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Advanced Joining Processes Unit

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Guidelines for designing modular connections for the maritime industry

VBE2023
International Conference
on Vehicle Body Engineering
2-3 November 2023
Porto, Portugal

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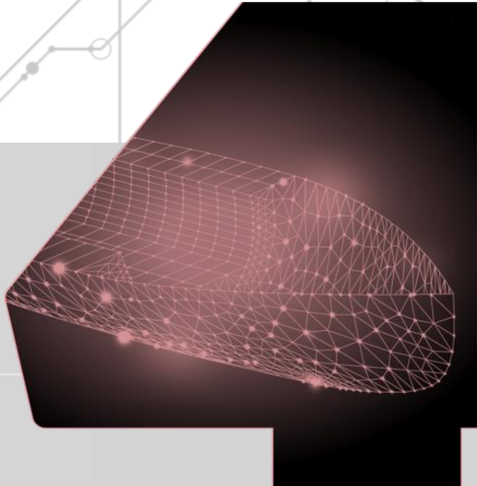


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 101006860.

Contents

Introduction

Fibre reinforced polymers

Marine industry (maritime commercial shipping industry) as the backbone of international trade

Concerning issues in using **conventional metallic materials**:

- Lack of **weight/fuel efficiency**
- Low **fatigue resistance**
- **Electrolytic corrosion**

Progresses towards **sustainability**, adopting technologies to meet ambitious carbon dioxide reduction

Fibre reinforced polymers

Glass fibre

Carbon fibre

- High **strength-to-weight ratio**
- High **fatigue failure resistance**
- Good **corrosion resistance**
- Good **vibration damping** and **noise absorption**
- Acceptable performance against **fire**

Introduction

Why joining is important?

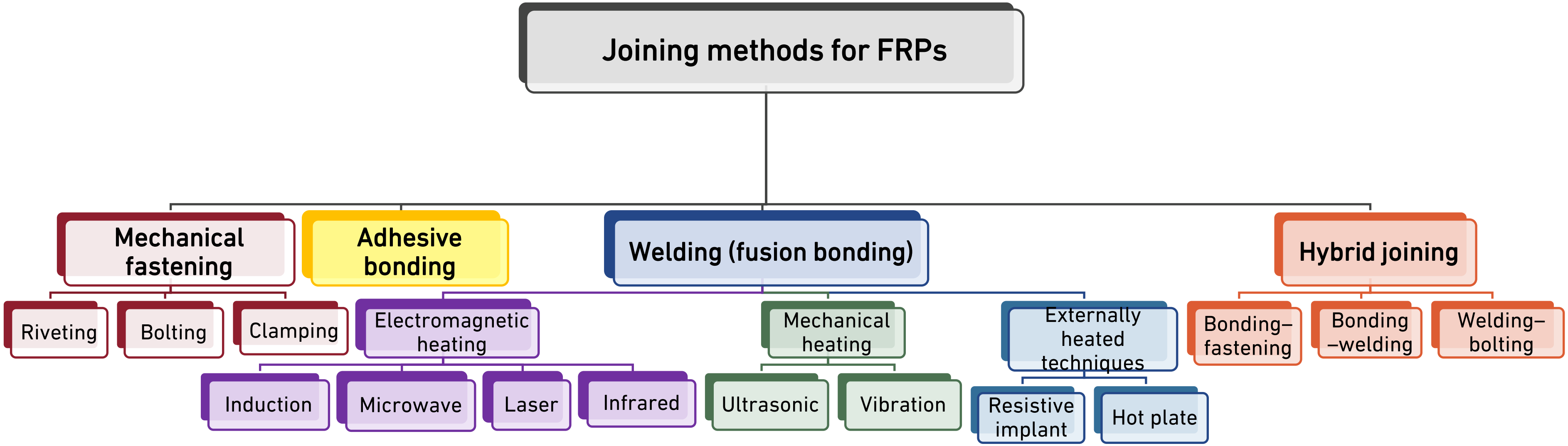
Shape the panels into a large and complex structure

Connect and transfer applied loads between the substructures

Maintain the ship stiffness under different loadings

Maintain the reliability and durability of the whole structure

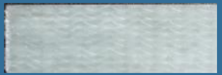
Joining methods



Motivation

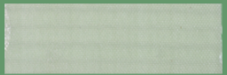
C1.1

- Glass fibre reinforced thermoset acrylic
- Out of die ultraviolet (UV) cured pultrusion manufacturing process



C1.2

- Glass fibre reinforced thermoset epoxy
- Adaptive mould manufacturing process



Composite systems

C2.2

- Glass fibre reinforced thermoplastic polypropylene
- 3D printing additive manufacturing process

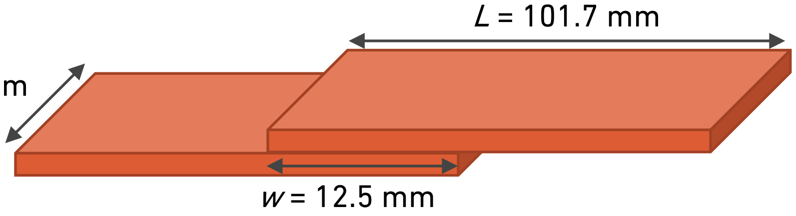
C2.1

- Carbon fibre reinforced thermoplastic polypropylene
- Hot-stamping manufacturing process

Materials and properties

The investigation path

- Single-lap joint (SLJ)



Considered configurations for the assessment of joining techniques

Induction welded joints	Ultrasound welded joints	Adhesively bonded joints	Bolted joints	Hybrid bonded–bolted joints
C2.1/C2.1	C2.1/C2.1	C1.1/C1.1	C1.1/C1.1	C1.1/C1.1
C2.2/C2.2	C2.2/C2.2	C1.2/C1.2	C1.2/C1.2	C1.2/C1.2
C2.1/C2.2	C2.1/C2.2	C2.2/C2.2	C2.2/C2.2	C2.2/C2.2
		C1.1/C1.2	C1.1/C1.2	C1.1/C1.2
		C1.1/C2.2	C1.1/C2.2	C1.1/C2.2
		C1.2/C2.2	C1.2/C2.2	C1.2/C2.2
				C1.1/C2.1
				C1.2/C2.1

Materials and properties

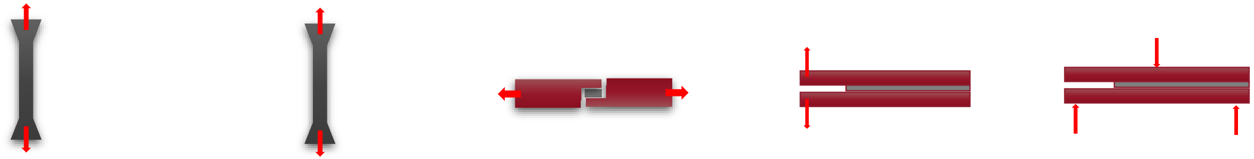
Composite materials

	C1.1	C1.2	C2.1	C2.2
Manufacturing company	IRURENA	CURVEWORKS	INEGI	10XL
Manufacturing technology	Out of die UV cured pultrusion	Adaptive mould	Hot stamping	3D printing
Substrate thickness (mm)	3.2 ± 0.0	3.7 ± 0.0	4.0 ± 0.0	3.7 ± 0.1
Matrix type	Thermoset	Thermoset	Thermoplastic	Thermoplastic
Matrix	Acrylic	Epoxy	Polypropylene	Polypropylene
Fibre	Glass	Glass	Carbon	Glass
Stacking sequence	[0/90/+45/−45]	[0/+45/90/−45]		Reinforced with 12% FVF short fibres
Maximum tensile strength (MPa)	592 ± 21	272 ± 28	478 ± 47	36 ± 0.6
Young's modulus (GPa)	33 ± 1	17 ± 0.3	32 ± 3	5.45 ± 0.34

