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Comparative mechanical assessment of the common structural joining techniques implemented in the marine industries

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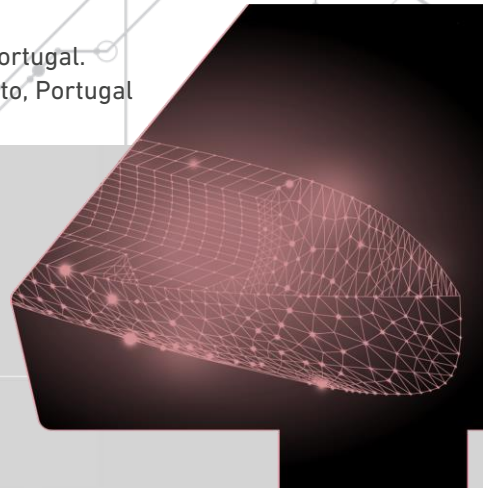

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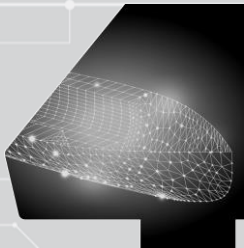

Introduction

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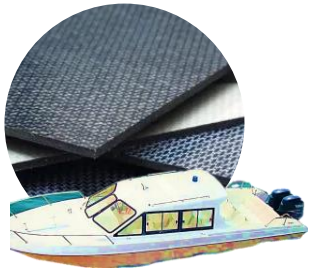
The role of Fibre Reinforced Polymers in the marine industry

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**, and **electrolytic corrosion**

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

Fiber reinforced Polymers



High **strength to weight ratio**

High **fatigue failure resistance**

good **corrosion resistance**.

Good **vibration damping** and **noise absorption**

acceptable performance against **fire**

Glass Fiber

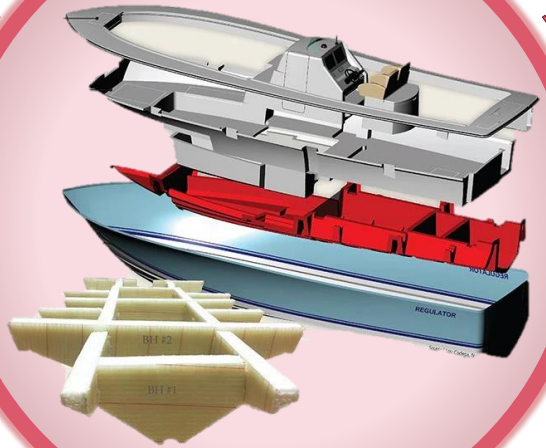
Carbon Fiber

Introduction

Why Joining is important?

shape the panels into a large and complex structure

connect and transfer applied load between the substructures

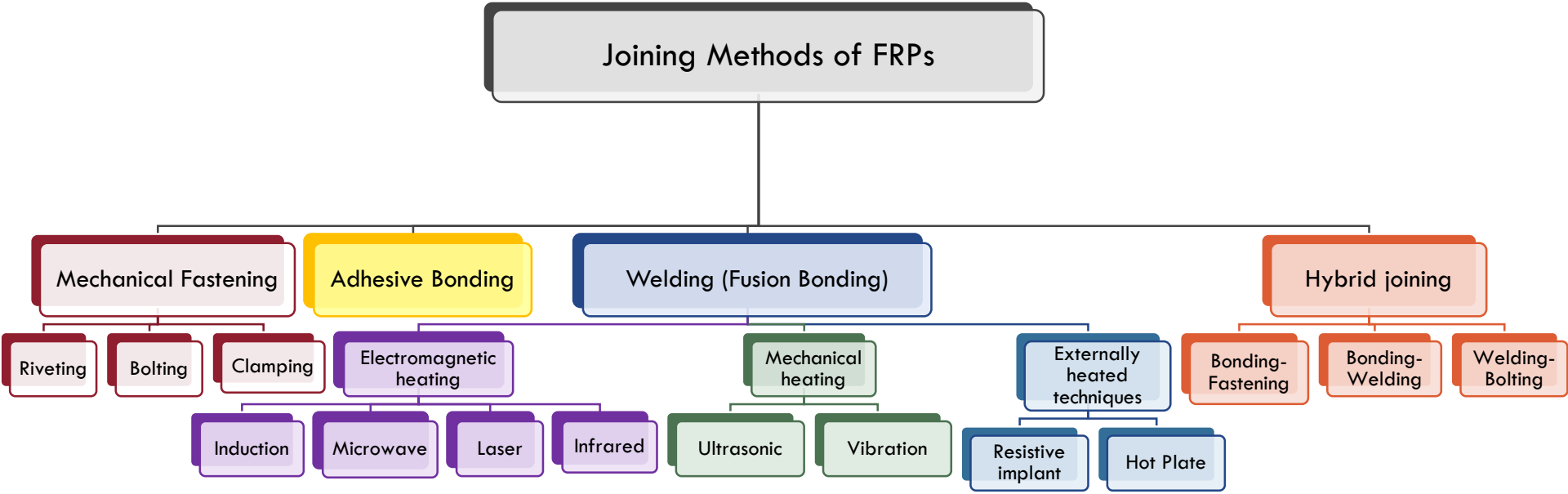


maintain the ship stiffness under different loadings

maintain the reliability and durability of the of the whole structures

Introduction

Which Joining method is suitable?



Introduction

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What is the motivation of the current study?

- Glass Fibre Reinforced Thermoset Acrylic
- Out of die ultraviolet (UV) cured pultrusion
- manufacturing process

C1.1

C1.2

- Glass Fibre Reinforced Thermoset Epoxy
- Adaptive Mould manufacturing process

Composite System

C2.2

C2.1

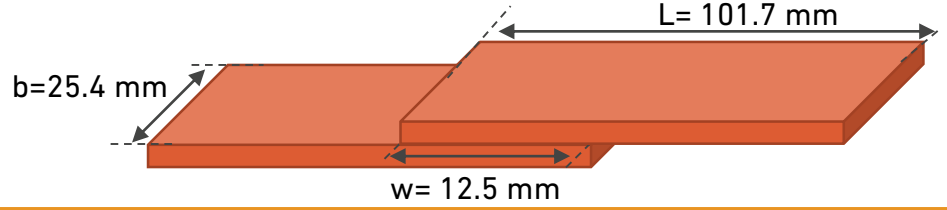
- Glass Fibre Reinforced
- Thermoplastic Polypropylene
- 3D printing additive manufacturing process

- Carbon Fibre Reinforced Thermoplastic Polypropylene
- Hot-Stamping manufacturing process

Material and Properties

The investigation path

Single Lap Joints



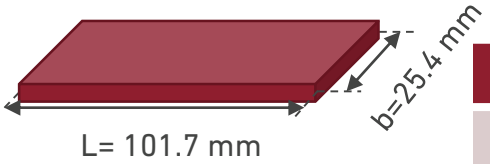
Considered Configurations for the Assessment of Joining Techniques

Induction Welded Joints			Ultrasound Welded Joints			Adhesive Bonded Joints						Bolted Joints						Hybrid Bonded-Bolted Joints							
C2.1/C2.1	C2.2/C2.2	C2.1/C2.2	C2.1/C2.1	C2.2/C2.2	C2.1/C2.2	C1.1/C1.1	C1.2/C1.2	C2.2/C2.2	C1.1/C1.2	C1.1/C2.2	C1.2/C2.2	C1.1/C1.1	C1.2/C1.2	C2.2/C2.2	C1.1/C1.2	C1.1/C2.2	C1.2/C2.2	C1.1/C1.1	C1.2/C1.2	C2.2/C2.2	C1.1/C1.2	C1.1/C2.2	C1.2/C2.2	C1.1/C2.1	C1.2/C2.1

- C1.1: Thermoset Photocurable acrylate matrix thermoset FRP composite
- C1.2: Thermoset Epoxy resin matrix thermoset FRP composite
- C2.1: Thermoplastic hot-stamped FRP Composite
- C2.2: Thermoplastic 3D printed FRP Composite

rial 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 Mold	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 Vf.% short fibers
Maximum Tensile Strength (MPa)	592±21	272±28	478±47	36±0.6
Maximum Young's Modulus (GPa)	33±1	17±0.3	32±3	5.45±0.34

Material and Properties

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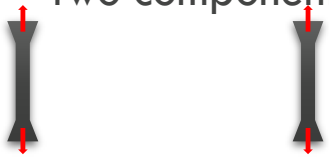
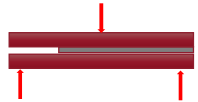
Adhesive Material

Two component MA560-1 Methacrylate Adhesive

PLEXUS





Mechanical Property	Tensile Strength (MPa)	Young Modulus (MPa)	Shear Strength (MPa)	Tensile Fracture Energy (Nmm)	Shear Fracture Energy (Nmm)
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

Effective Parameters

- W/D (width of substrate to diameter of the bolt)
- E/D (edge distance to diameter of the bolt)
- Clearance between bolt and hole ➡ Damage
- Clamping Torque ➡ Friction Coefficient

