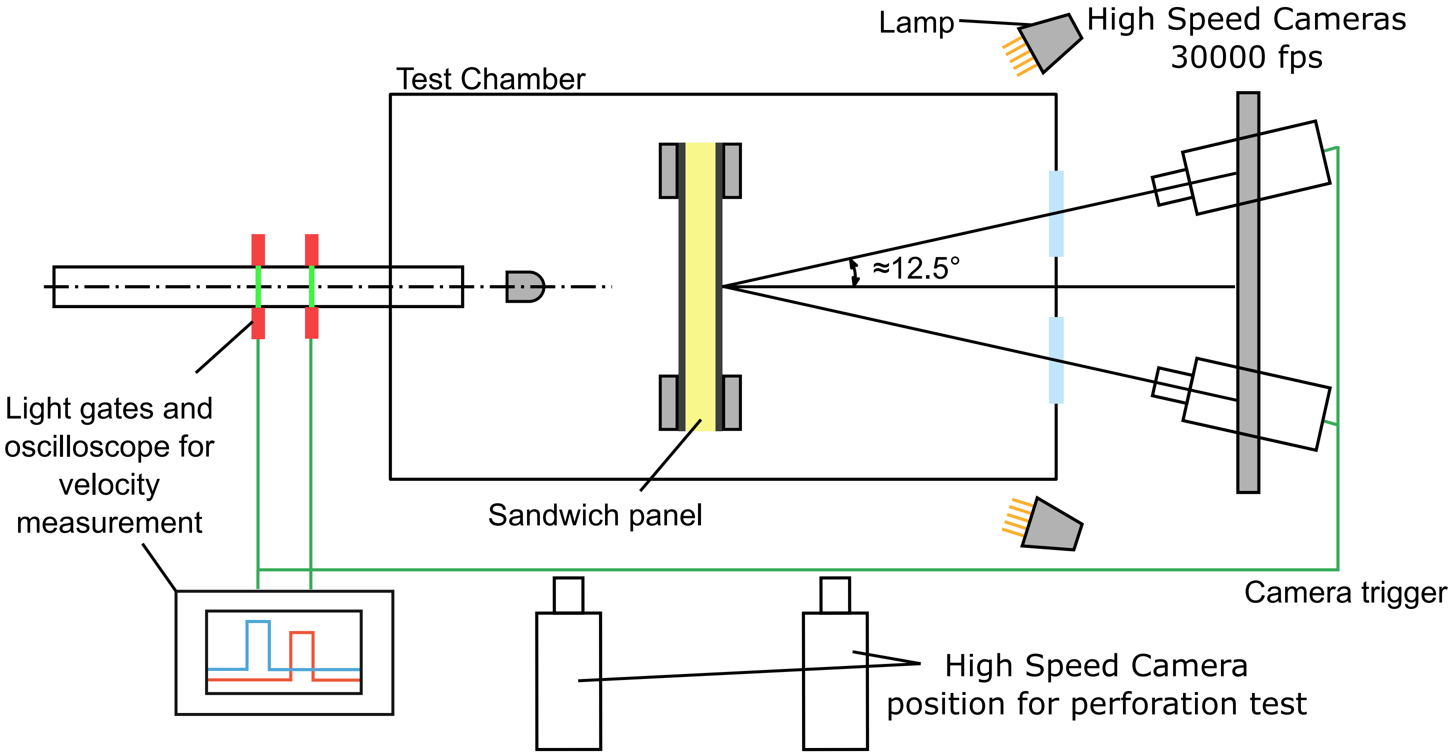
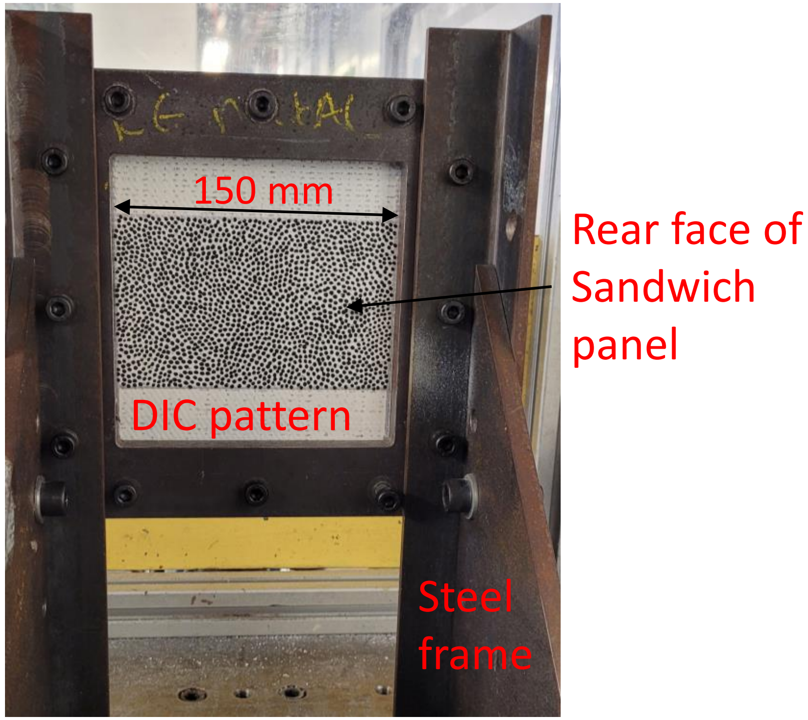
Impact test: Deflection and Perforation





28 g Hemispherical aluminium projectile, **130 m/s** for deflection **170 m/s** for perforation

High speed cameras combined with GOM 3D DIC software for full field out-of-plane displacements.

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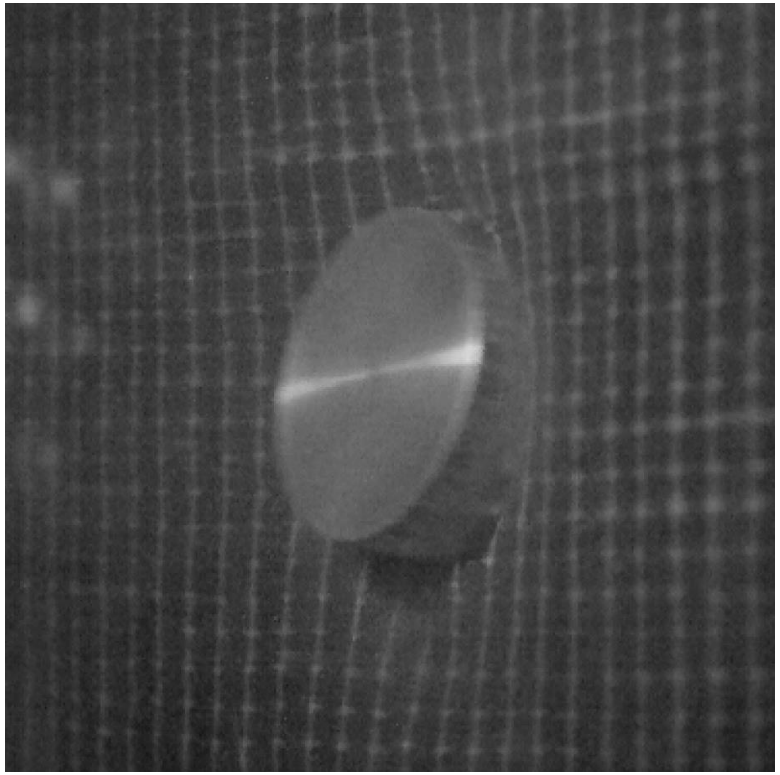
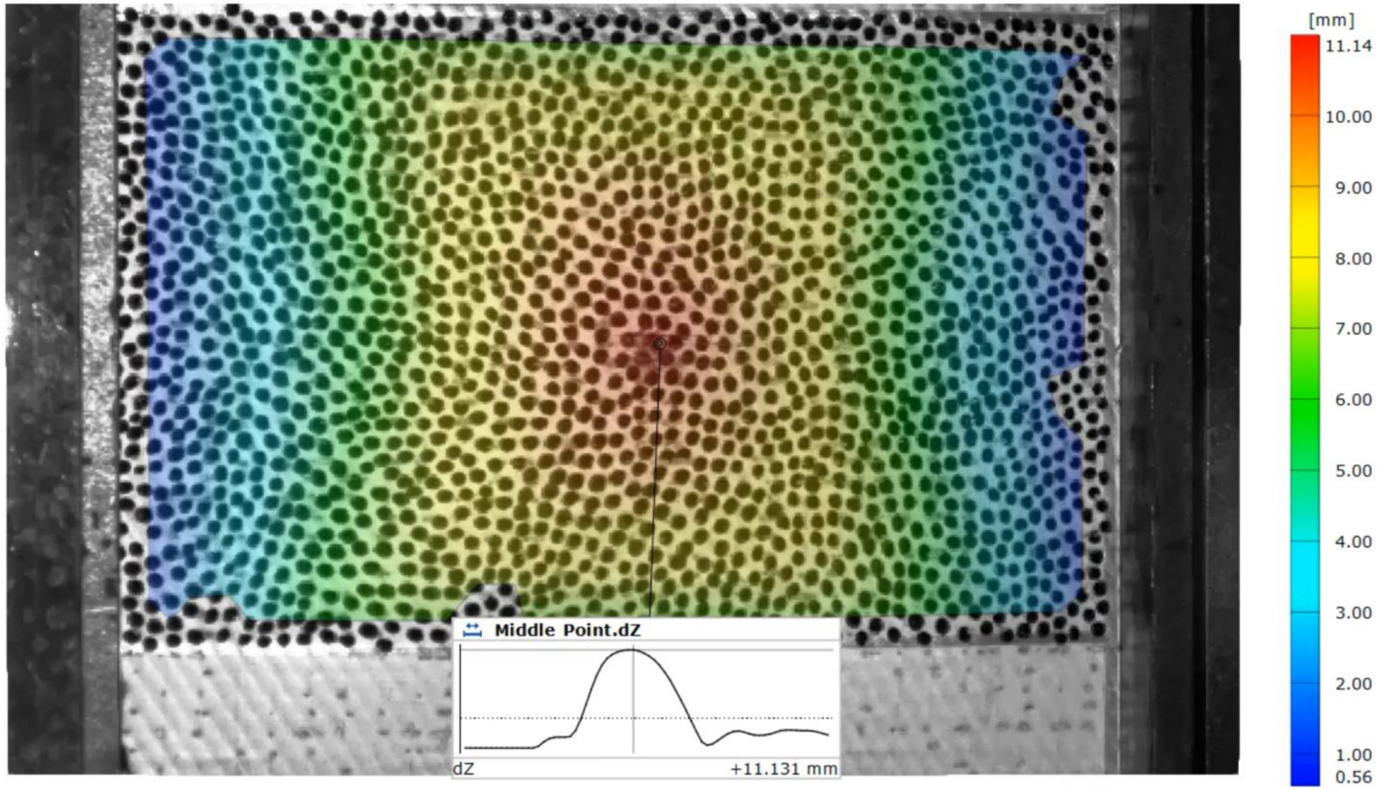
Example DIC output