Materials and properties

Adhesive material

Two-component MA560-1 methacrylate adhesive

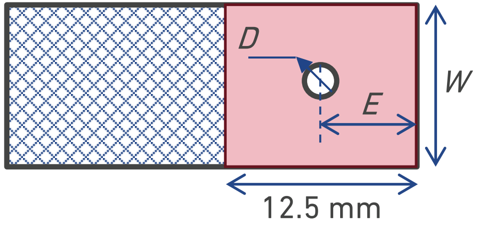


	Tensile strength (MPa)	Young's modulus (MPa)	Shear strength (MPa)	Tensile fracture energy (N/mm)	Shear fracture energy (N/mm)
Property value	14.6 ± 2%	668 ± 6%	11.6 ± 15%	2.4 ± 11%	8.6 ± 13%
Standard	ASTM D638-14	ASTM D638-14	ASTM D5656	ASTM D3433	ASTM D7905

Bolt material

Stainless steel **M2** bolt class 70

ASTM D5961
(Standard Test Method for Bearing Response of Polymer Matrix Composite Laminate)



Effective parameters:

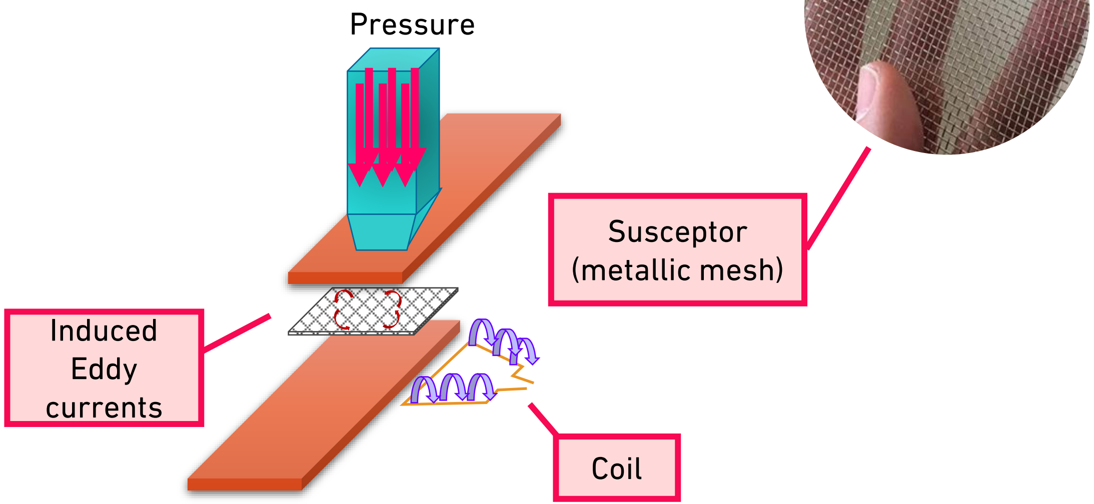
- W/D
- E/D
- Clearance between bolt and hole ➡ Damage
- Clamping torque ➡ Friction coefficient

$\left\{ \begin{array}{l} W/D \geq 3 \\ E/D \geq 3 \end{array} \right.$ ➡ $W = 25$ mm, $E = 6.25$ mm, $D \leq 2.08$ mm

Manufacturing process

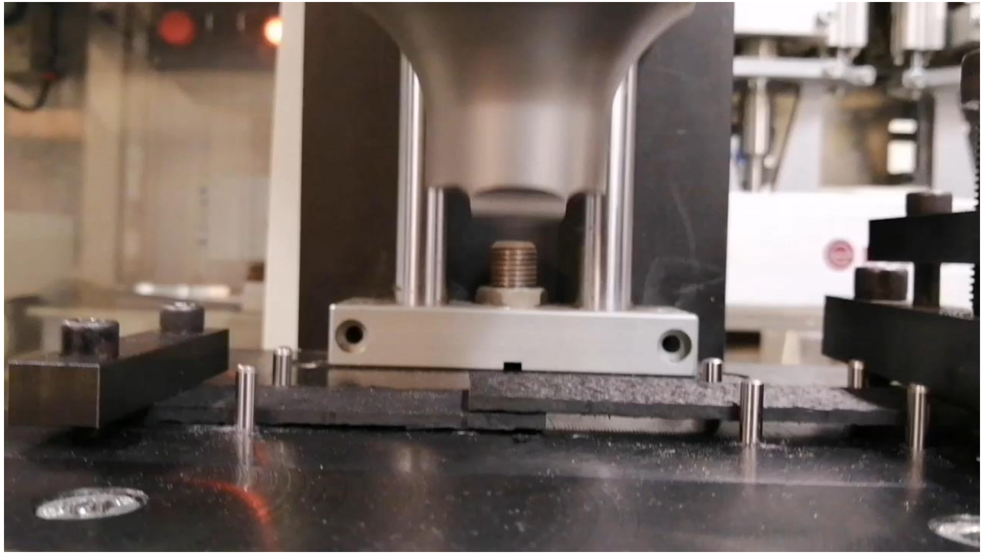
Induction welding

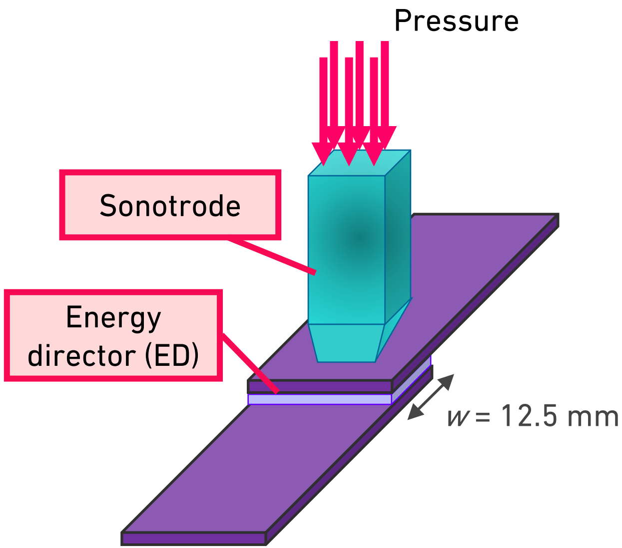
- Metallic mesh had been used as susceptor between composites
- In the case of CFRP substrates, a nozzle was used to cool down the materials.