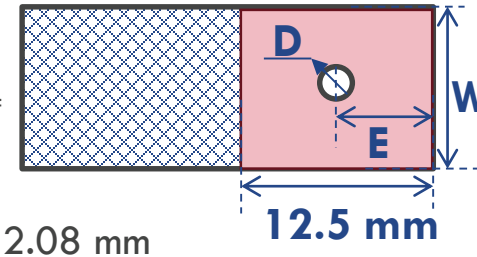
ASTM D5961

Standard Test Method for Bearing Response of Polymer Matrix Composite Laminate

$3 \le W/D$ → $W = 25$ mm

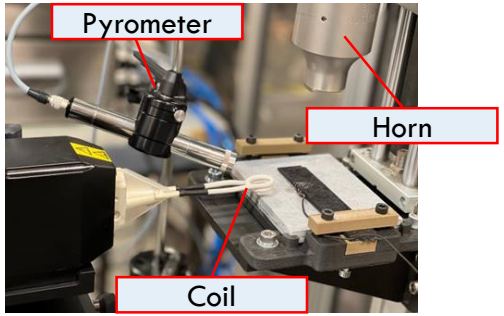
$3 \le E/D$ → $E = 6.25$ mm

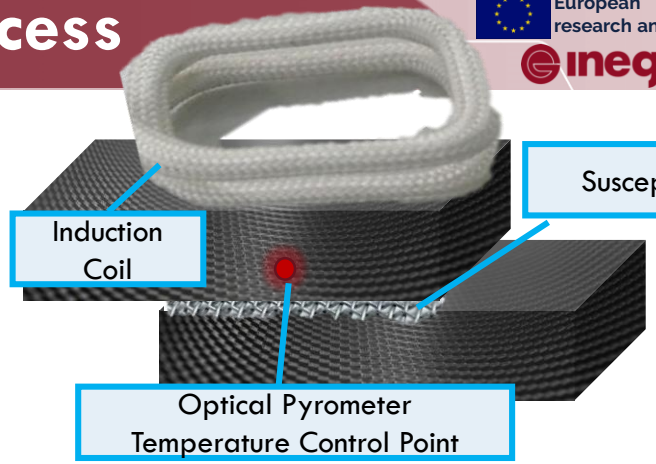
$D <= 2.08$ mm



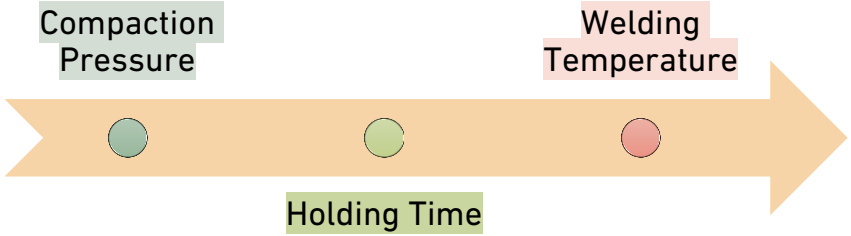
Manufacturing Process

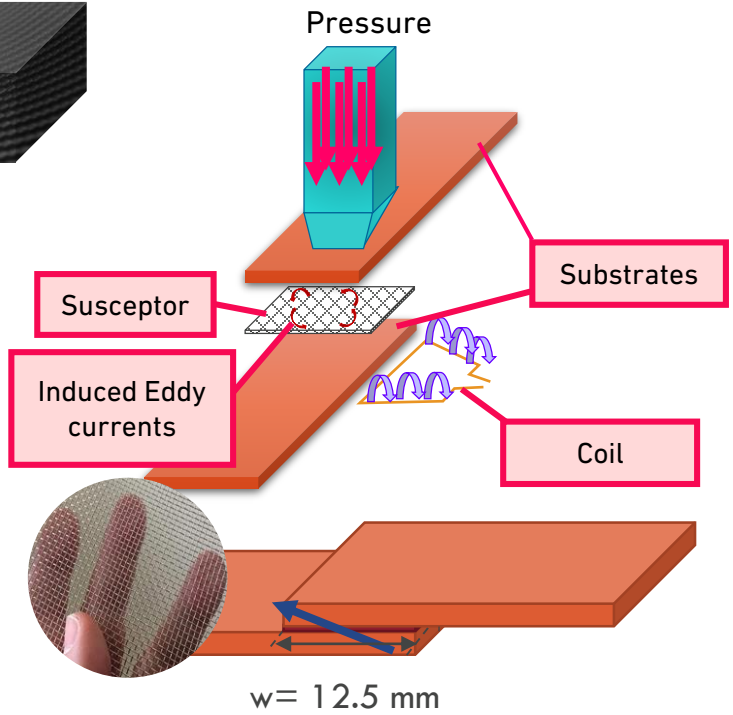
Induction Welding





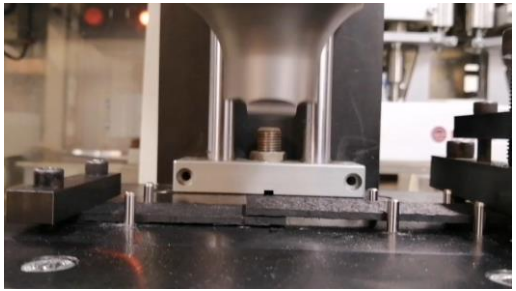
- Metallic mesh had been used as susceptor between composites
- In the case of CFRP substrates, a nozzle was used to cool down the materials.