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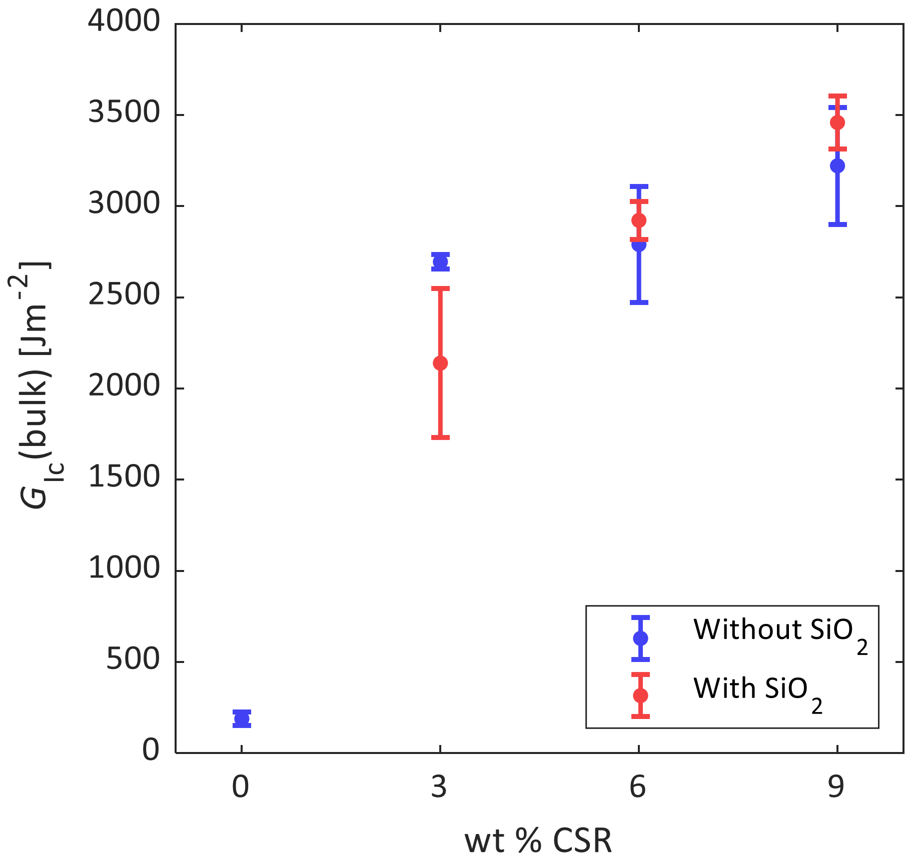
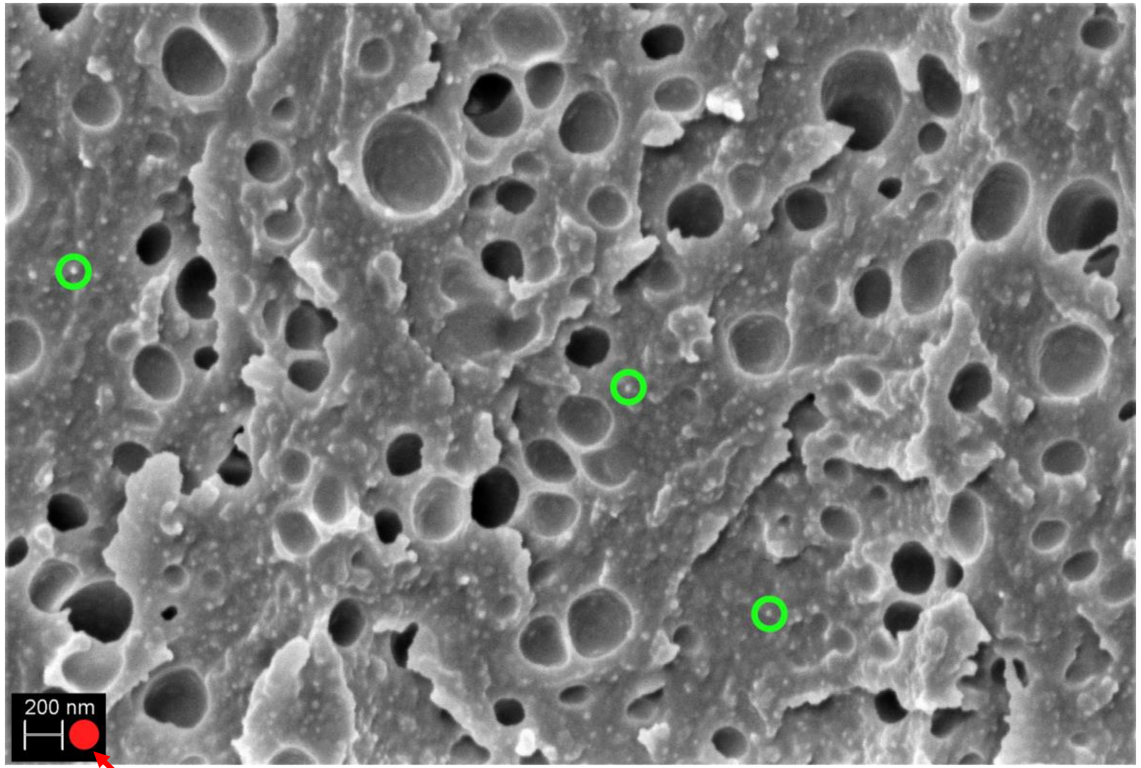
Results: Bulk polymer fracture





160 nm, average size of pre cavitated particle

Addition of CSR leads to significant increase in fracture energy, 188 – 3459 J/m2

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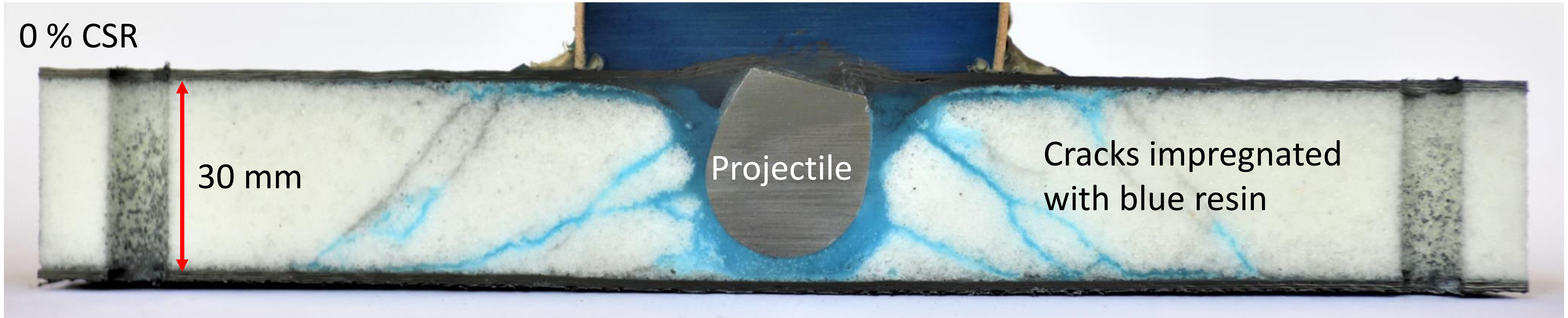
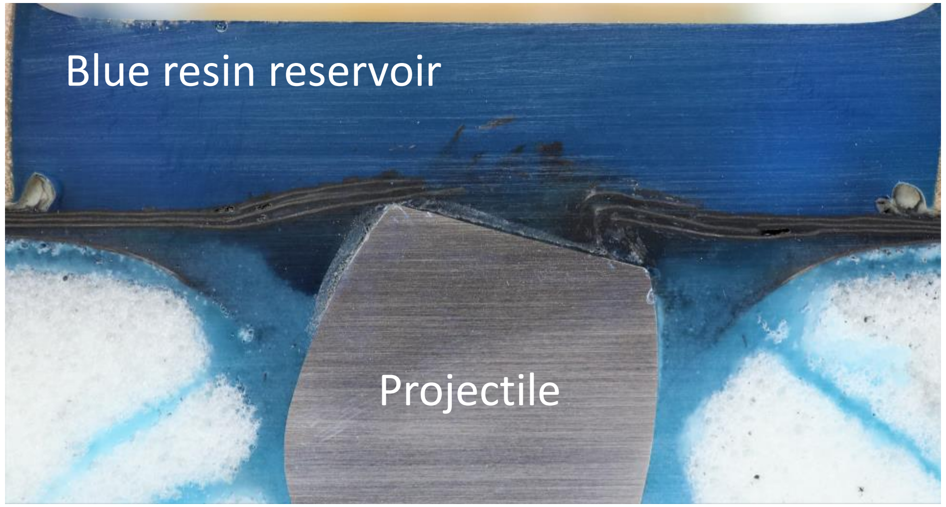
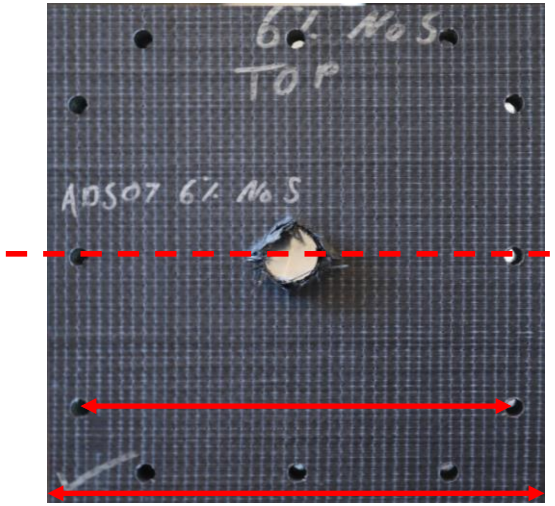
Impact response