Manufacturing process

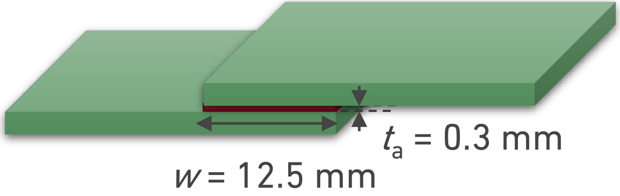
Ultrasonic welding



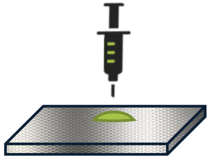


Manufacturing process

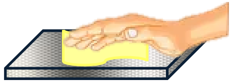
Adhesive bonding



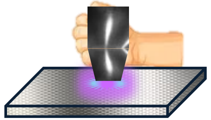
- **Curing time**: 7 h
- **Curing Temperature**: room temperature
- **Relative humidity (RH)**: 50%
- **Applied pressure**: 20 bar



1. Measurement of substrate surface energy



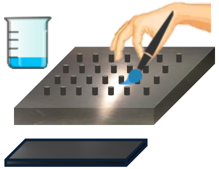
2. Alcohol cleaning of the substrate



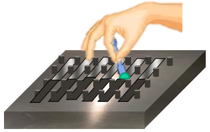
3. Atmospheric plasma treatment of substrates

4. Applying the resin and hardener in container

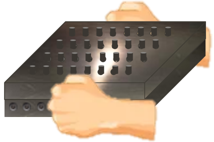
5. Mixing the combination in mixer



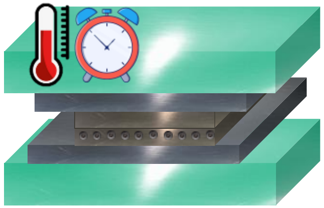
6. Applying the release agent



7. Applying the adhesive



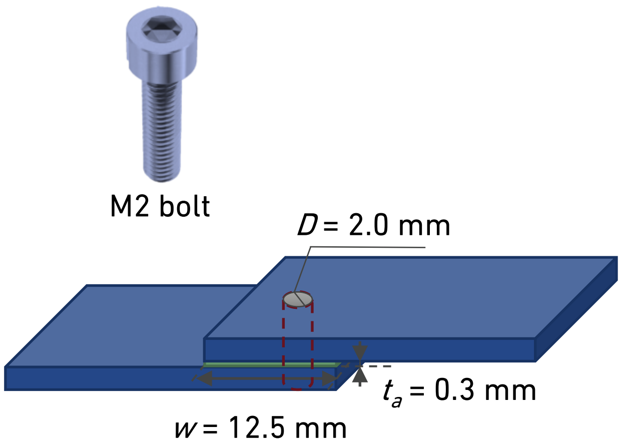
8. Moulding the joints

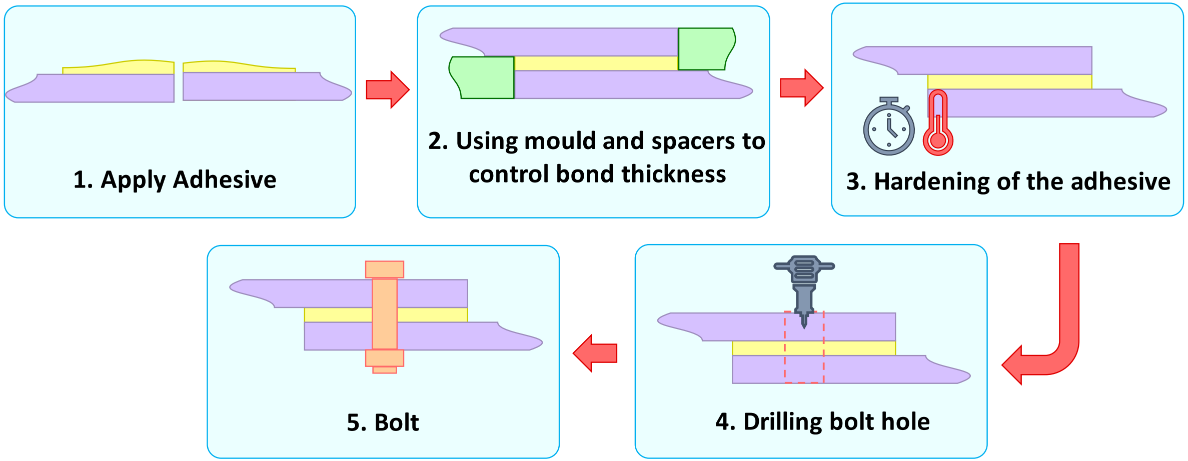


9. Placing the mould in press machine for curing

Manufacturing process

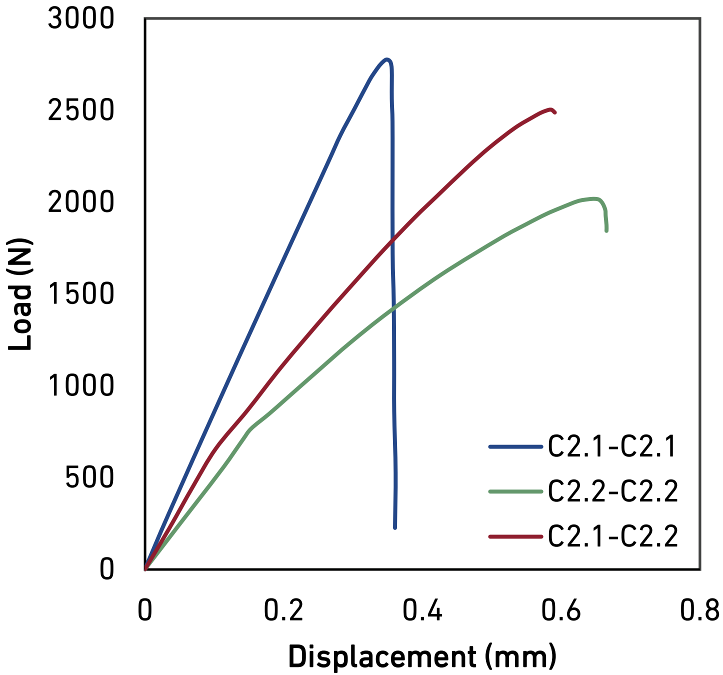
Hybrid bonding–bolting

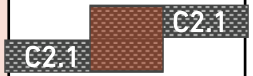
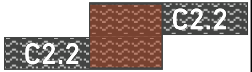
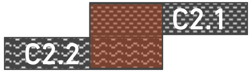