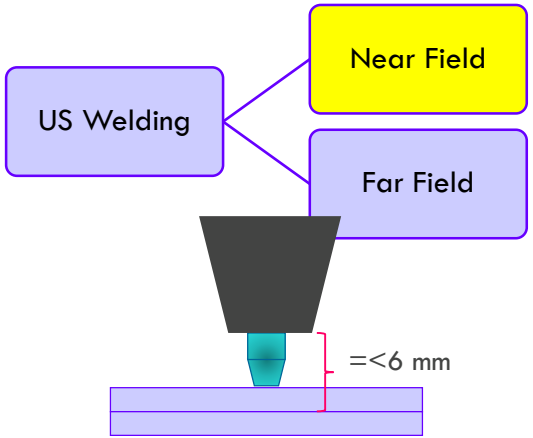


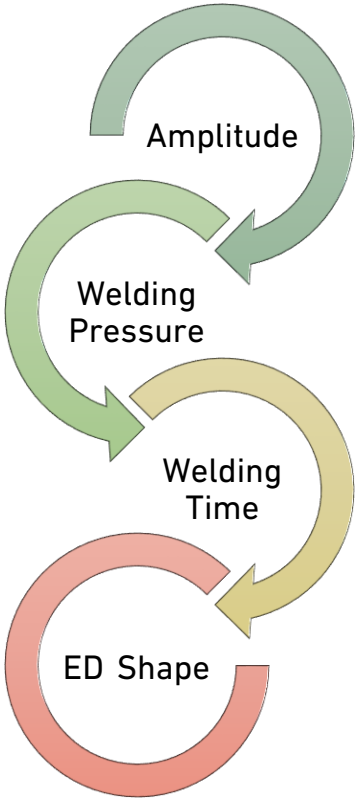


Manufacturing Process

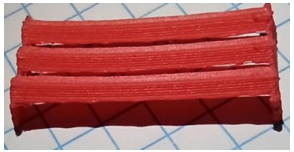
Ultrasonic Welding



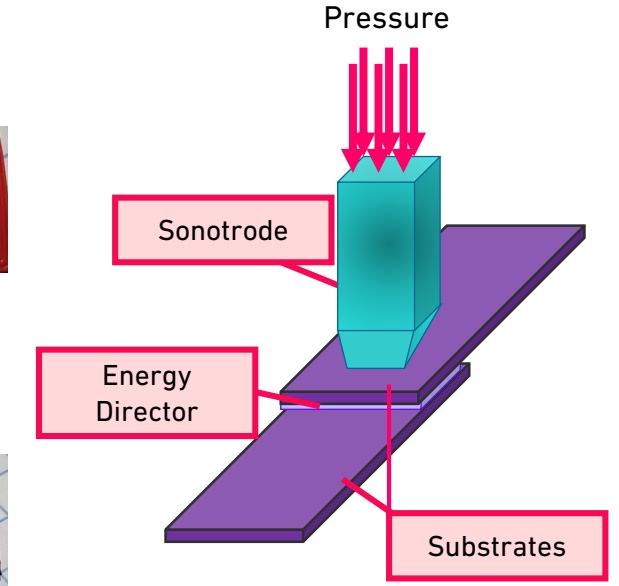


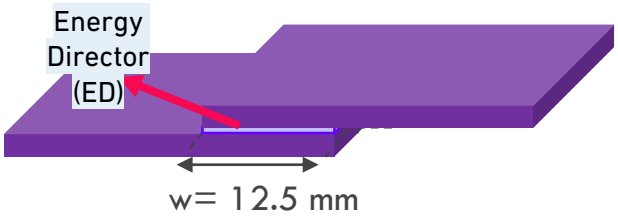


Flat Surface



3D-Triangular Surface





Manufacturing Process

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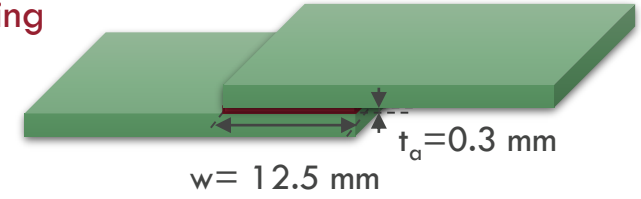
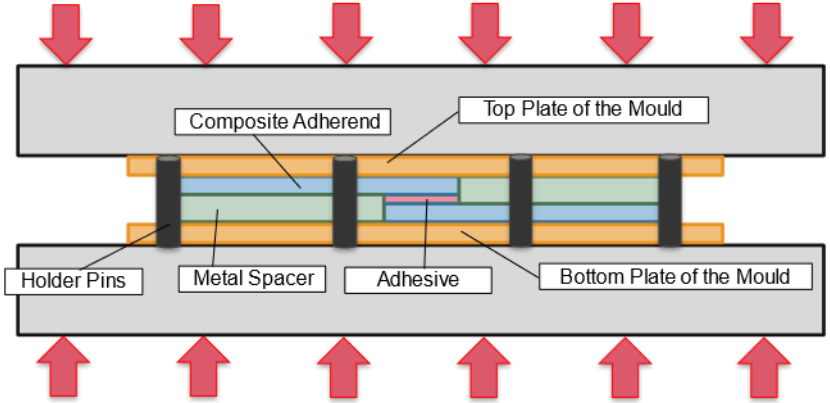
Adhesive Bonding

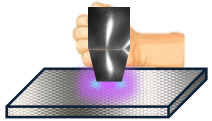


Curing Time: 7 h
Curing Temperature/Relative Humidity: Room Temperature/ 50 % RH
Applied Pressure: 20 bar



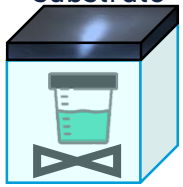
1. Measurement of substrate surface energy

2. Alcohol cleaning of the substrate

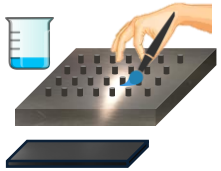


3. Atmospheric plasma treatment of substrates

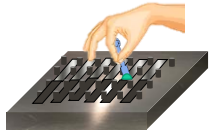
4. Applying the resin and hardener in container



5. Mixing the combination in mixer

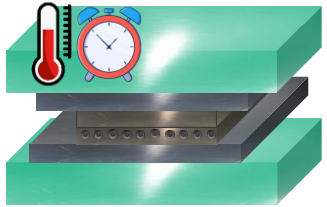


6. Applying the release agent



7. Applying the adhesive

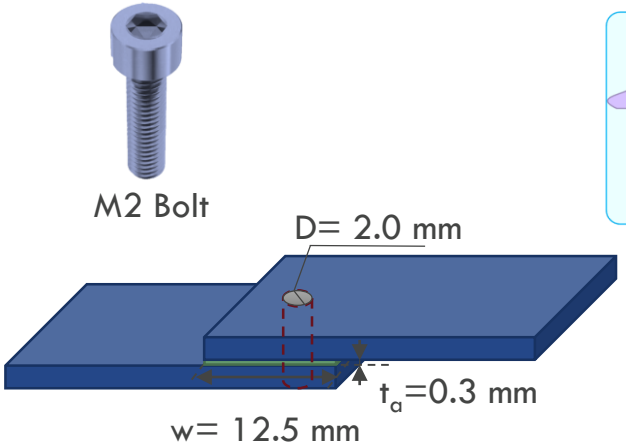
8. Moulding the joints

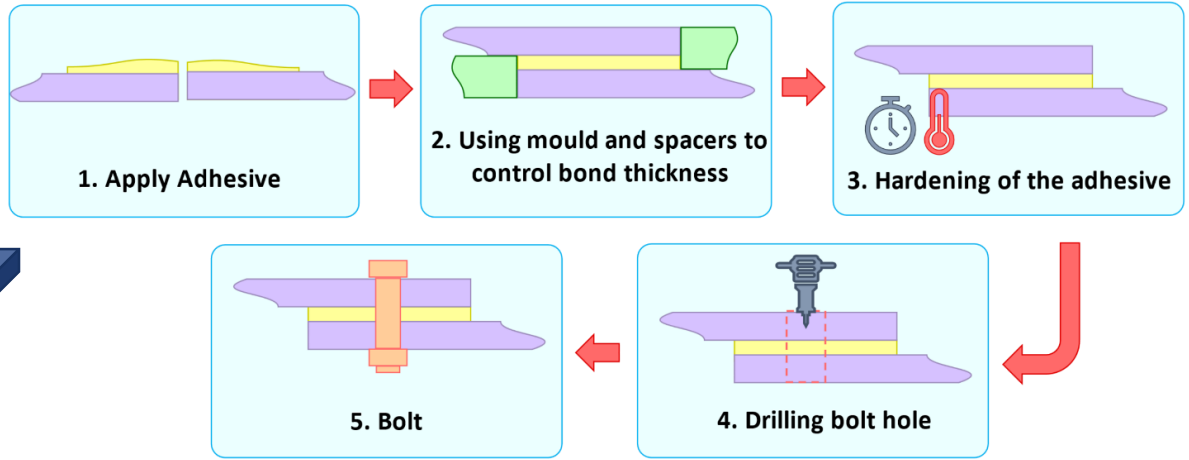


9. Placing the mould in press machine for curing

Manufacturing Process

Hybrid Bonding-Bolting





Applied Clamping Torque: 0.6-0.7 Nmm

Results and Discussion

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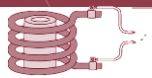
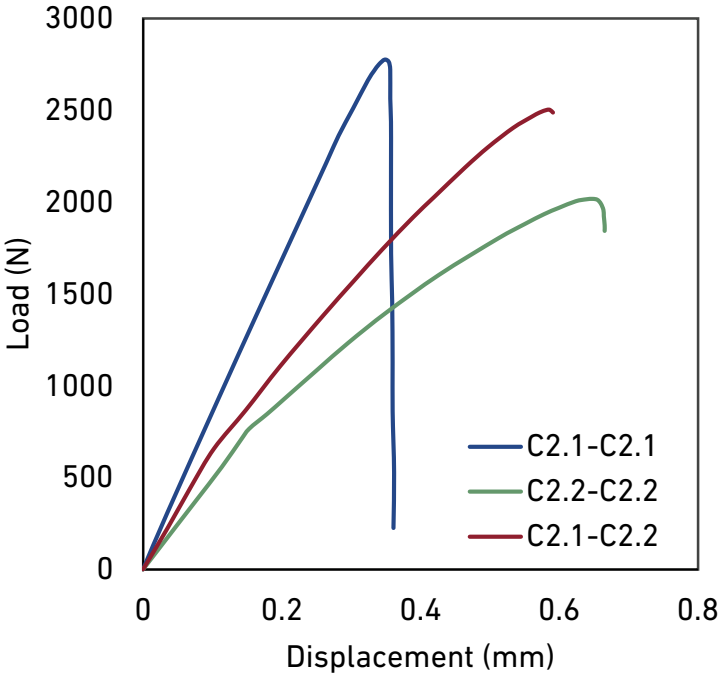
Induction Welding

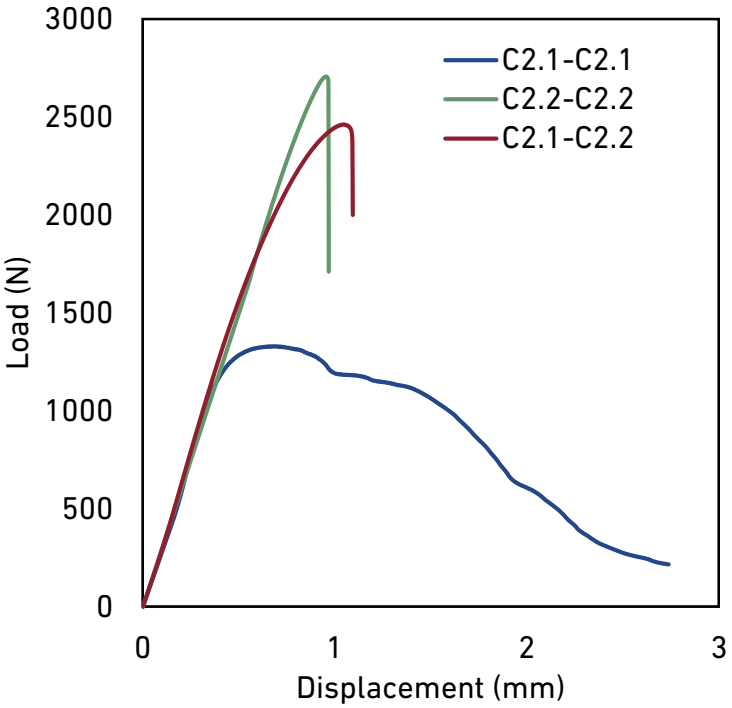


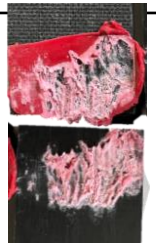


Configuration / Optimized Parameters	C2.1-C2.1	C2.2-C2.2	C2.1-C2.2
Temperature (°C)	220	200	220
Holding Time (s)	8	4	4
Compaction Pressure (Bar)	22	22	22
Average Maximum Load (N)	2634 ± 25%	1924 ± 12%	2564 ± 9%
Fracture Surfaces			