Sectioned

200 mm

230 mm

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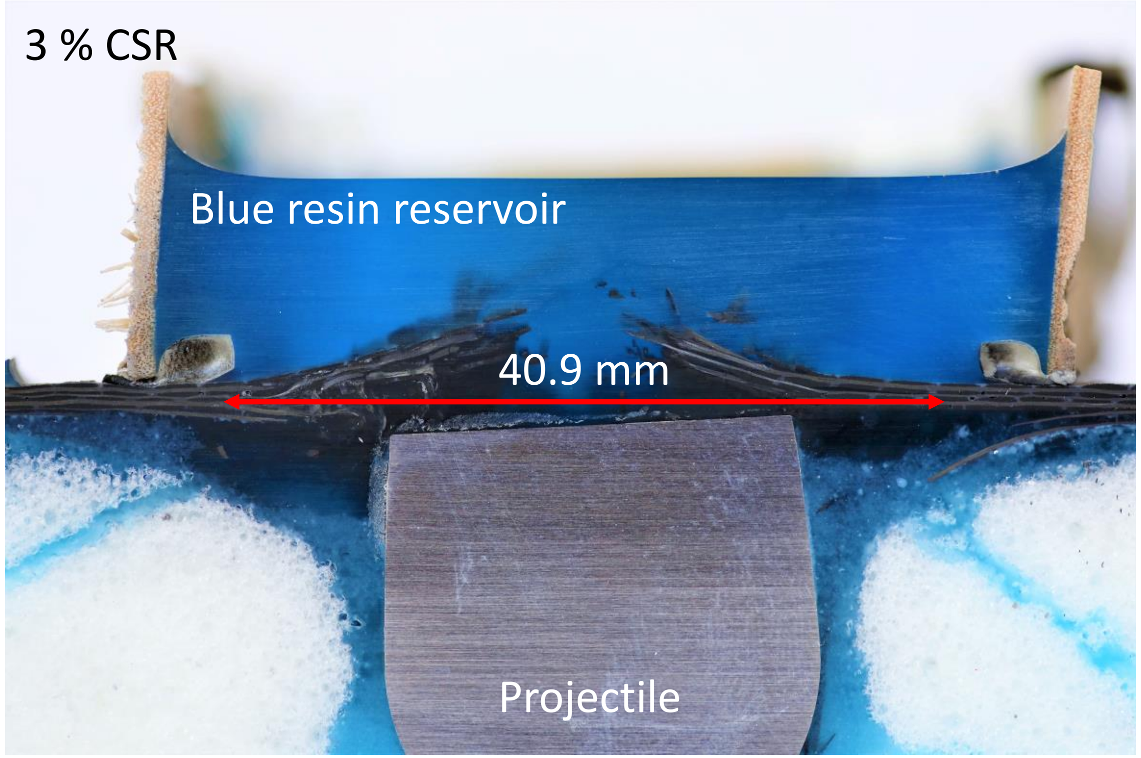
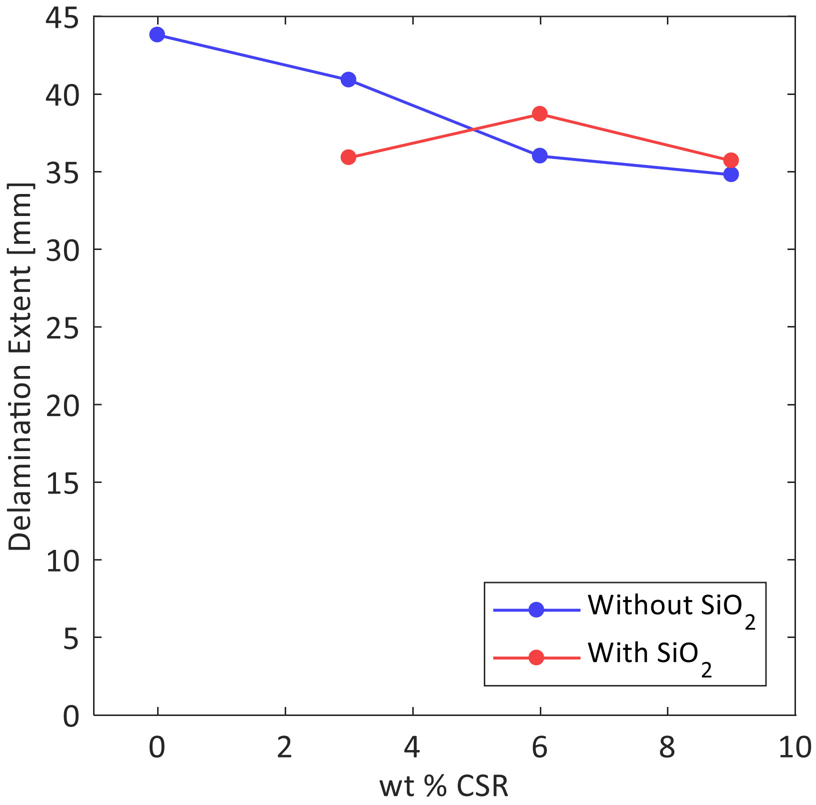
Front skin delamination





CSR reduces the extent of delamination in the front skin

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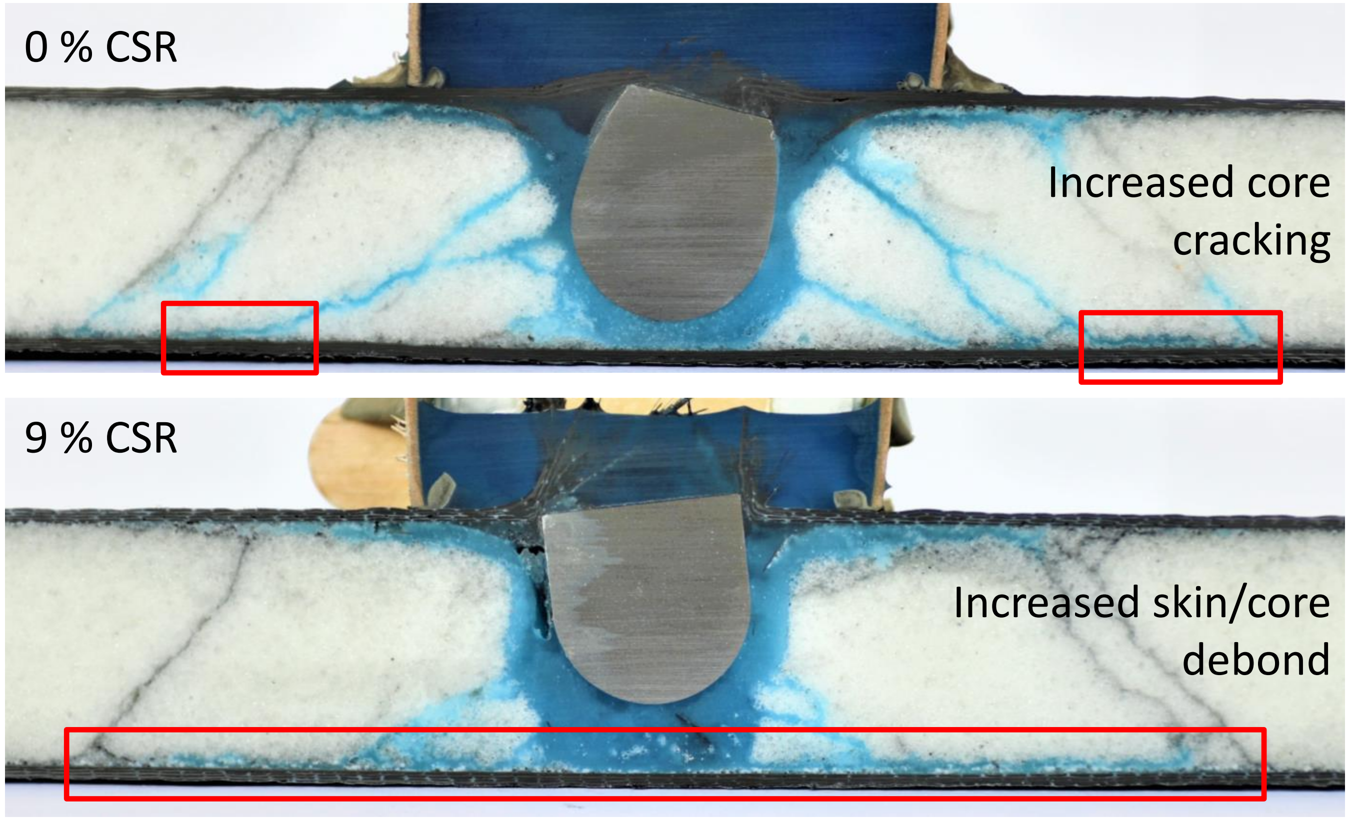
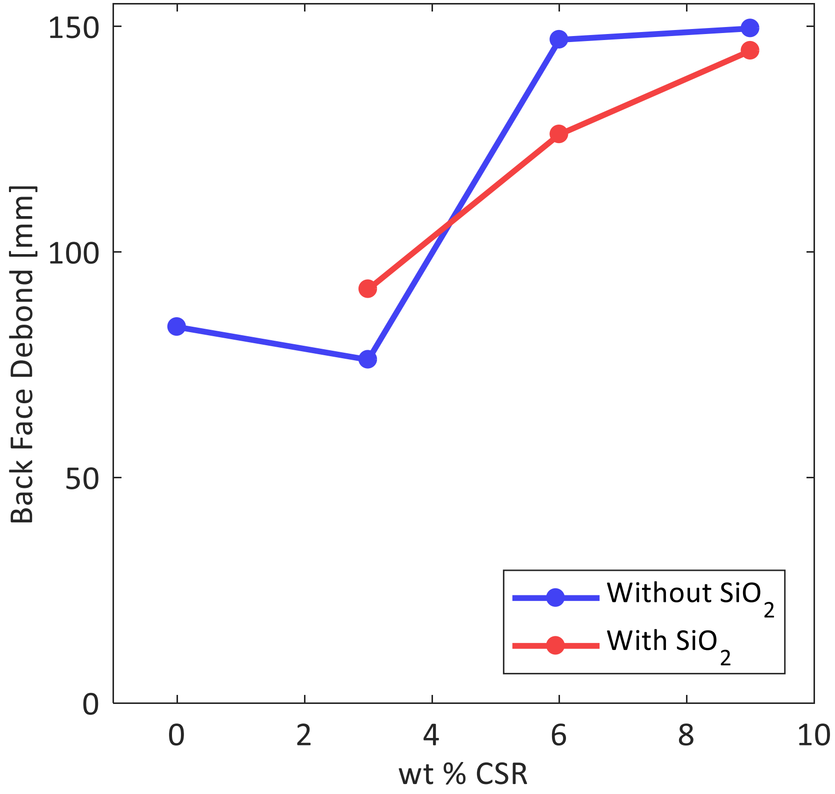
Back face skin/core debond





Addition of 6-9 wt % CSR trades core cracking for widespread back face skin/core debonding.