- **Applied clamping torque**: 0.6–0.7 N mm

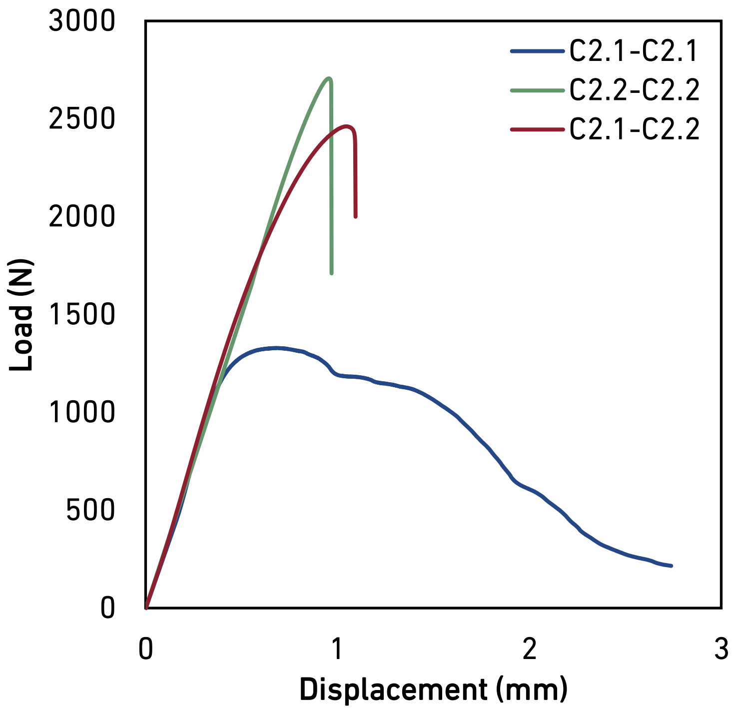
Induction welding

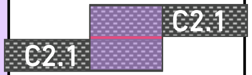
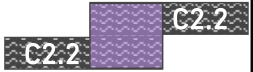
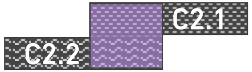
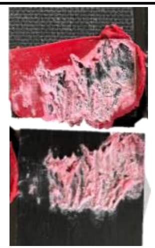


Configuration / Optimised parameters			
Temperature (°C)	220	200	220
Holding time (s)	8	4	4
Compaction pressure (bar)	22	22	22
Average maximum load (N)	2634 ± 25%	1924 ± 12%	2564 ± 9%
Fracture surfaces			

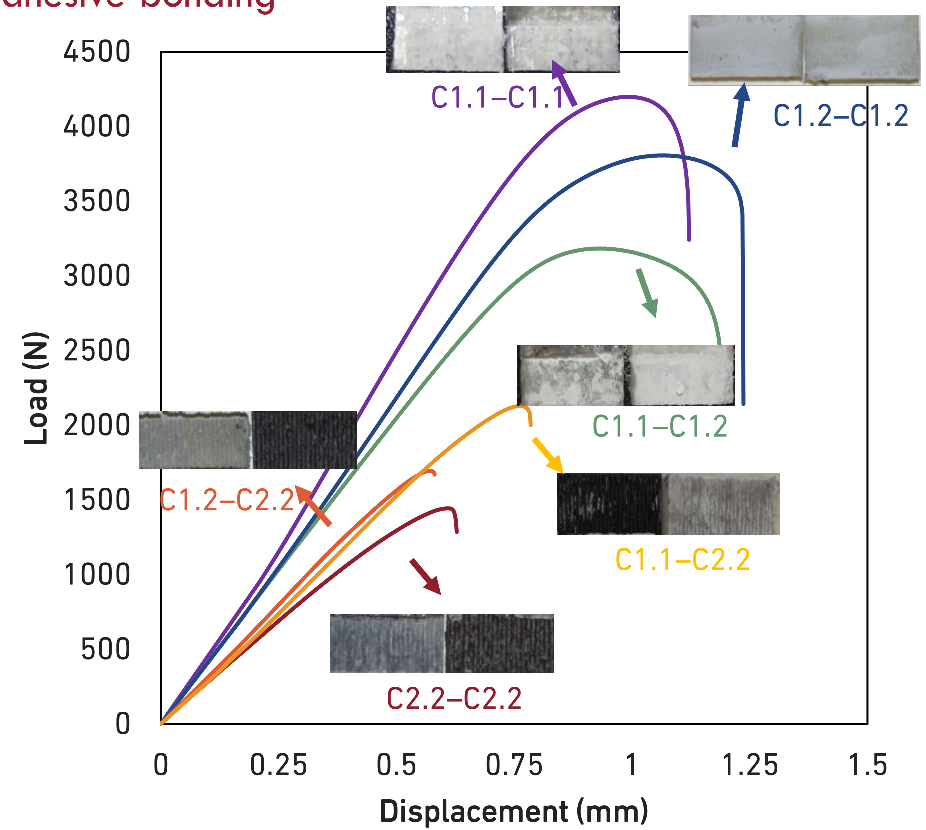
Results and discussion

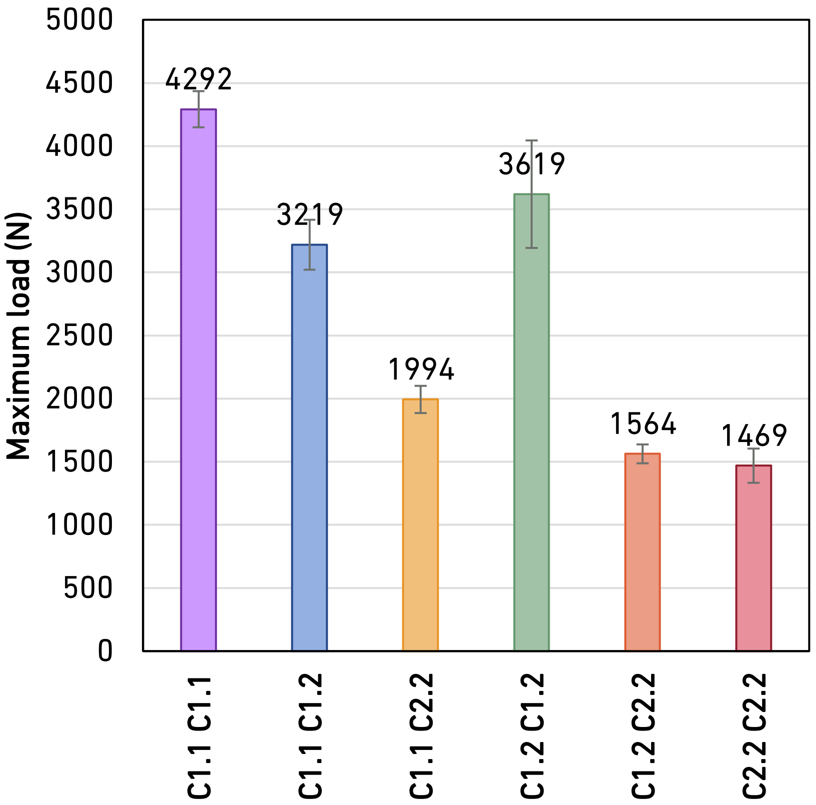
Ultrasonics welding



Configuration / Optimised parameters			
Amplitude (%)	80	90	90
Welding time (s)	2.5	1.5	2
Compaction pressure (bar)	10.7	10	10
Average maximum load (N)	1494 ± 21%	2335 ± 5%	2564 ± 9%
Fracture surfaces			