Results and Discussion

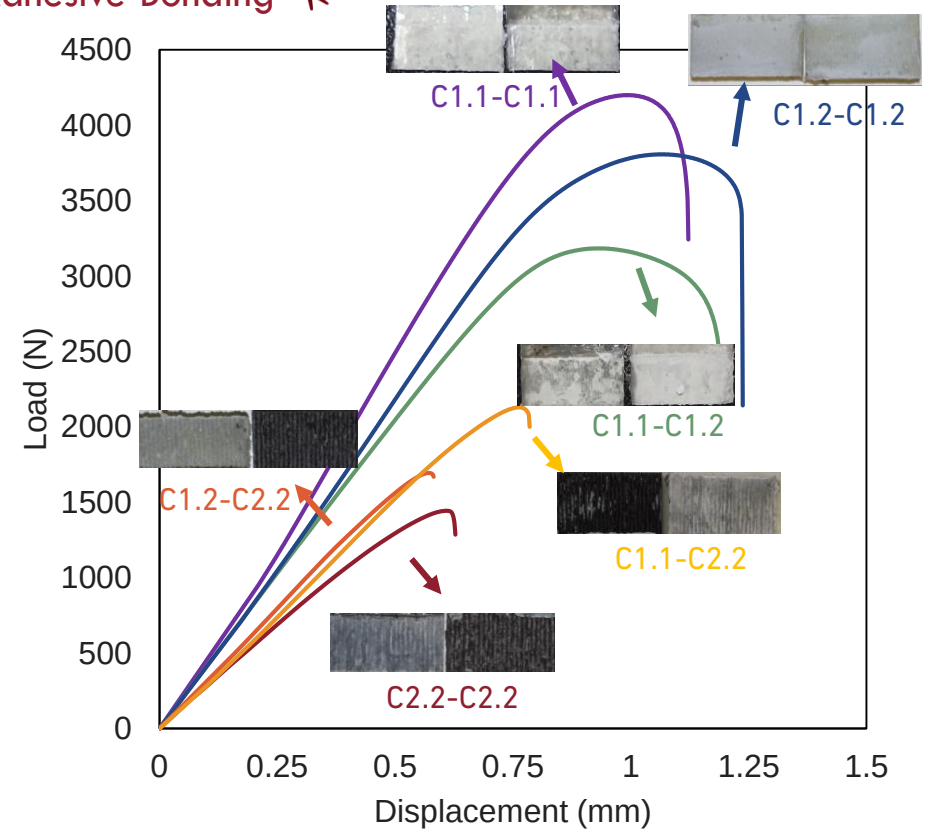
Ultrasonics Welding

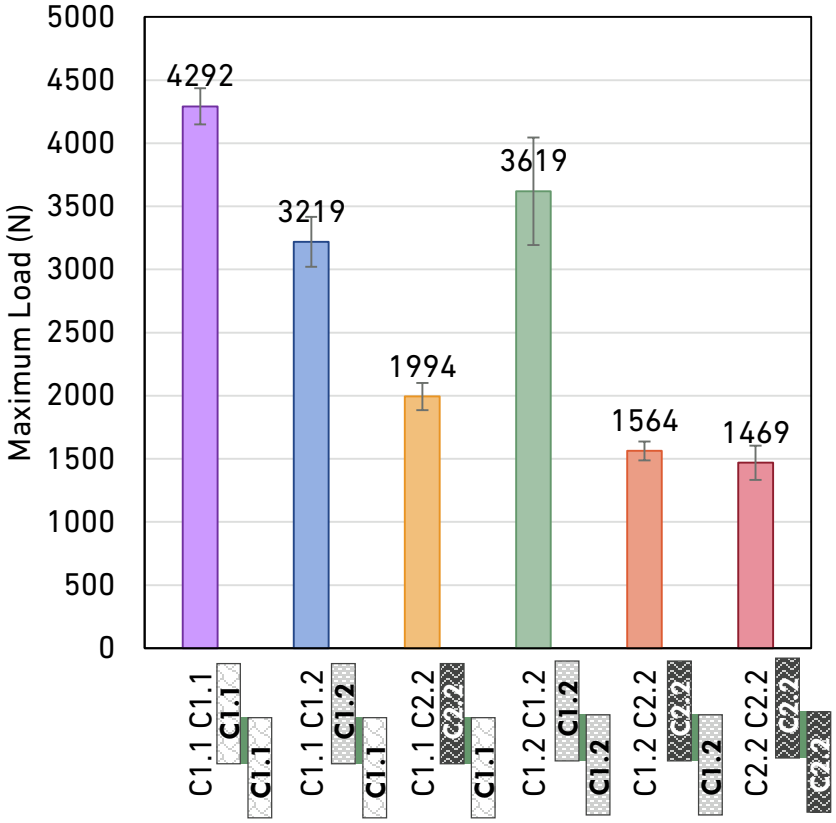


Configuration / Optimized Parameters	C2.1 C2.1	C2.2 C2.2	C2.1 C2.2
Amplitude (%)	80	90	90
Welding Time (s)	2.5	1.5	2
Compaction Pressure (Bar)	10.7	10	10
Average Maximum Load (N)	1494 ± 21%	2335 ± 5%	2564 ± 9%
Fracture Surfaces			

Results and Discussion

Adhesive Bonding

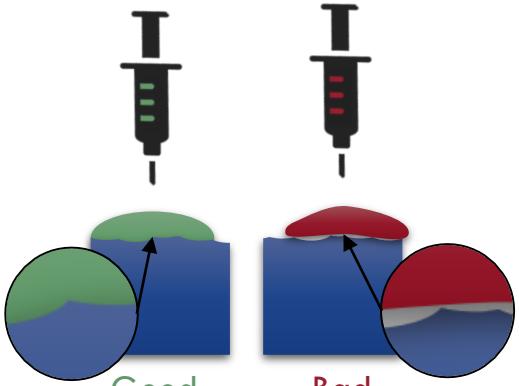


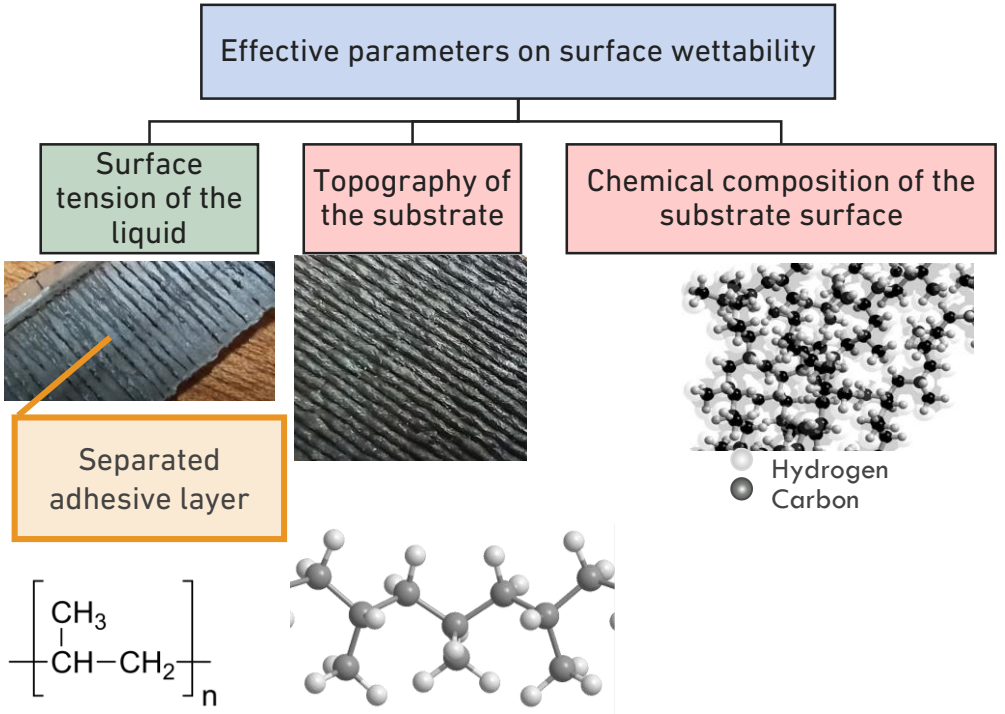


Results and Discussion

Adhesive Bonding

Why Thermoplastic 3D Printed Polypropylene (PP) composites represented Adhesive Failure?