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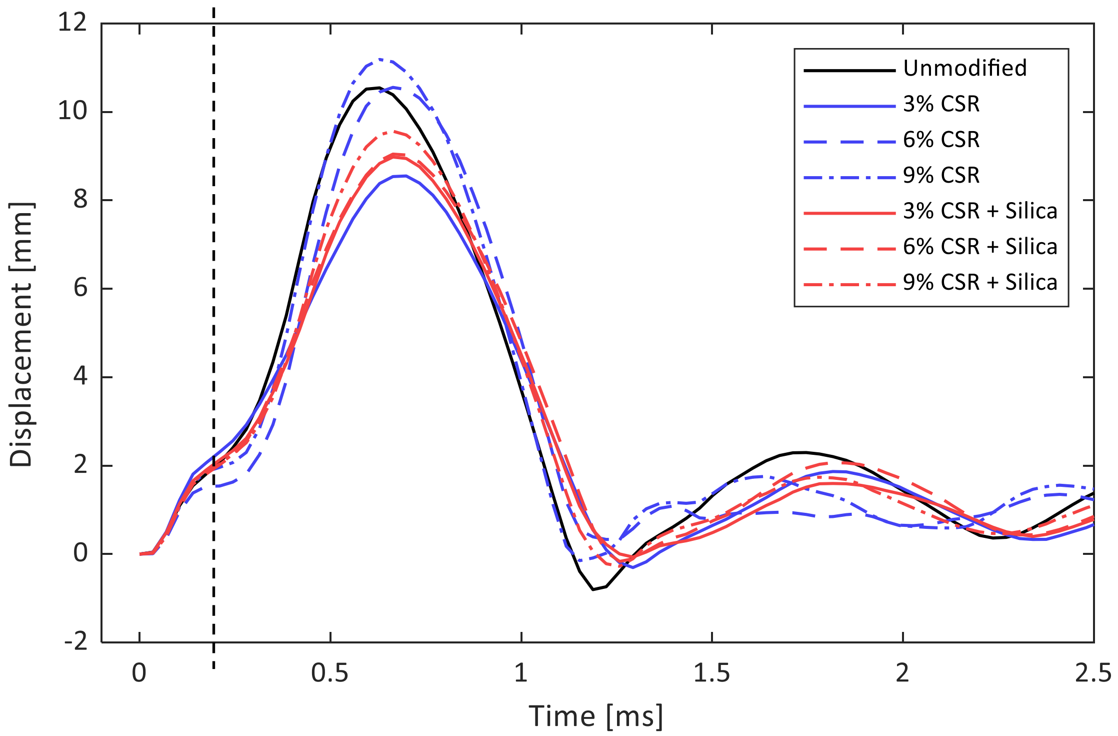
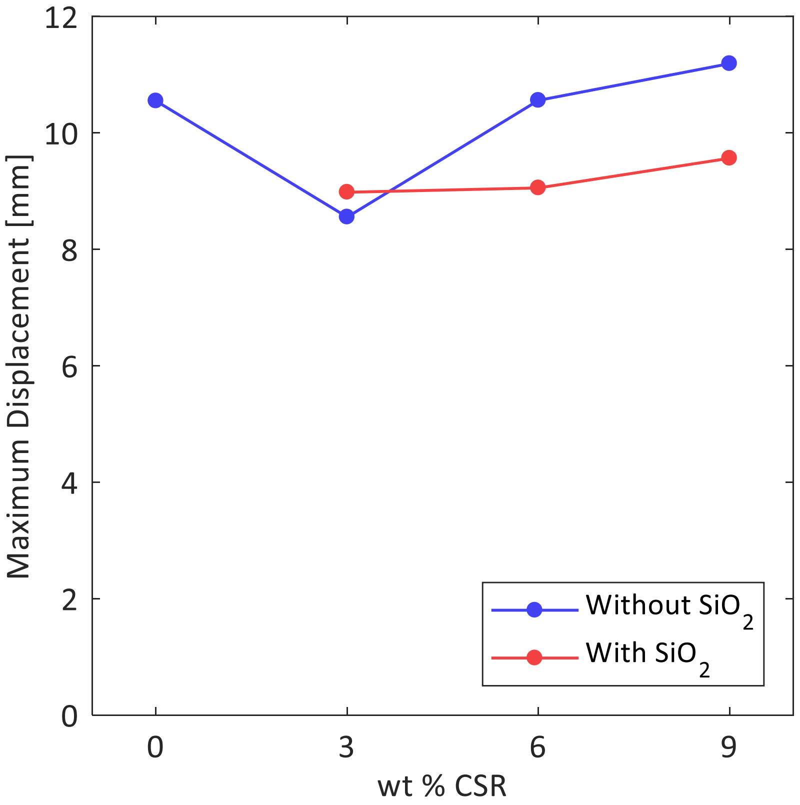
Displacement over time

Perforation point





3 wt % CSR reduces deflection. 6 and 9 wt % caused increased displacement due to excessive drop in modulus outweighing toughening effects. The subsequent addition of silica nanoparticles mitigated this reduction in modulus and reduced displacement.

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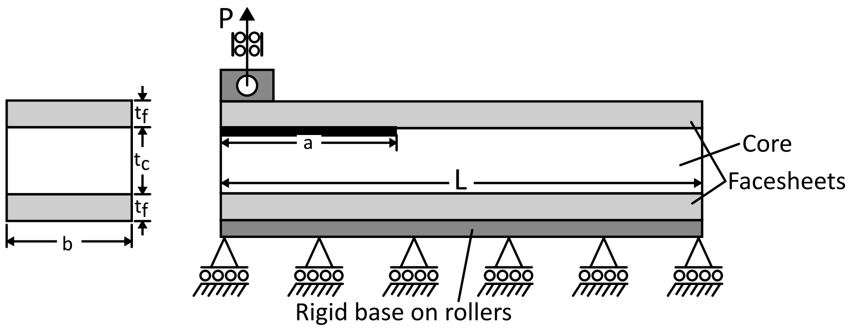
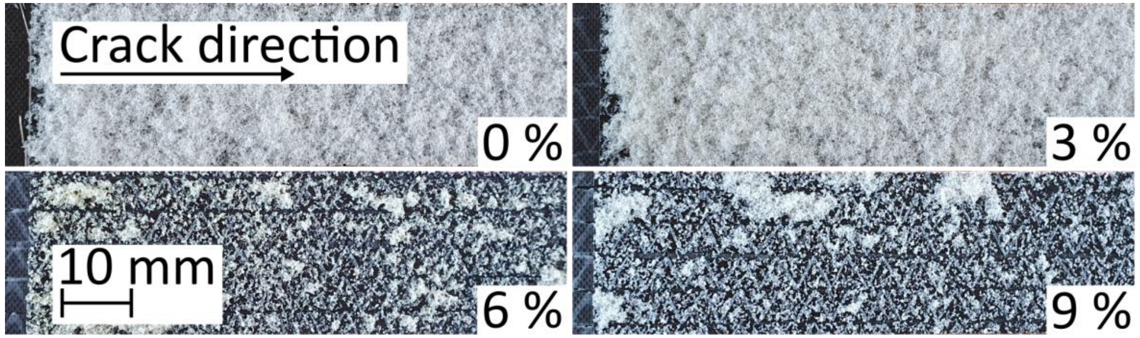
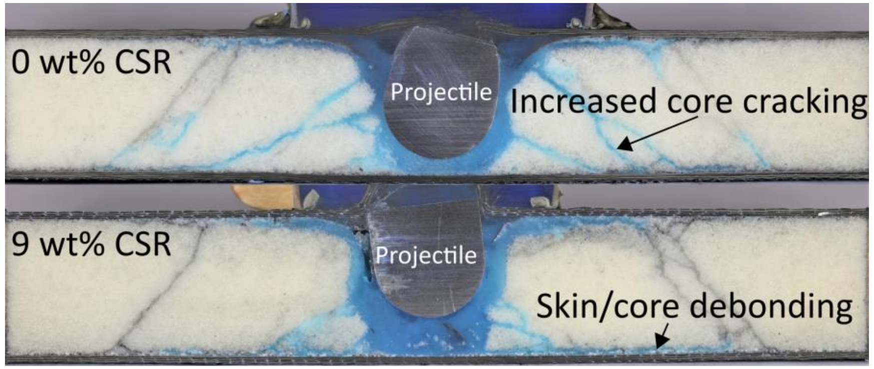
Skin/Core bond results







High toughness lower strength resin

Increased skin/core bond failure

Quasi static test outcomes replicated in impact tests.

Improving Skin/Core Bond

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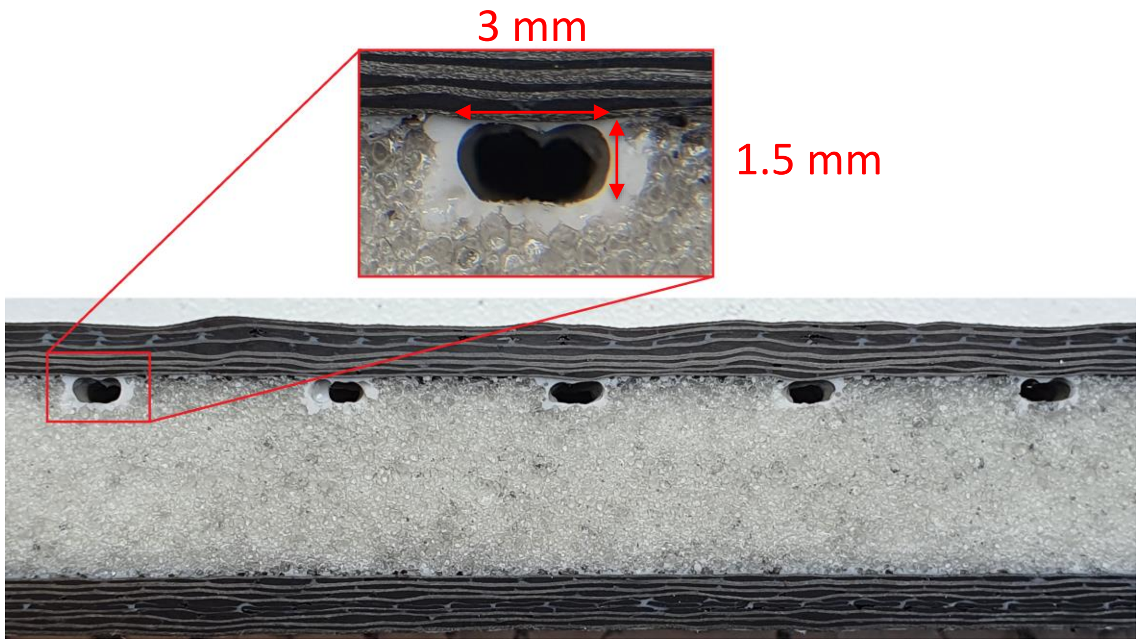