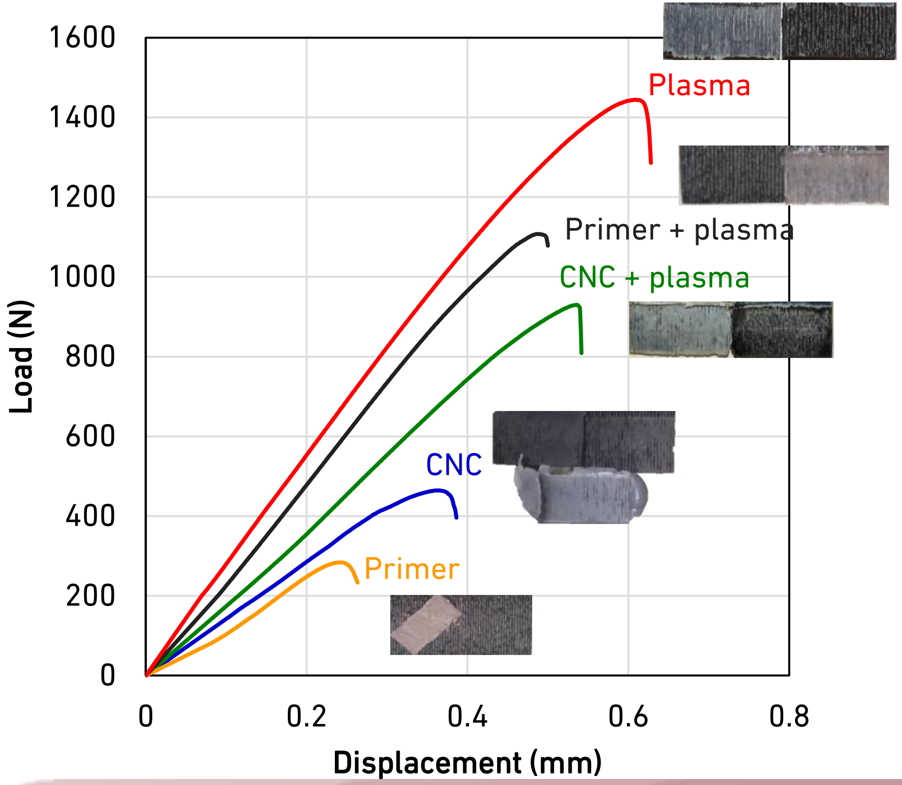
Adhesive bonding

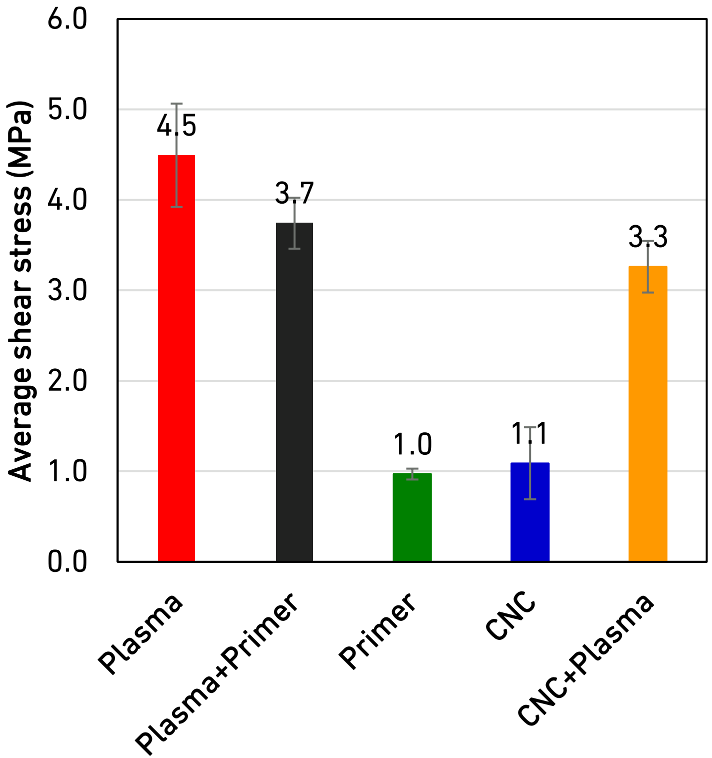




Adhesive bonding

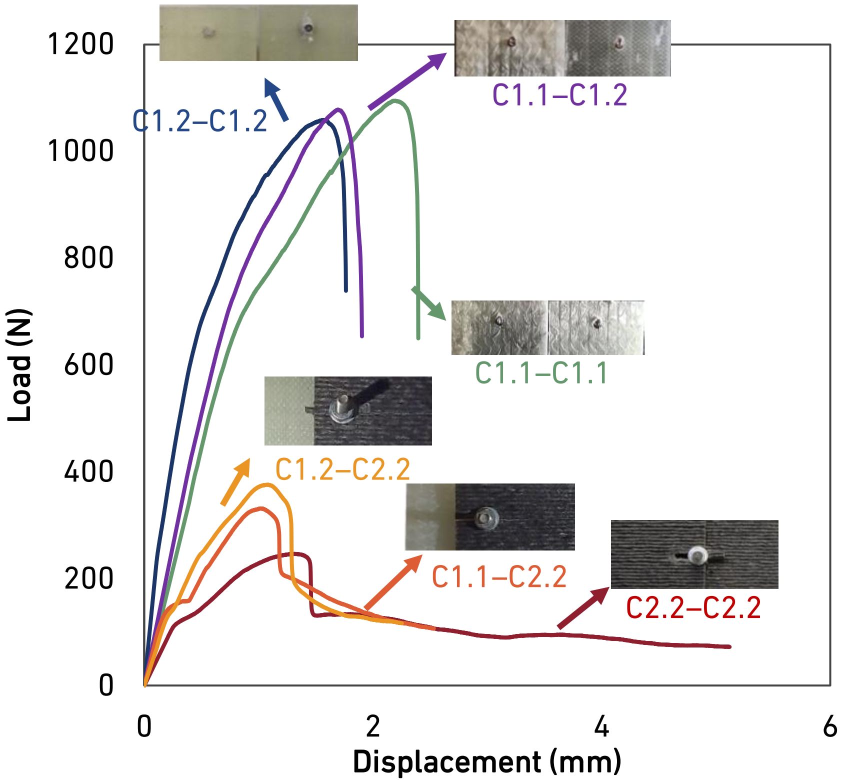
Challenges with C2.2 thermoplastic 3D printed polypropylene (PP) composites