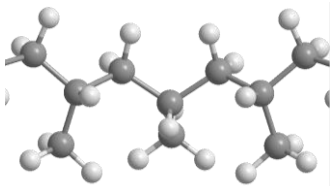


Polypropylene

Results and Discussion

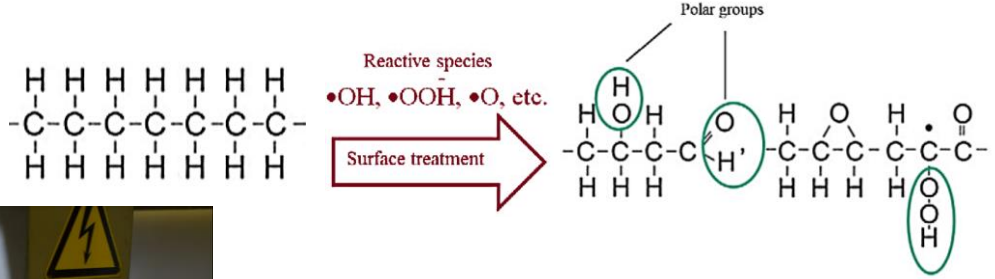
Adhesive Bonding

Why Thermoplastic 3D Printed Polypropylene (PP) composites represented Adhesive Failure? [1]



Material	Treatment	Surface Energy (mJ/m²)
Pure PP	-	31-32
Glass Fiber Reinforced PP	-	33.12
	Plasma	61.64

Surface free energy (Glass fibers) ~ Surface free energy (Substrate)



Atmospheric pressure plasma

oxygen-containing functional groups

Carbonyl

Hydroxyl R–OH

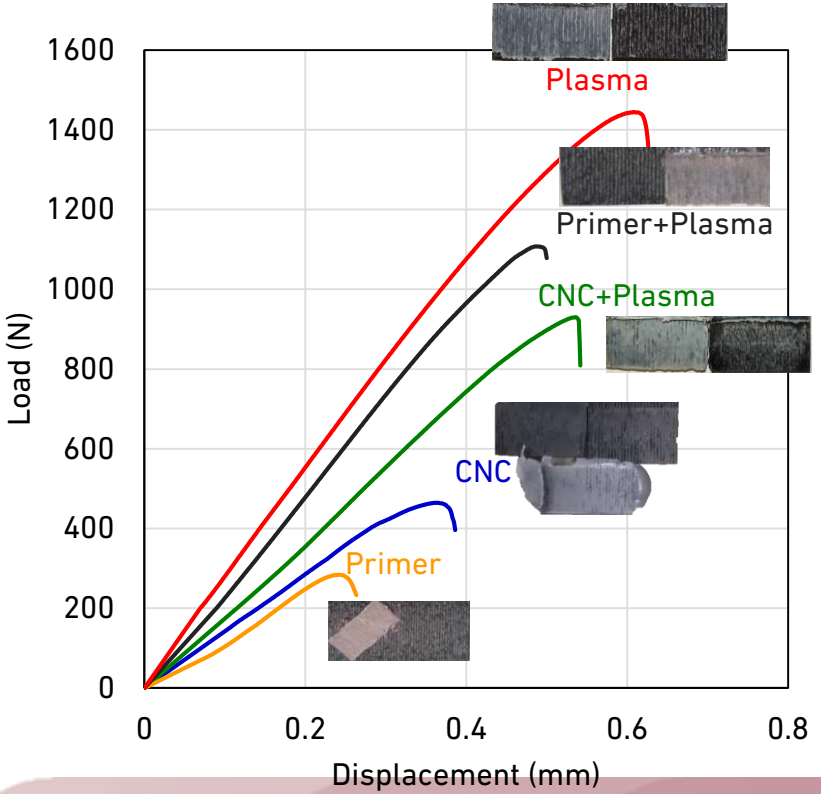
The surface's free energy → Wettability

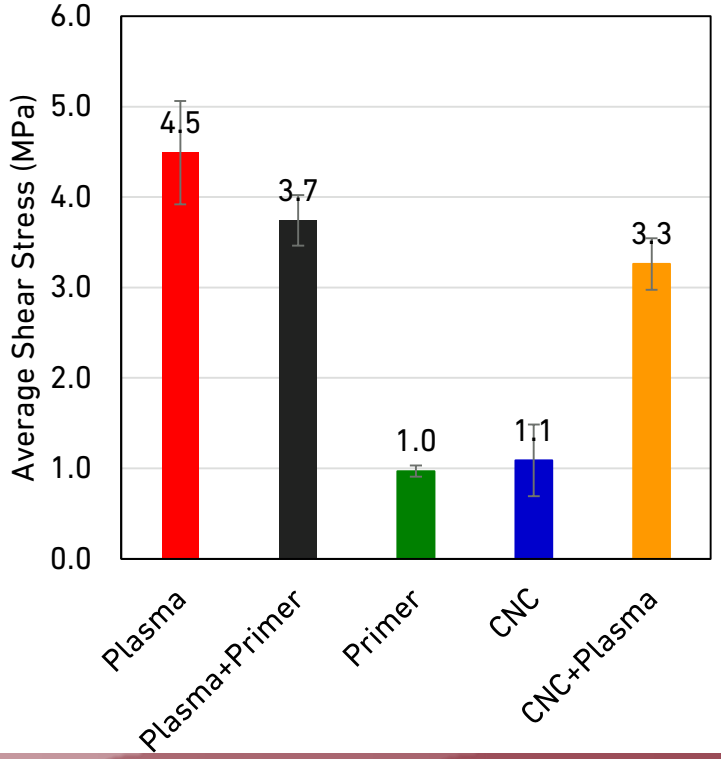
[1] Sauerbier, P., Anderson, J. and Gardner, D.J., 2018. "*Surface preparation and treatment for large-scale 3D-printed composite tooling coating adhesion*". Coatings, 8(12), p.457.

Results and Discussion

Adhesive Bonding

Challenges with C2.2 Thermoplastic 3D Printed Polypropylene (PP) composites





Results and Discussion

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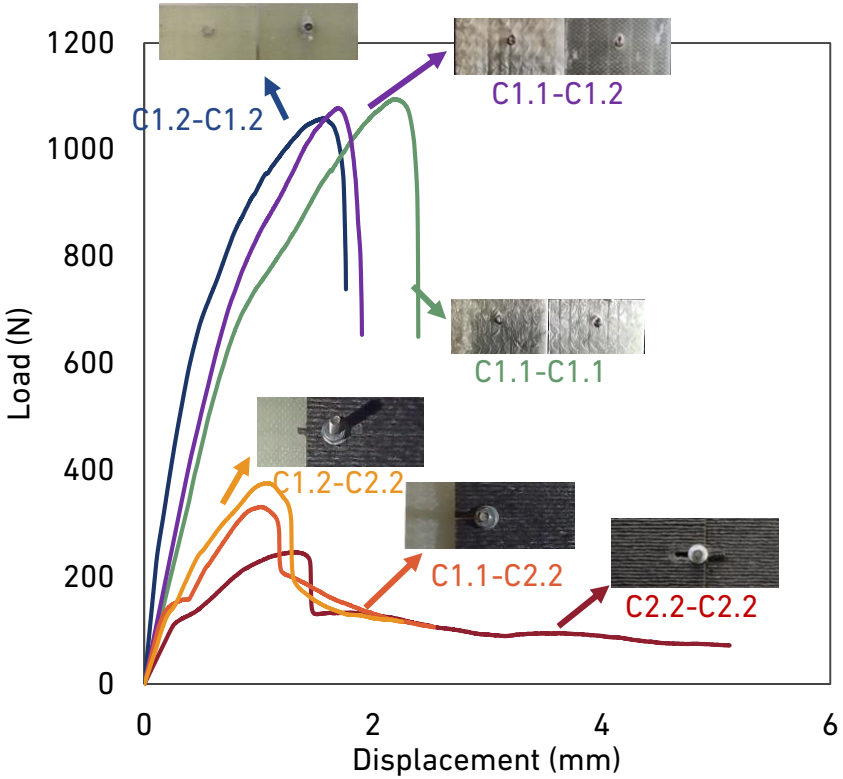
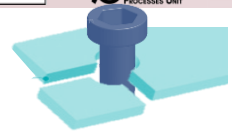
Bolting

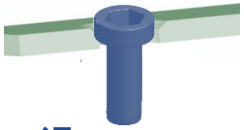


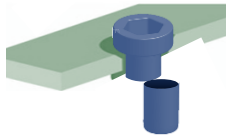

(Bearing)


(Net-Tension)

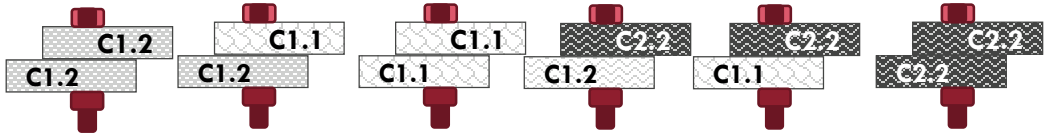

(Shear-out)