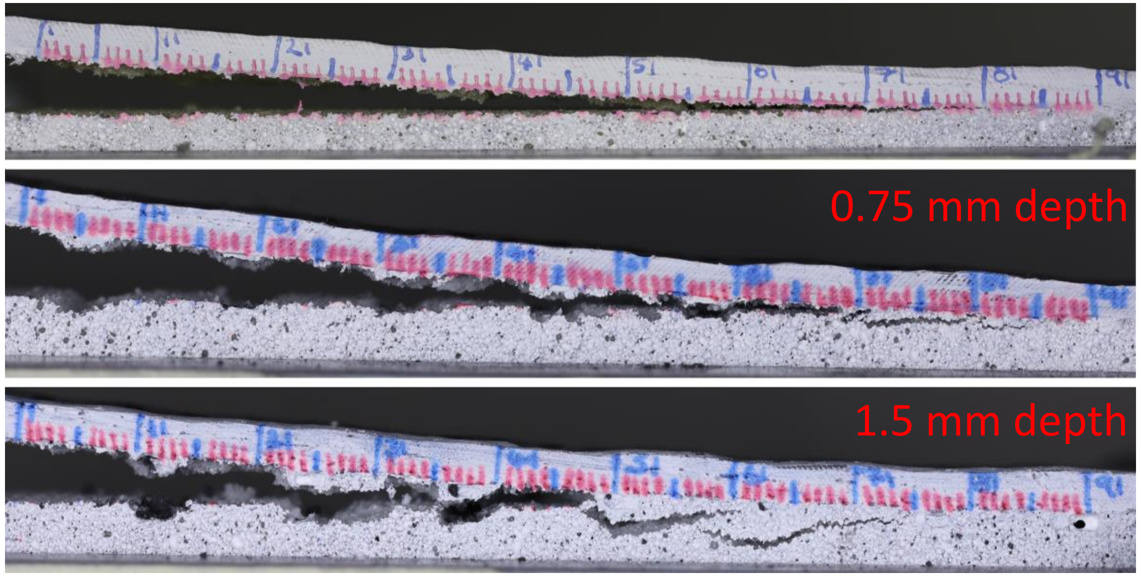

Grooves improve skin/core bond toughness by 50% for a 9% CSR skin matrix resin

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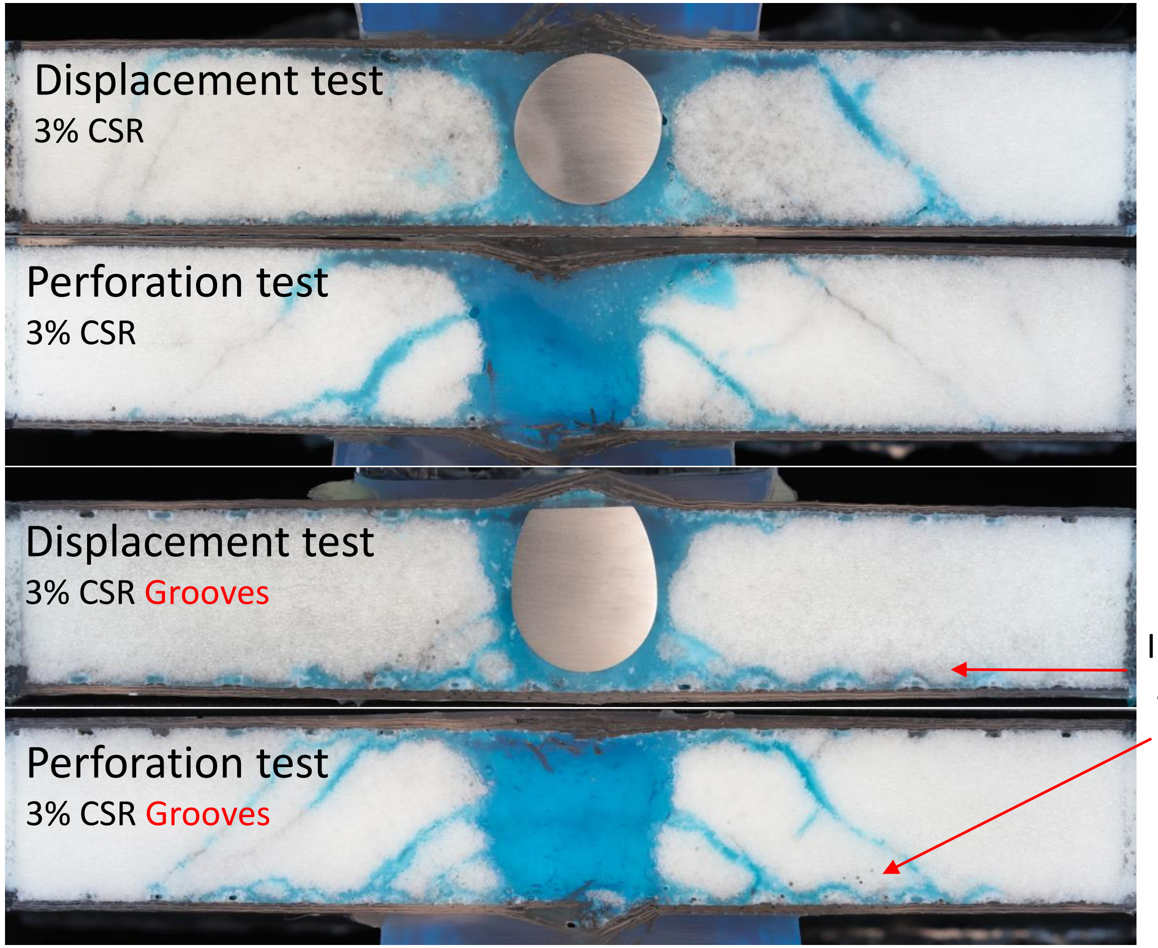
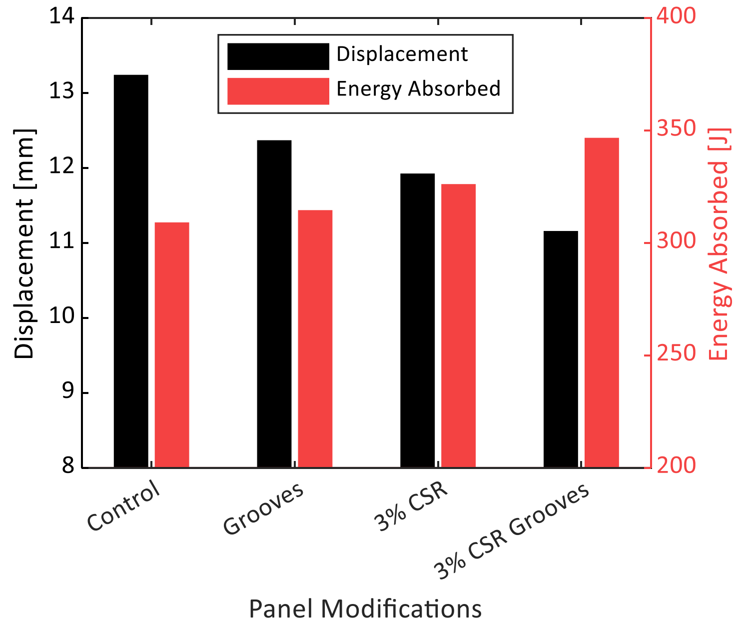
Impact response: Grooved cores



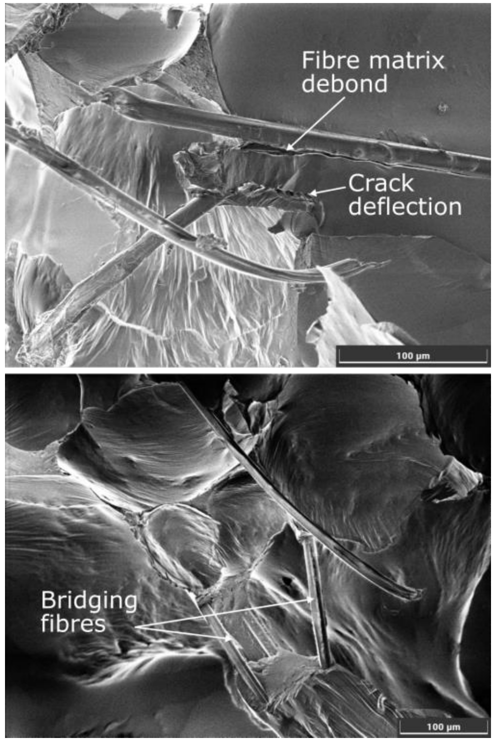
Increased energy absorbed at the interface



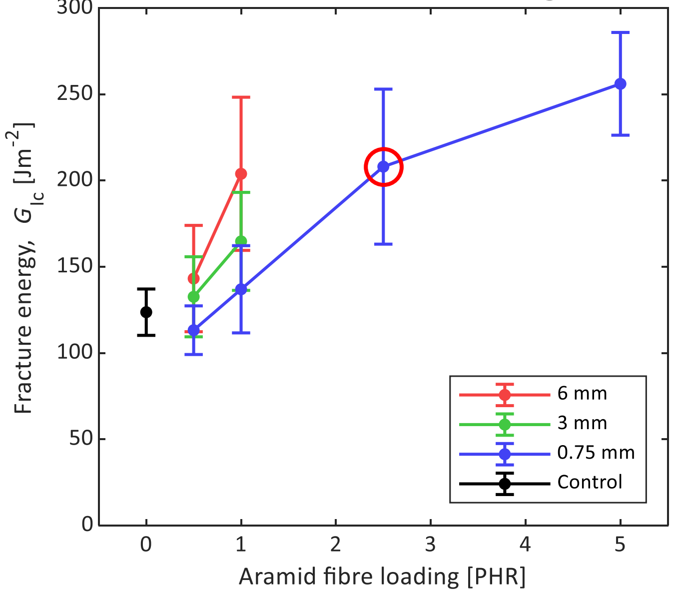
Skin toughening and interface toughening improve both back face deflection and energy absorption

Improve core toughness

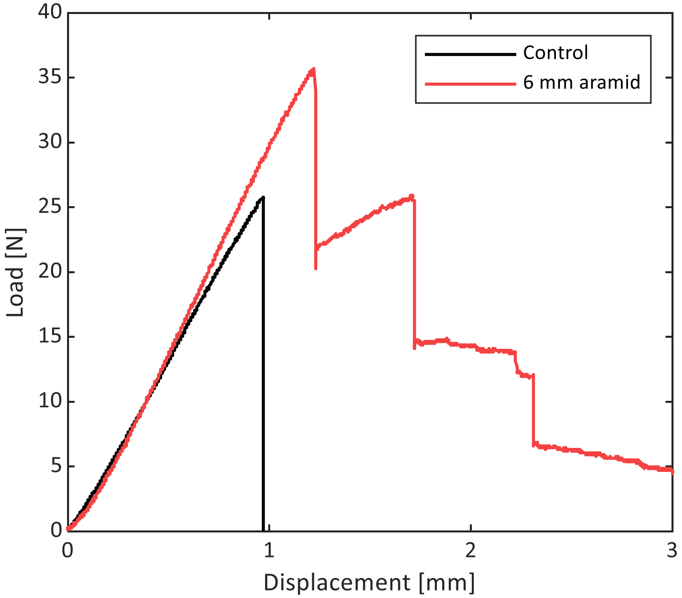
SEM of SENB surfaces of 0.75 mm aramid fibre-reinforced foam