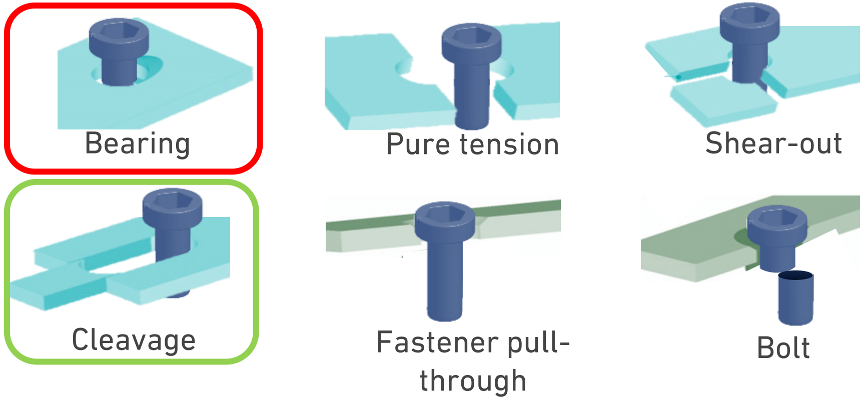




Results and discussion

Bolting

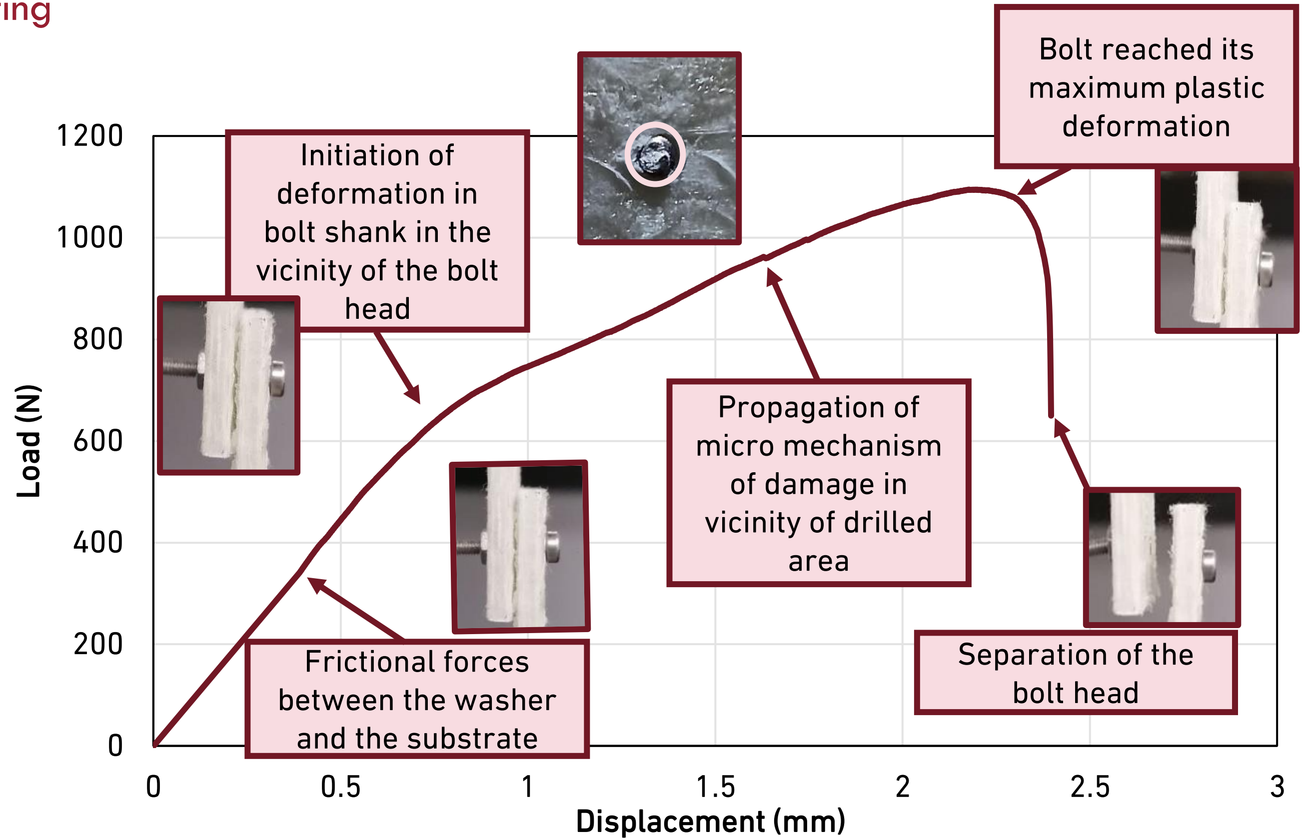


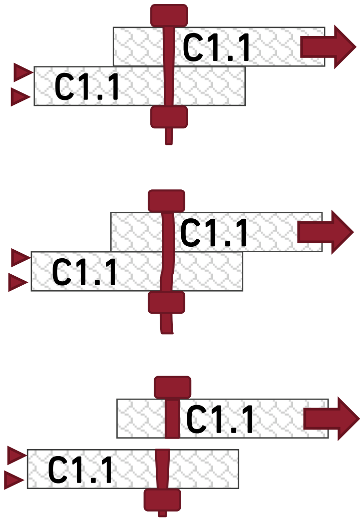


C1.2–C1.2	C1.1–C1.2	C1.1–C1.1	C1.2–C2.2	C1.1–C2.2	C2.2–C2.2
1606 ± 8%	1050 ± 5%	1046 ± 5%	341 ± 5%	339 ± 4%	255 ± 4%
Bearing	Bearing	Bearing	Cleavage	Cleavage	Cleavage