(Cleavage)


(Fastener Pull-Through)

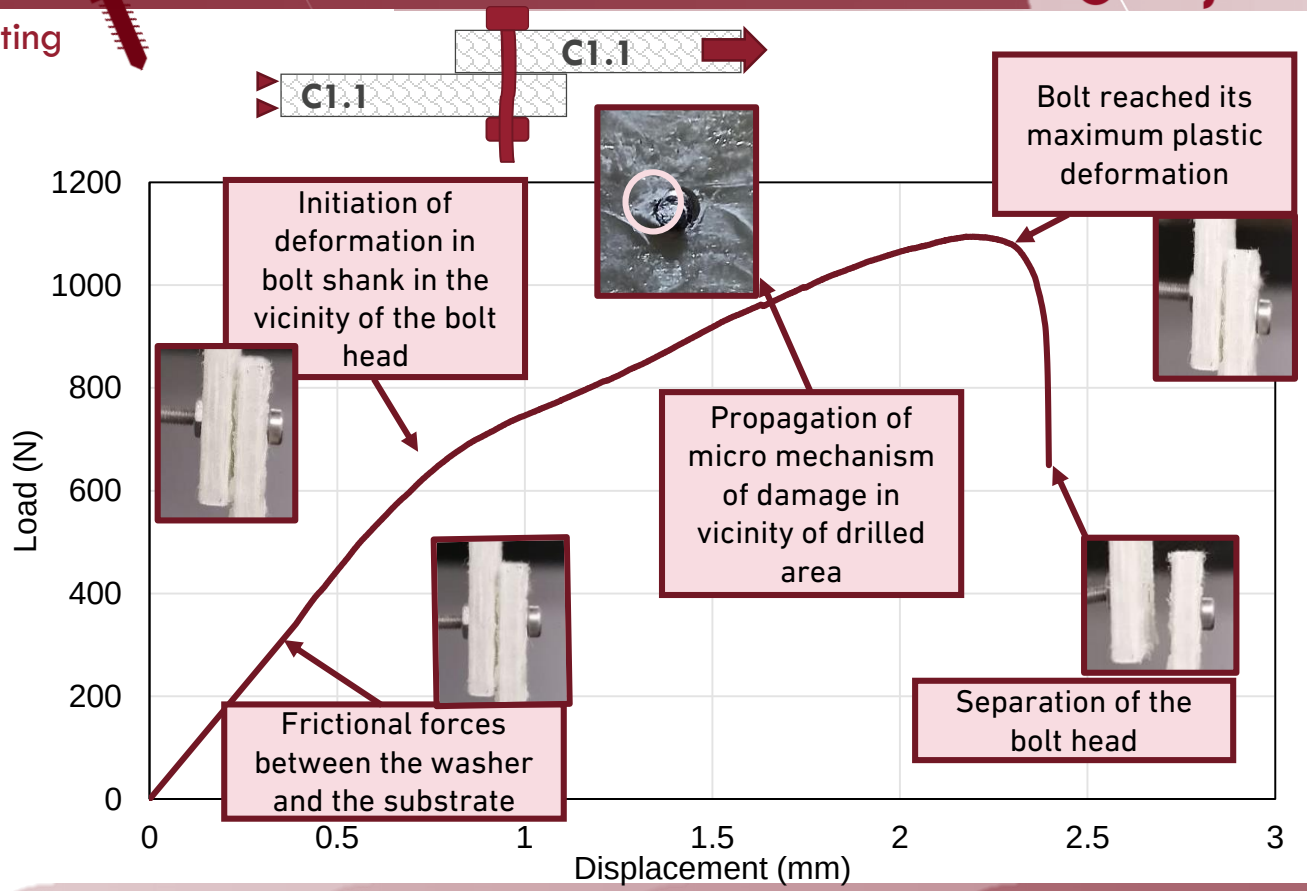

(Bolt)

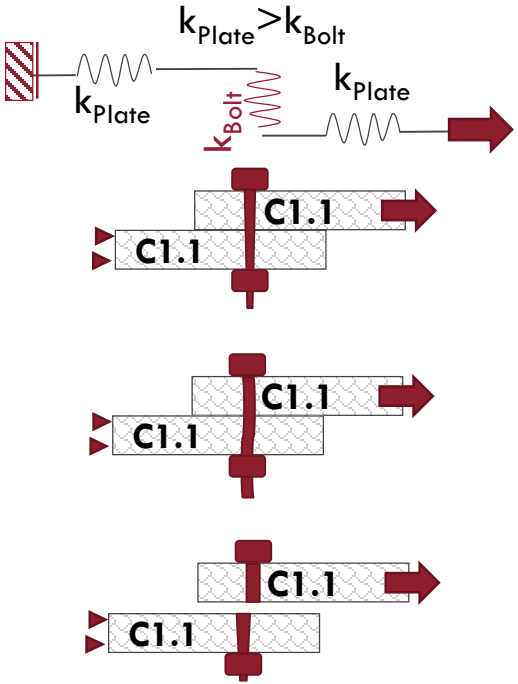
C1.2 – C1.2	C1.1 – C1.2	C1.1 – C1.1	C1.2 – C2.2	C1.1 – C2.2	C2.2 – C2.2
1606 ± 8%	1050 ± 5%	1046 ± 5%	341 ± 5%	339 ± 4%	255 ± 4%
Bearing	Bearing	Bearing	Cleavage	Cleavage	Cleavage



Results and Discussion

Bolting





Results and Discussion

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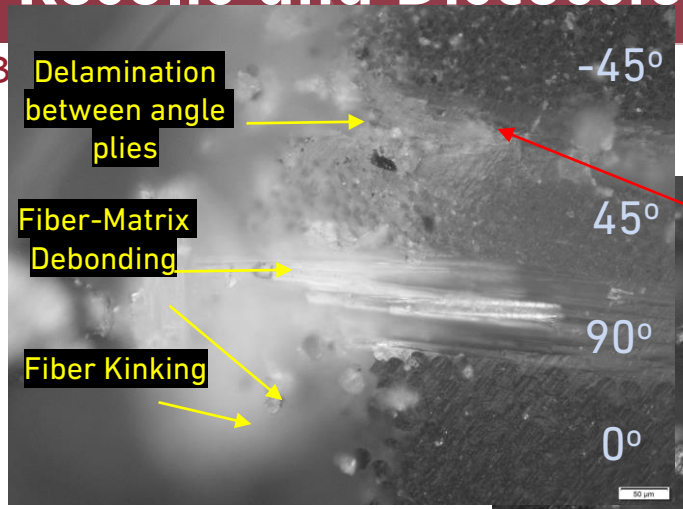
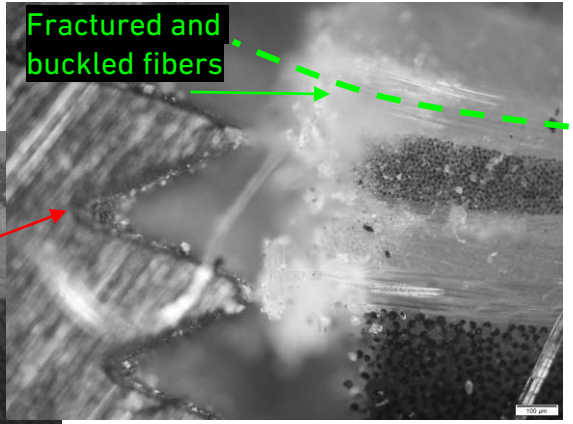
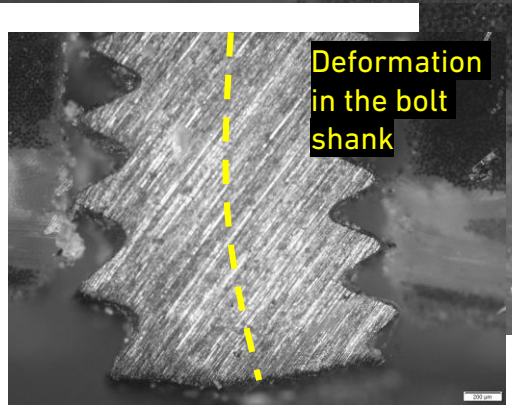
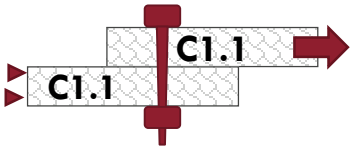