Fracture energy versus aramid fibre loading



Load displacement curve for 6 mm aramid fibres



Short cut aramid fibres can double foam fracture energy

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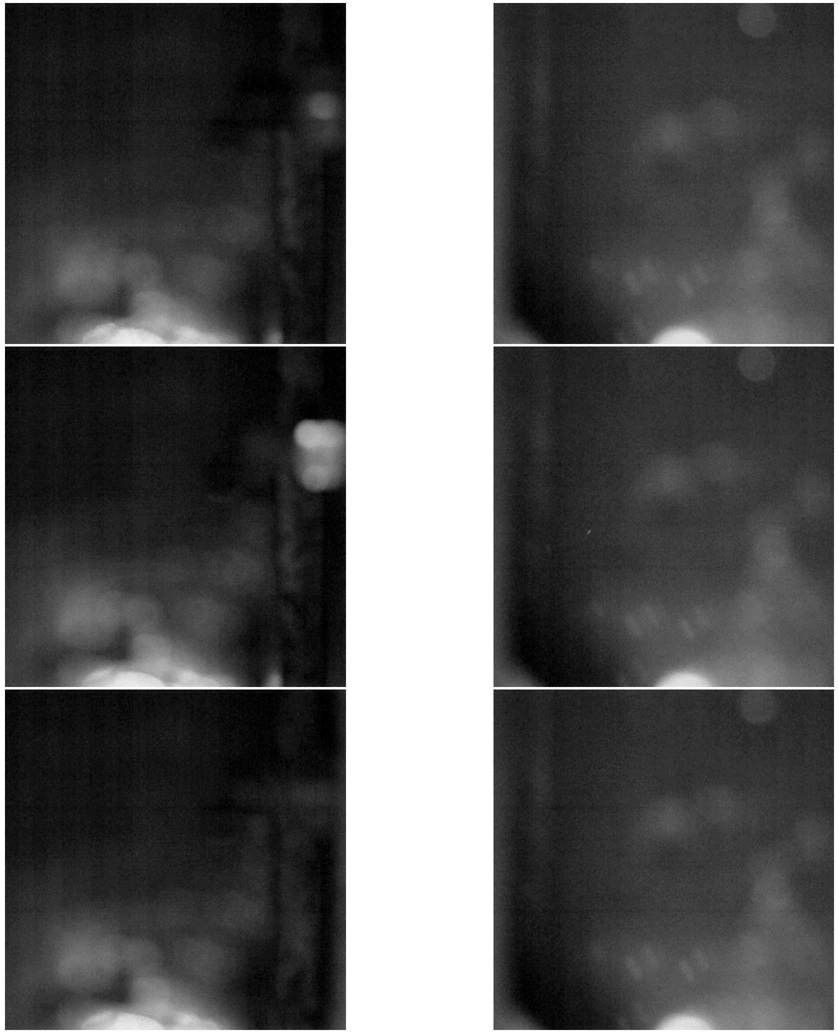
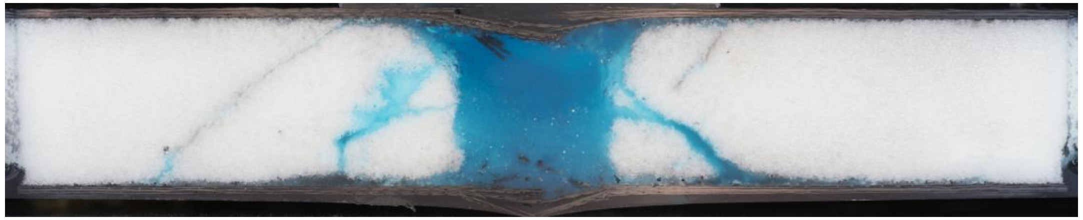
Impact response: Aramid fibre Foams

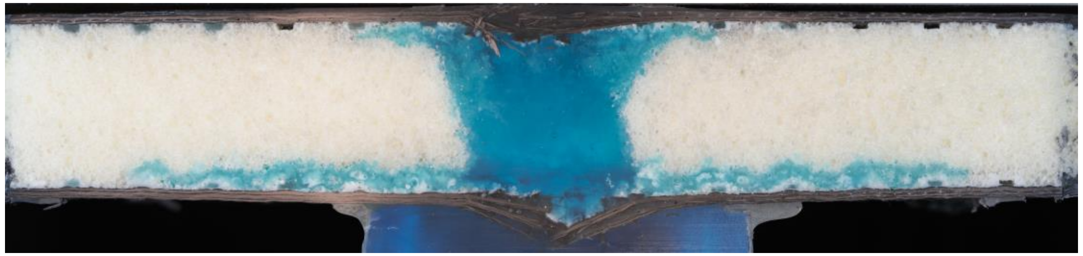


Control Foam



Control foam: Less tough, less energy absorbed. High projectile exit velocity.

Aramid Foam with grooves



Less cracking in the tough core, energy absorbed on the back face debond.

Aramid Foam

Core cracking and back face debond have absorbed large amount of energy.

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Conclusions

Skin

- CSR causes a significant increase in bulk epoxy fracture energy
- Improving skin toughness with 3% CSR is optimal for a sandwich structure under impact loading

Skin/core bond

- Core grooves cause an increase in skin/core bond fracture energy in quasi static testing
- This increase translates to improved energy absorption and reduced back face deflection in a sandwich structure

Core

- Short cut aramid fibres cause a significant increase in foam fracture energy
- This increase causes a significant improvement to energy absorption during sandwich structure impact events

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Questions

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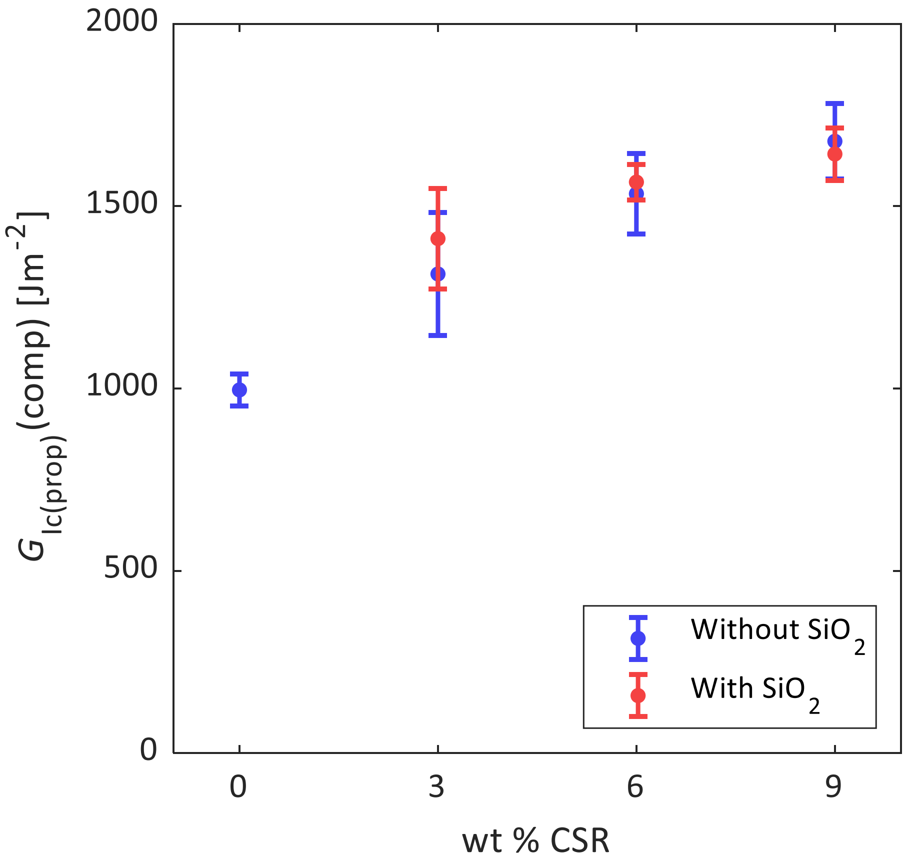
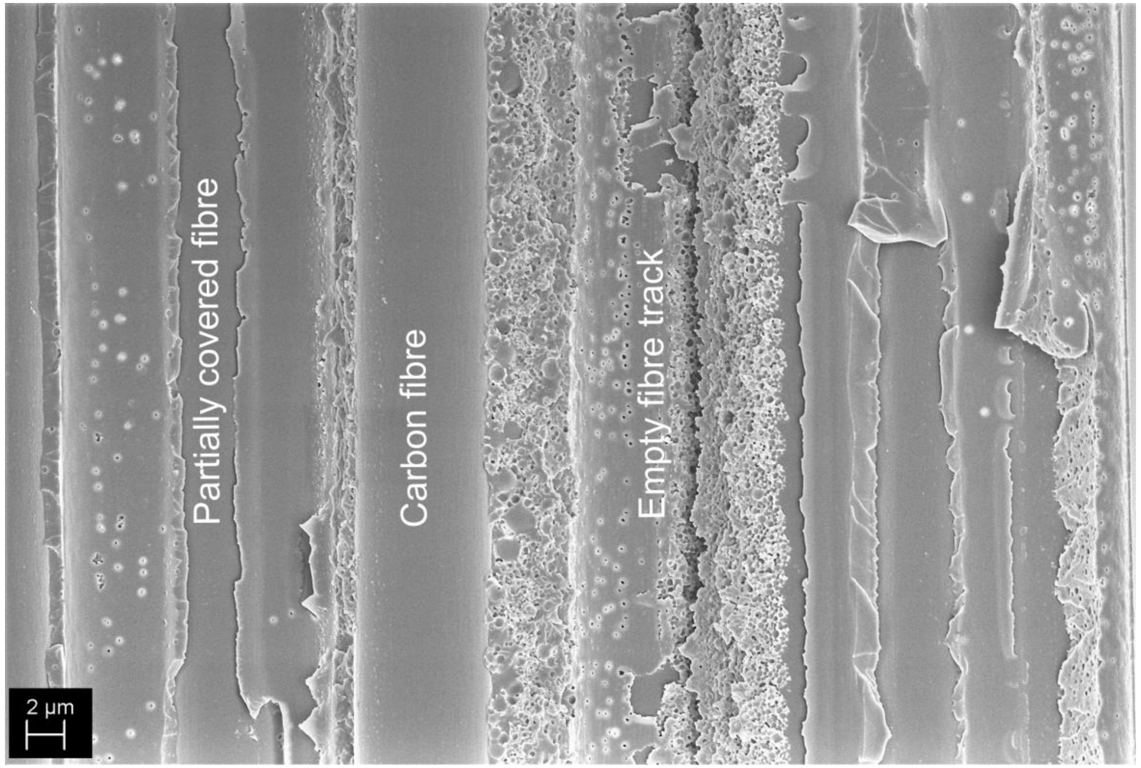
Results: Laminate fracture properties





Addition of CSR leads to significant increase in propagation fracture energy, 996 – 1678 J/m^2