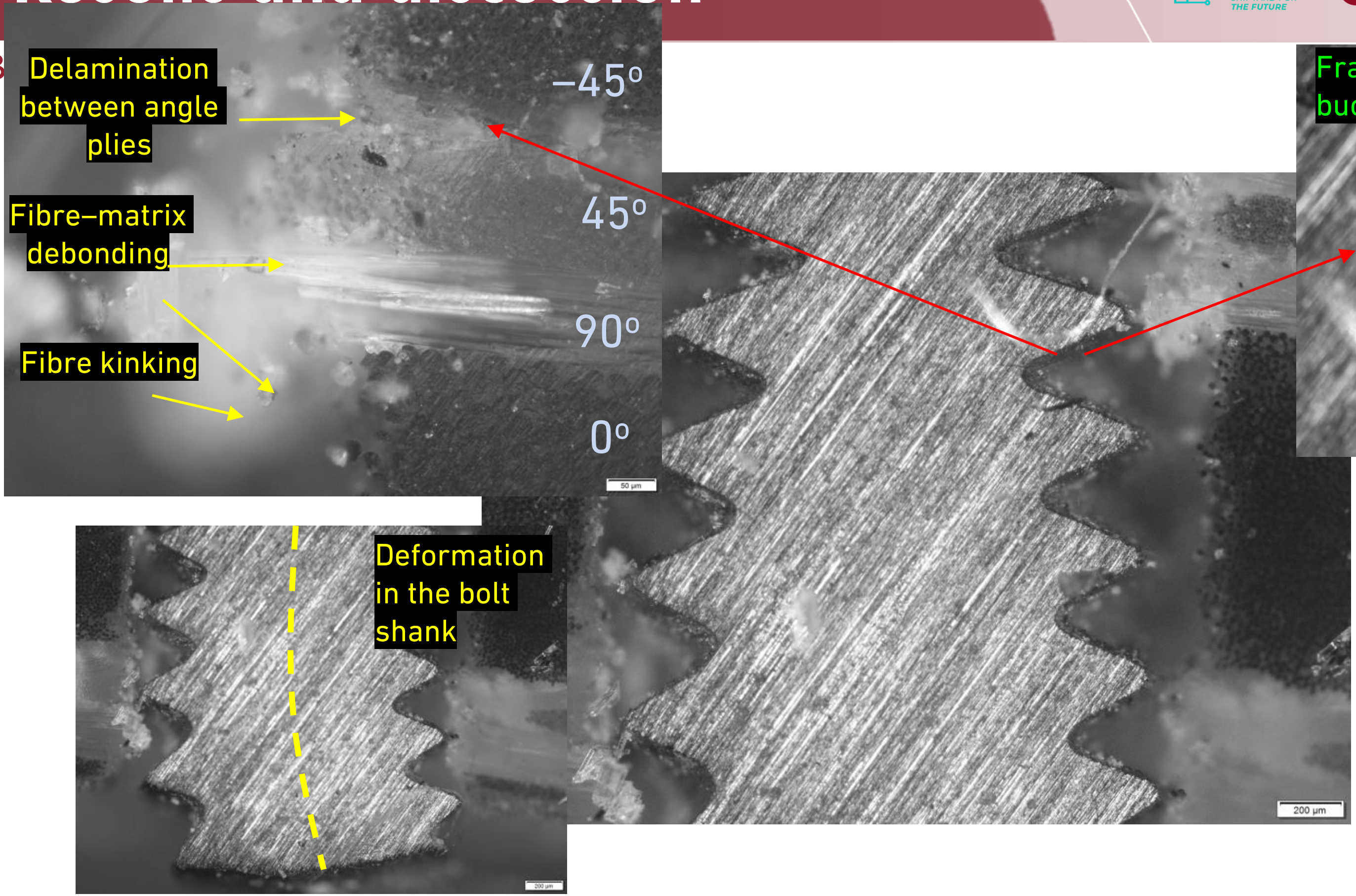
Results and discussion

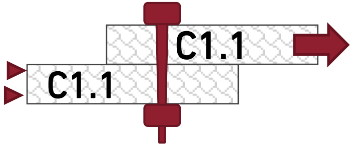
Bolting





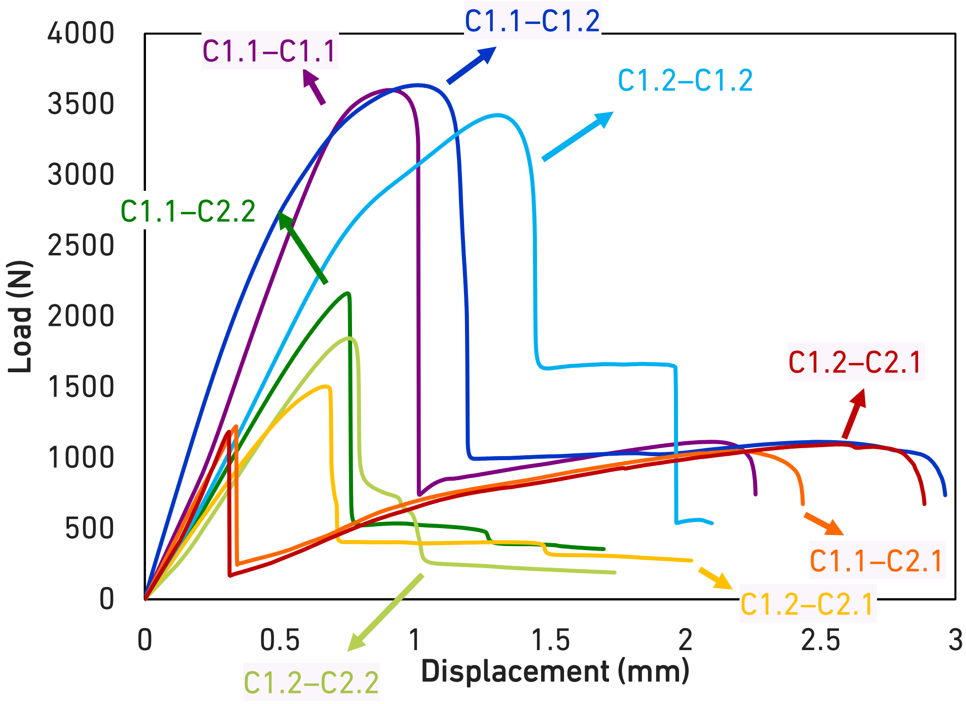
Results and discussion





Results and discussion

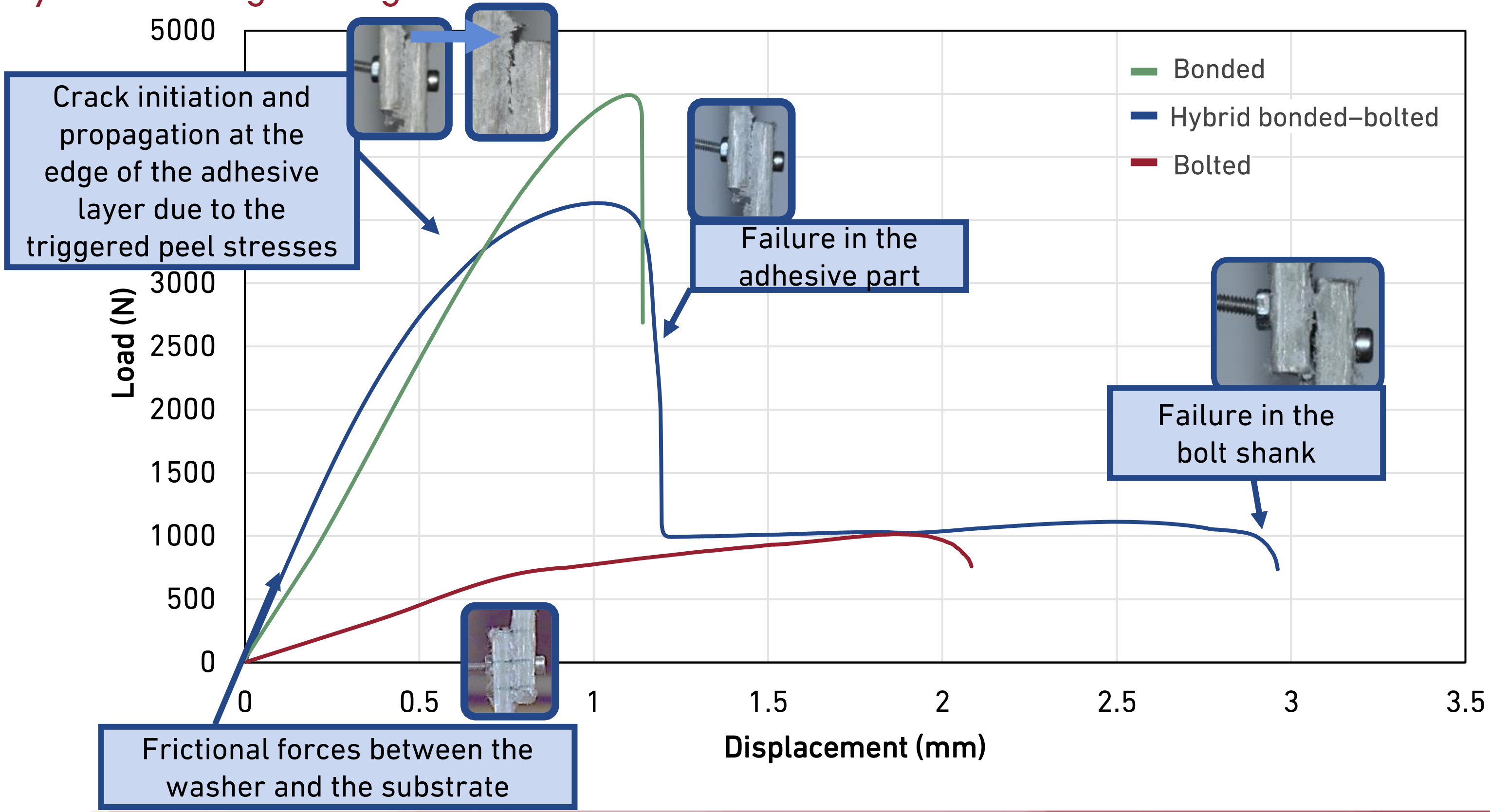
Hybrid bonding–bolting

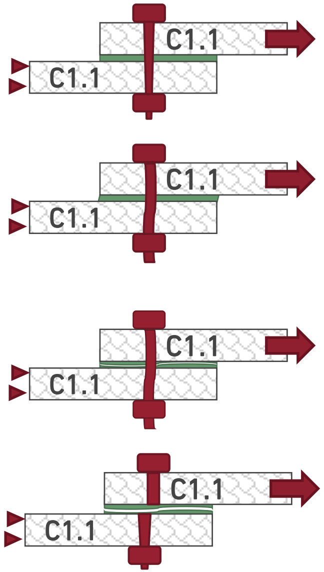


Configuration	Maximum load (N)	Failure mode
C1.1–C1.1	3488 ± 4%	Cohesive + bearing
C1.1–C1.2	3408 ± 3%	Cohesive + bearing
C1.2–C1.2	3296 ± 6%	Cohesive + bearing
C1.1–C2.2	2026 ± 2%	Adhesive + cleavage
C1.2–C2.2	1831 ± 4%	Adhesive + cleavage
C2.2–C2.2	1290 ± 14%	Adhesive + cleavage
C2.1–C1.1	1237 ± 15%	Adhesive + bearing
C2.1–C1.2	1237 ± 10%	Adhesive + bearing

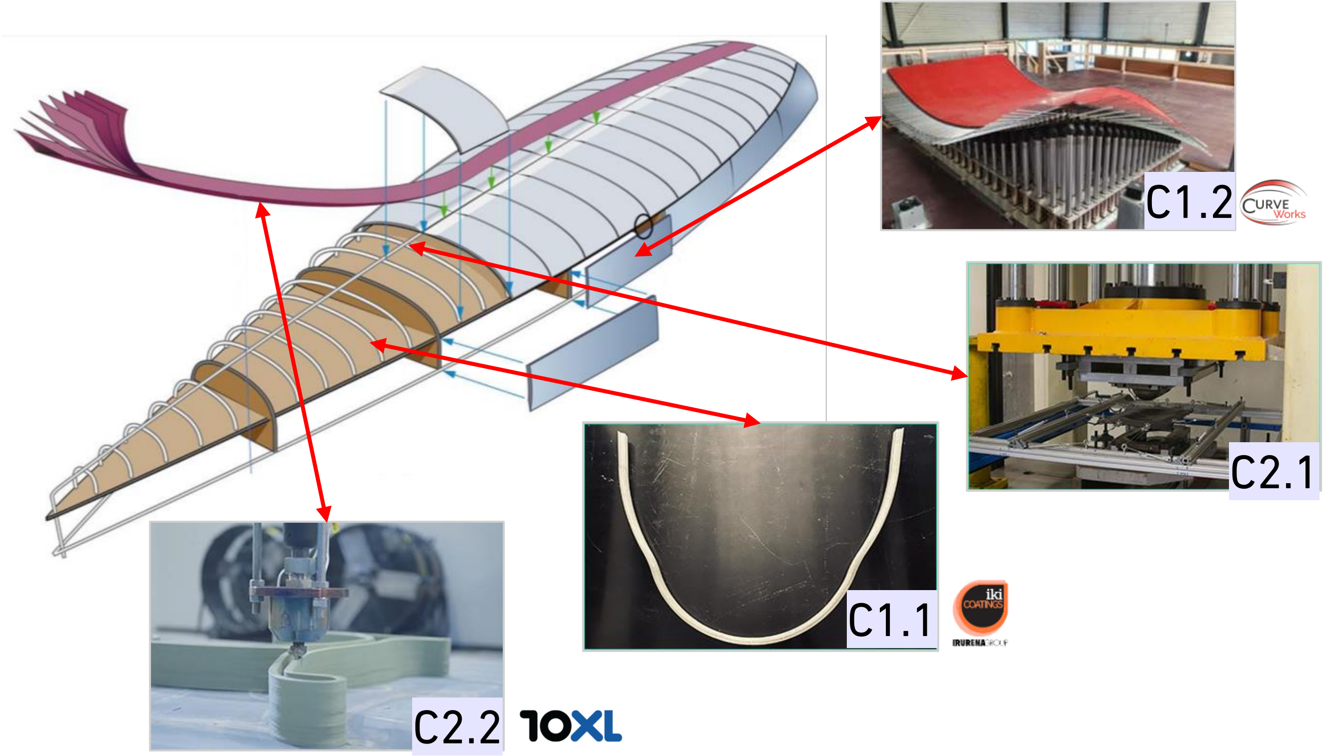
Results and discussion

Hybrid bonding–bolting





Summary and conclusion



- Induction welding
- Ultrasound welding
- Adhesive bonding
- Bolting
- Hybrid bonding–bolting

Summary and conclusion

- This work represents a comprehensive evaluation of common joining methods for different FRPs manufactured by various thermoset and thermoplastic matrices as well as fabrication techniques.
- Similar thermoset composites: **adhesively bonded** joining is highly recommended:
  - **Most feasible method**
  - Provides **higher strength**
- Dissimilar thermoset composites: **hybrid joining** is highly recommended:
  - **Most efficient method**
  - Provides higher strength
- Similar thermoplastic composites: welding techniques
- Ultrasonic welding of similar carbon fibre reinforced PP composites:
  - **High energy absorption of carbon fibres**
  - Requires a set of **experimental designs**

Summary and conclusion

- **Ultrasonic welding** seems to be **more efficient** and **straightforward** to perform, compared with **induction welding**.
- To employ **fusion-based welding** methods for continuous joining application, **further research** is required.
- **Thermoplastic 3D printed PP composites**:
    - Improve the manufacturing and surface finishing quality
    - Solve the cleavage and adhesive failure of experimental designs

European Union's Horizon 2020 research and innovation programme

Thank you for your attention!

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