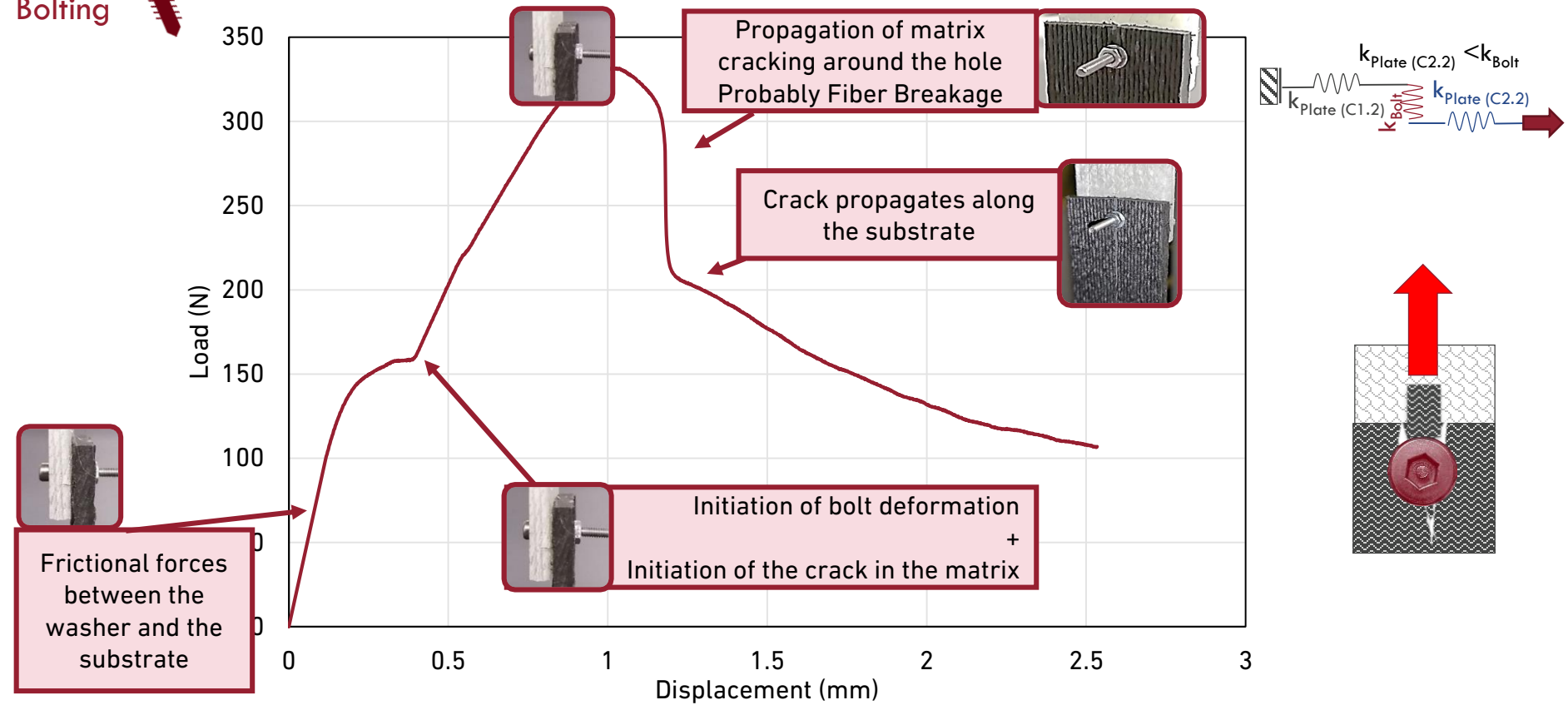






Results and Discussion

Bolting



Results and Discussion

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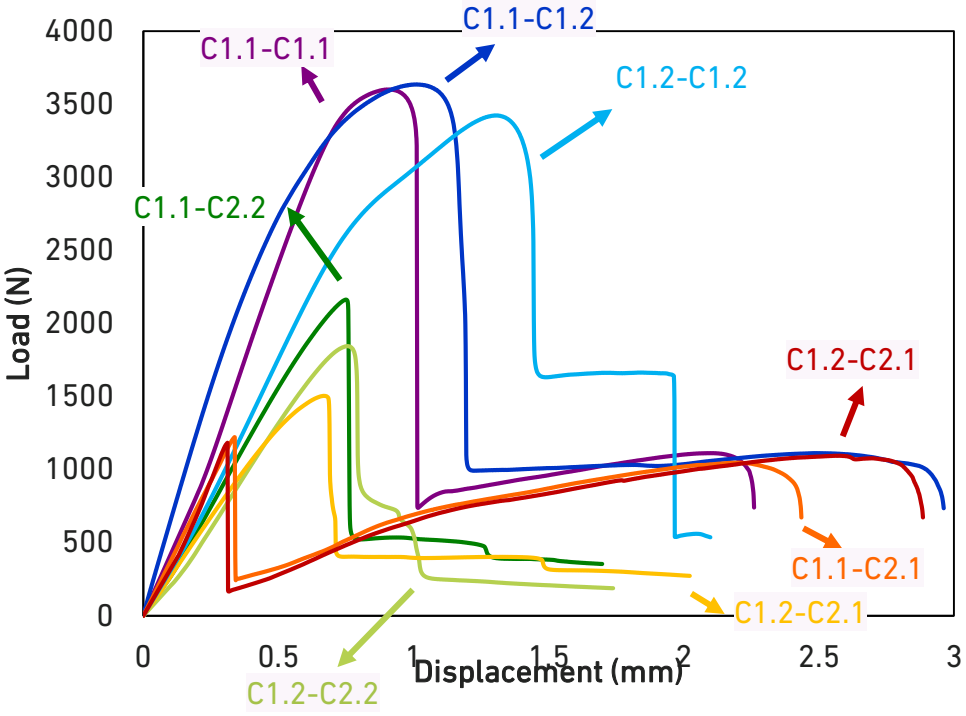
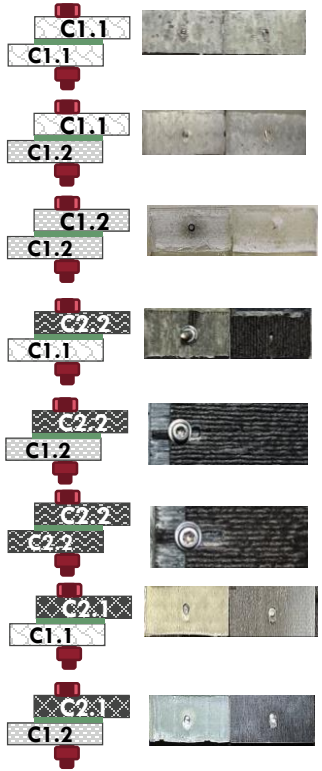
Hybrid Bonding-Bolting