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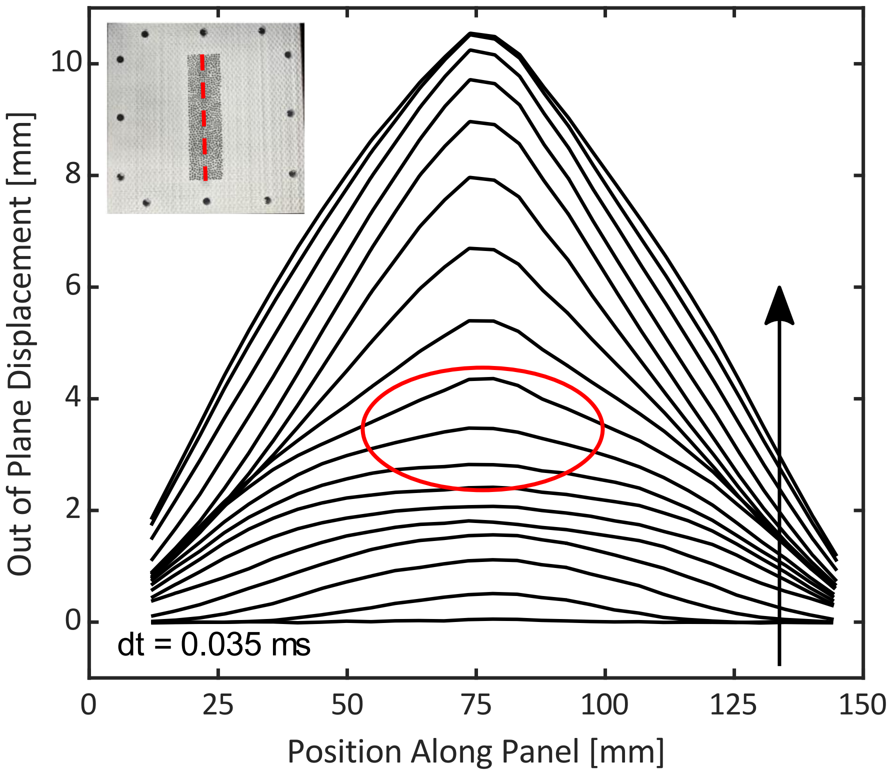
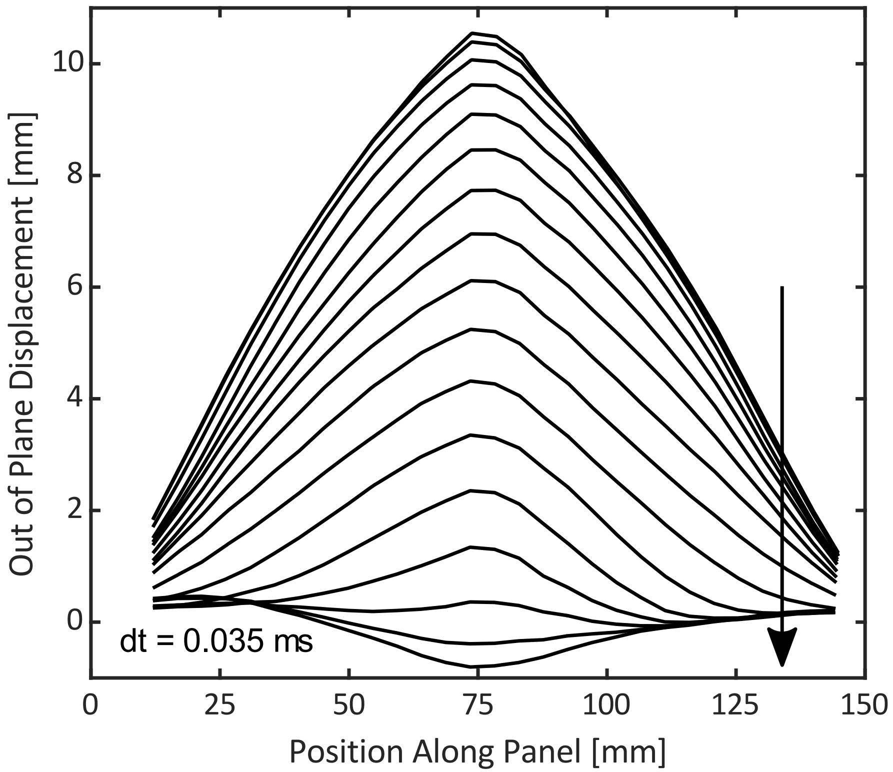
Cross-section displacement





Perforation point visible as transition from curved to angular peak

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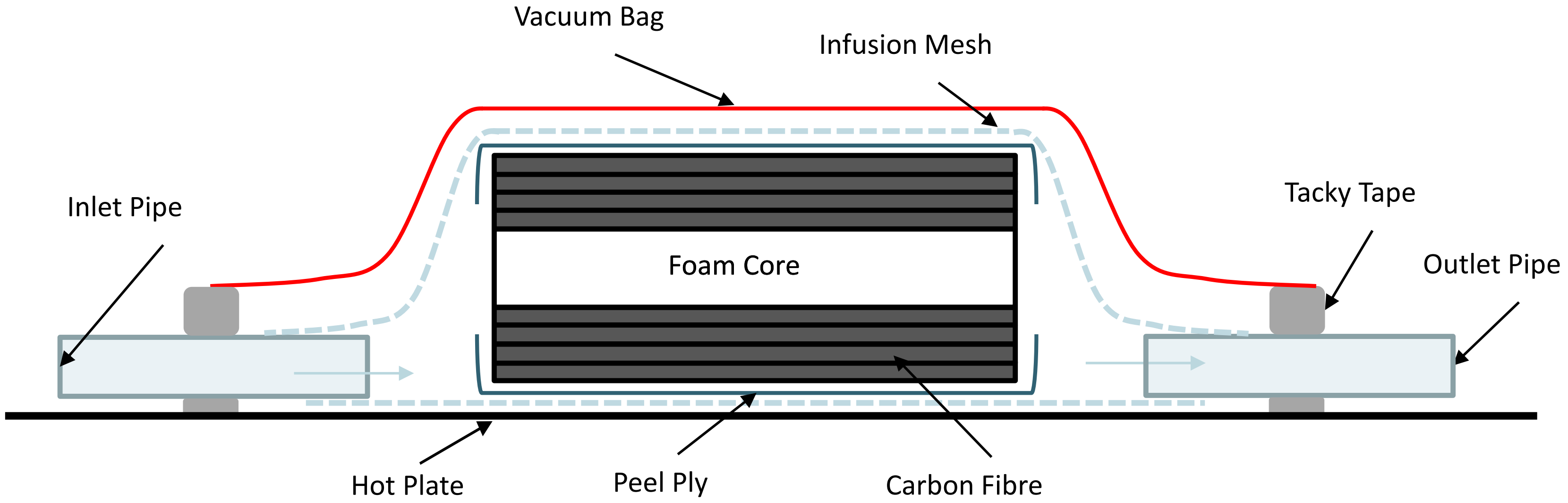
Manufacture

- Bulk plates: Cast in silicone moulds, cure 30°C, post-cure 60°C

- Laminates and sandwiches: Resin infusion over 50°C plate, post-cure 60°C



Use of temperature to reduce viscosity when infusing with highly modified resins.

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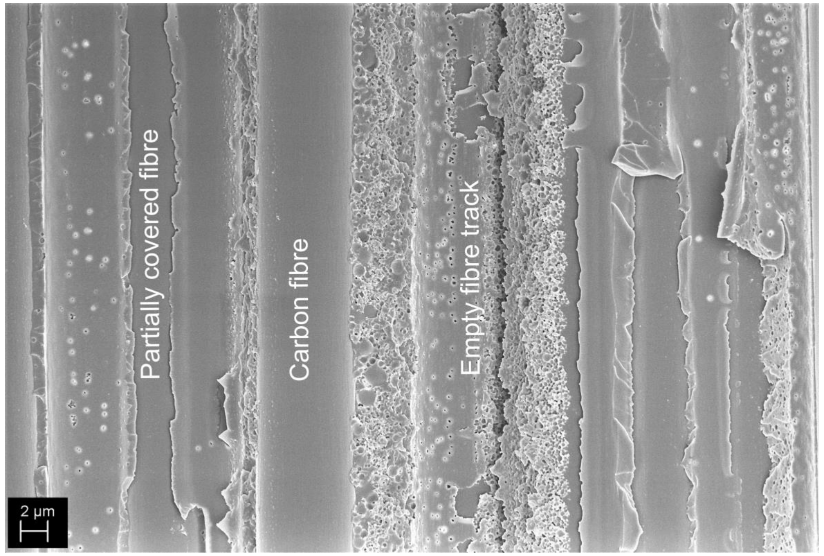
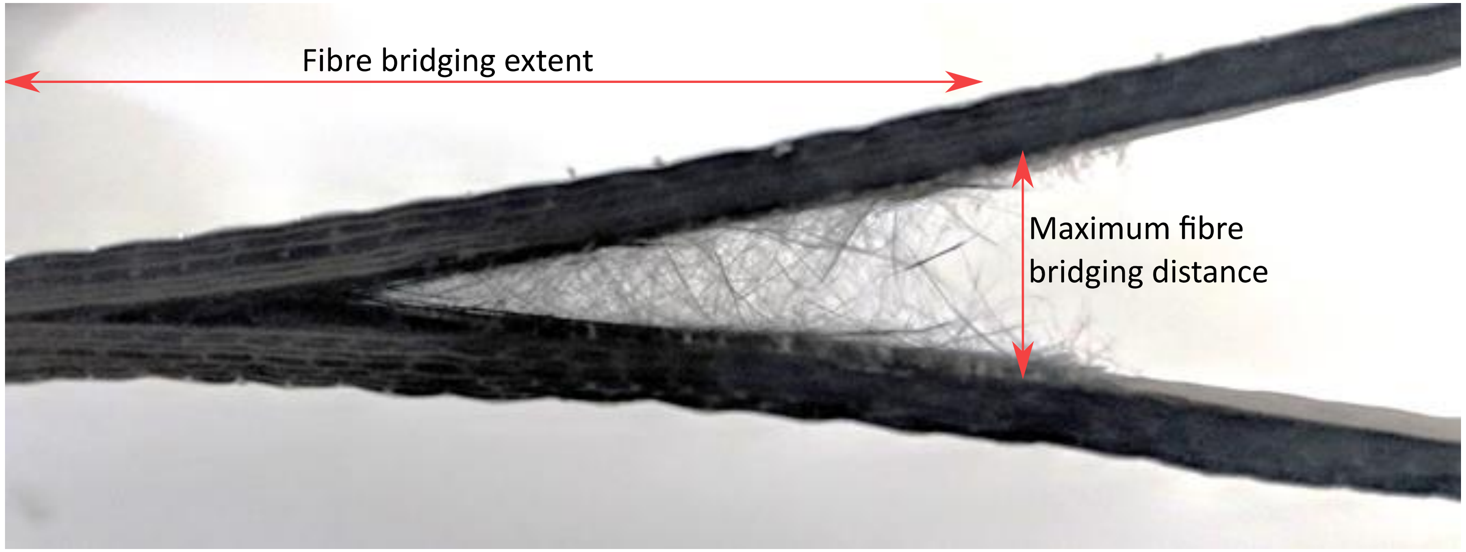
Fibre bridging and CSR





CSR lines empty fibre tracks, fibre bridging induced by reducing bond strength, contributes to energy absorption.

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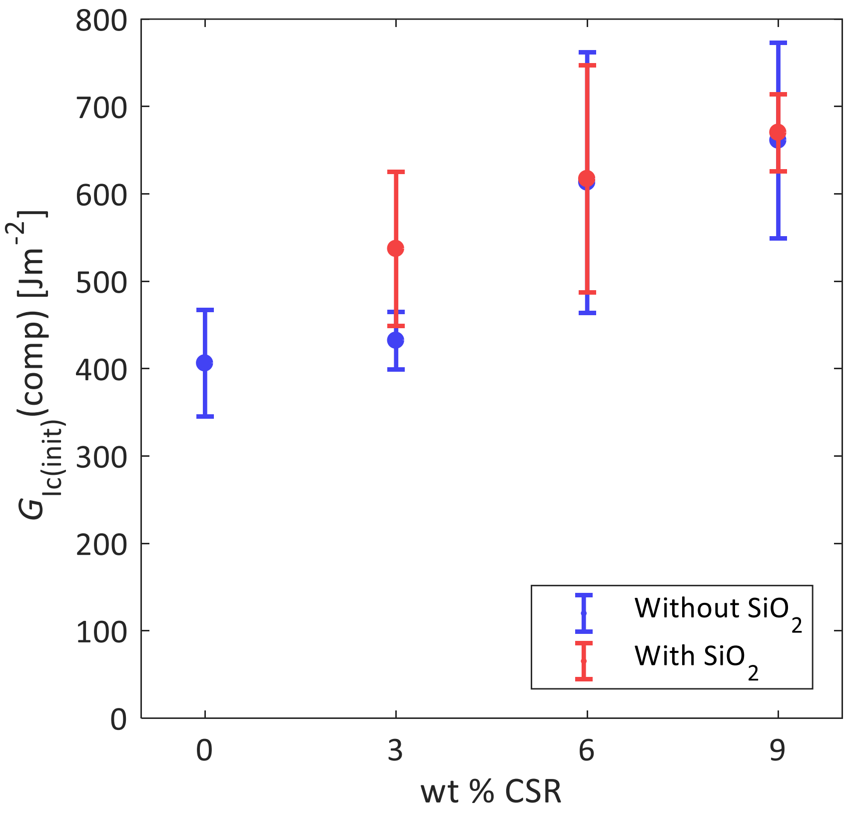
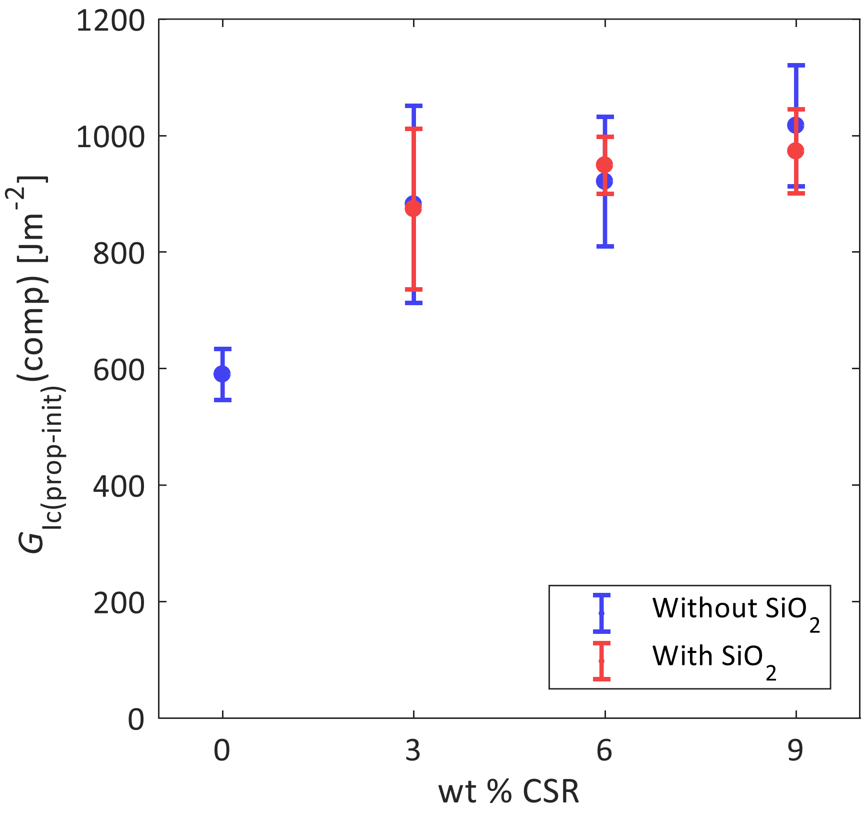
DCB Data





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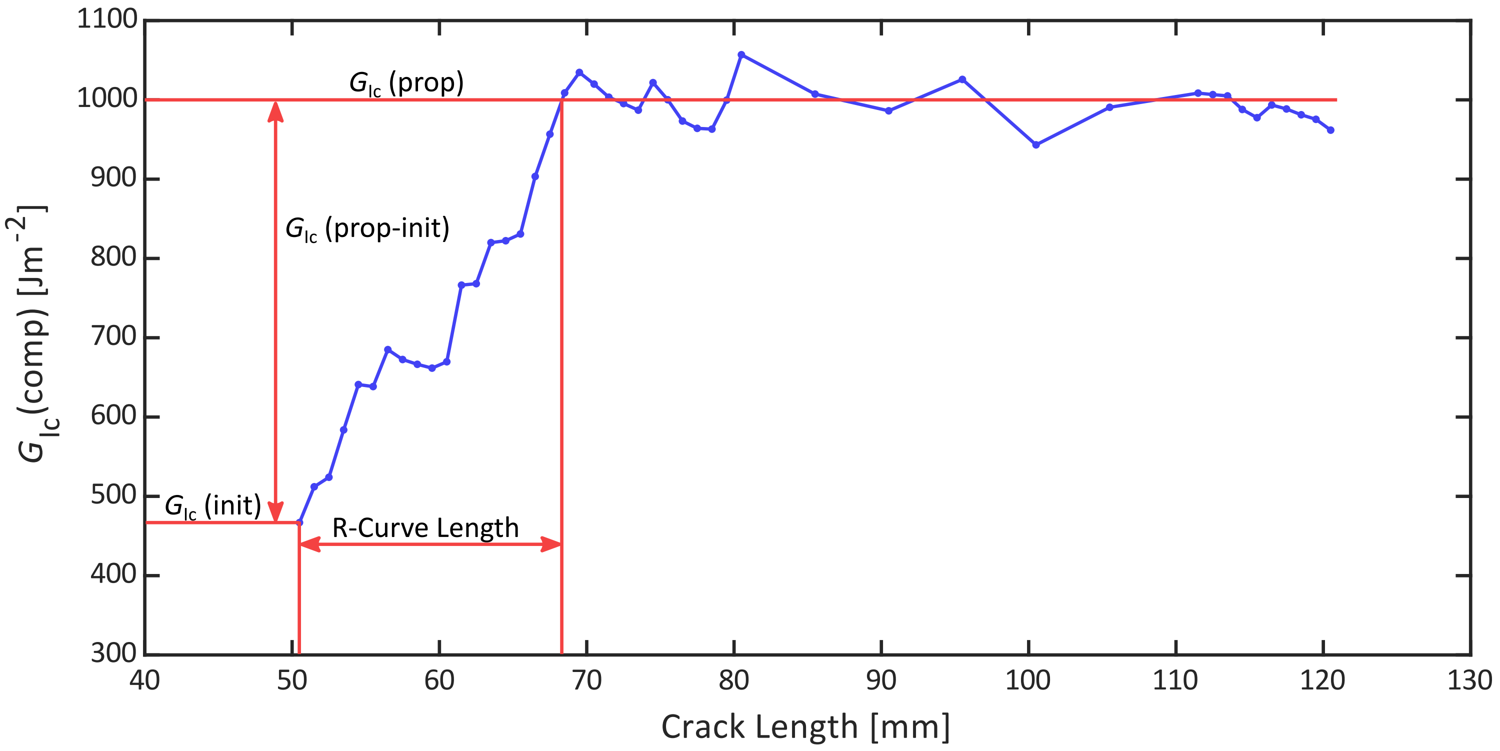
DCB Data (2)



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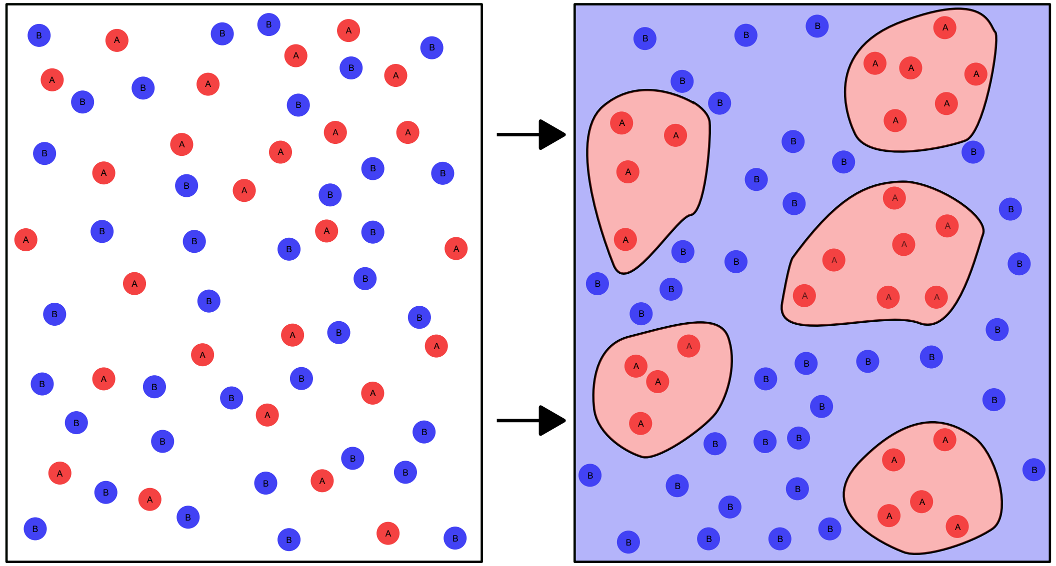
Resin Formulations

- 3, 6, 9 % CSR
- Same with silica calculated to regain stiffness using cascade Halpin-Tsai

$$E_t = \frac{1 + \zeta\eta V_f}{1 - \eta V_f} E_m$$

$$\eta = \frac{E_f/E_m - 1}{E_f/E_m + \zeta}$$



wt % CSR	wt % Silica
0	0
3	0
6	0
9	0
3	5.9
6	11.7
9	17.2

Split matrix between each filler according to volume fraction. Perform calculation for two systems separately. Then perform calculation as if one system is a filler in the other.