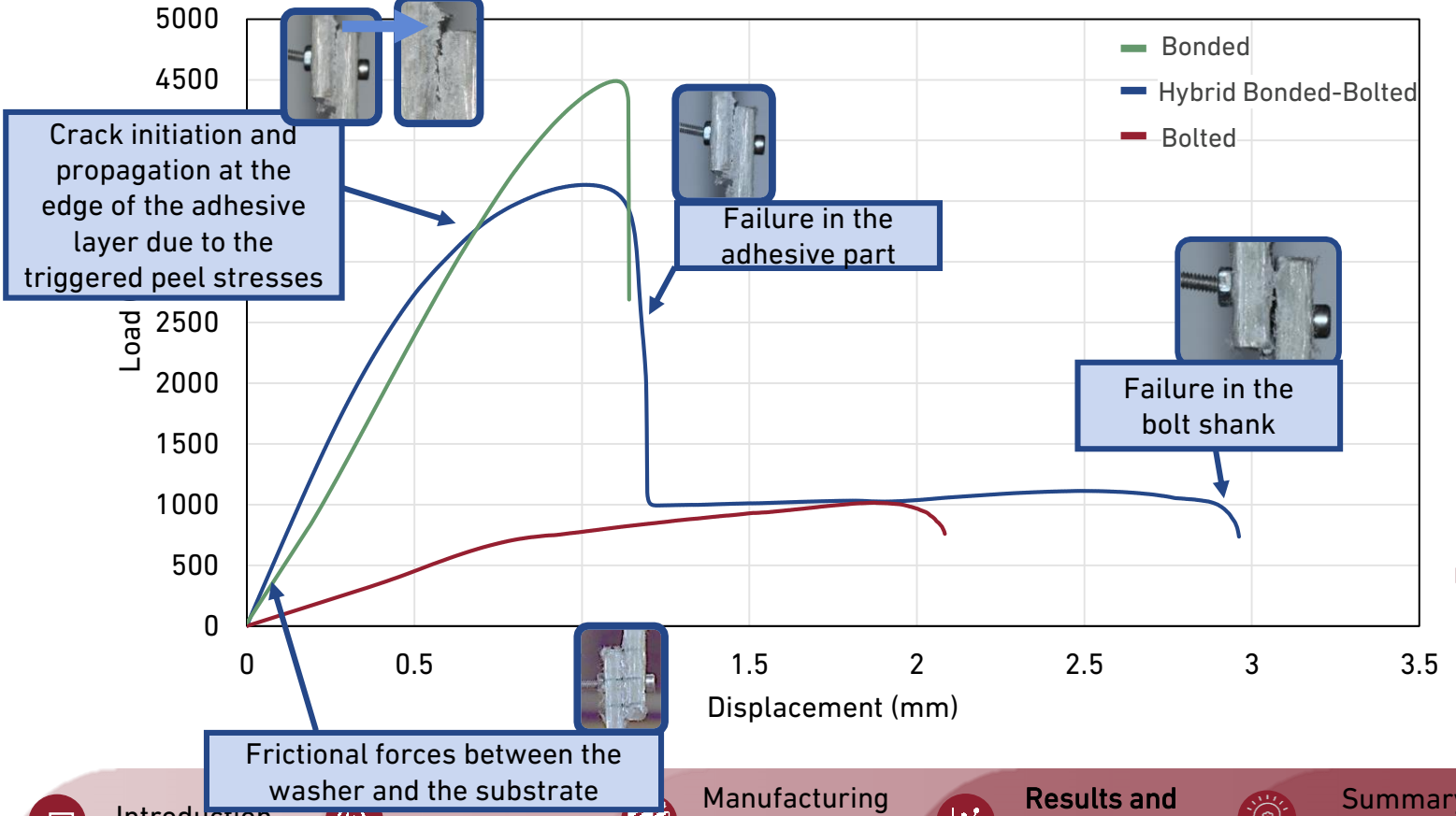


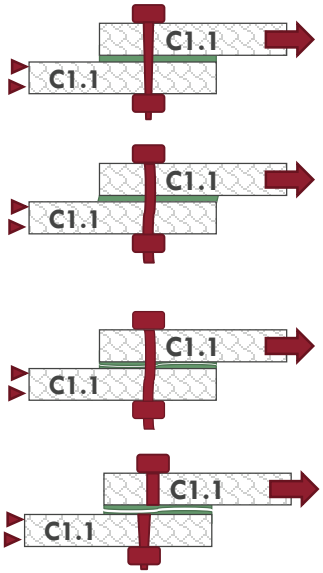
Configurations	Maximum Load (N)	Failure Type
C1.1 – C1.1	3488 ± 4%	Cohesive + Bearing
C1.1 – C1.2	3408 ± 3%	Cohesive + Bearing
C1.2 – C1.2	3296 ± 6%	Cohesive + Bearing
C1.1 – C2.2	2026 ± 2%	Adhesive + Cleavage
C1.2 – C2.2	1831 ± 4%	Adhesive + Cleavage
C2.2 – C2.2	1290 ± 14%	Adhesive + Cleavage
C2.1 – C1.1	1237 ± 15%	Adhesive + Bearing
C2.1 – C1.2	1237 ± 10%	Adhesive + Bearing



Results and Discussion

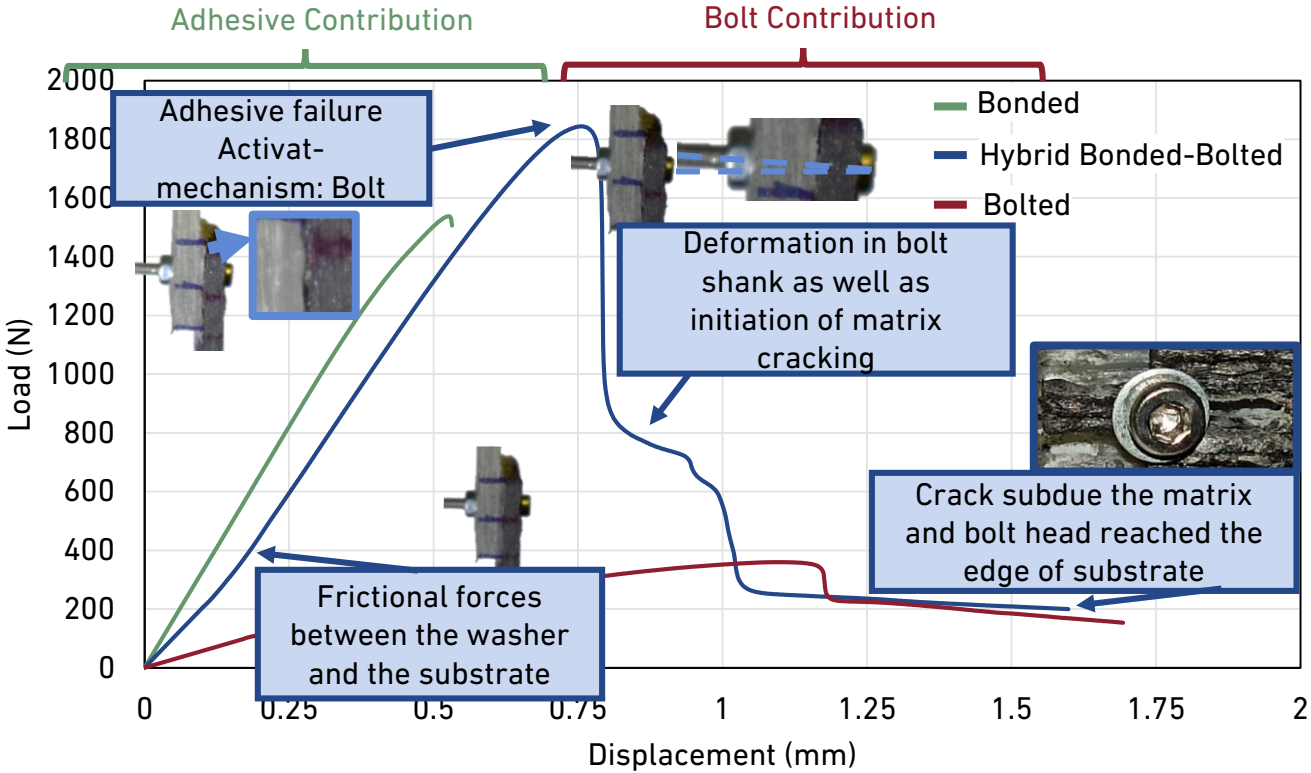
Hybrid Bonding-Bolting

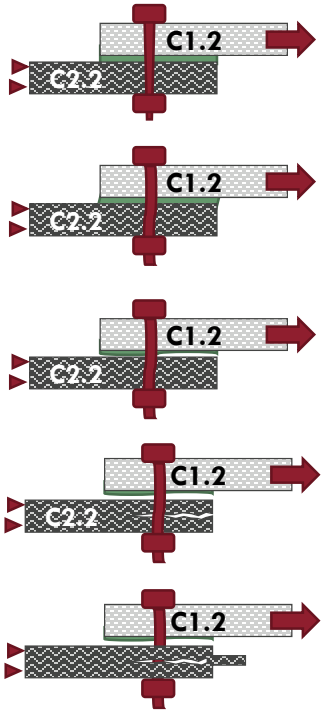




Results and Discussion

Hybrid Bonding-Bolting





Summary and Conclusion

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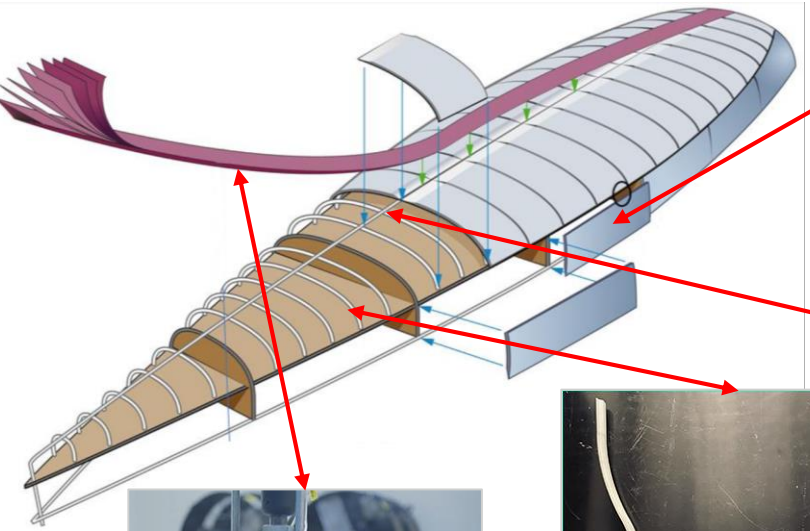
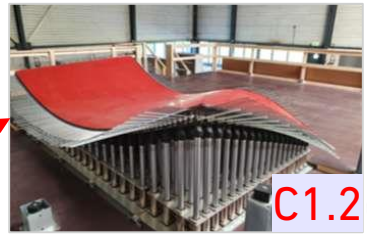
Summary





CURVE Works

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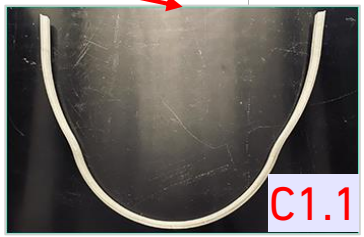
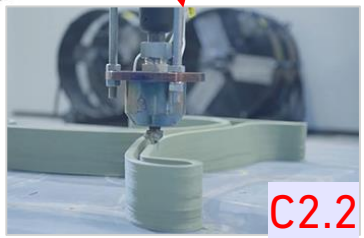


IRURENA GROUP ADVANCED TECH COATINGS



10XL

- Induction Welding
- Ultrasound Welding
- Adhesive Bonding
- Bolting
- Hybrid Bonding-Bolting

Summary and Conclusion

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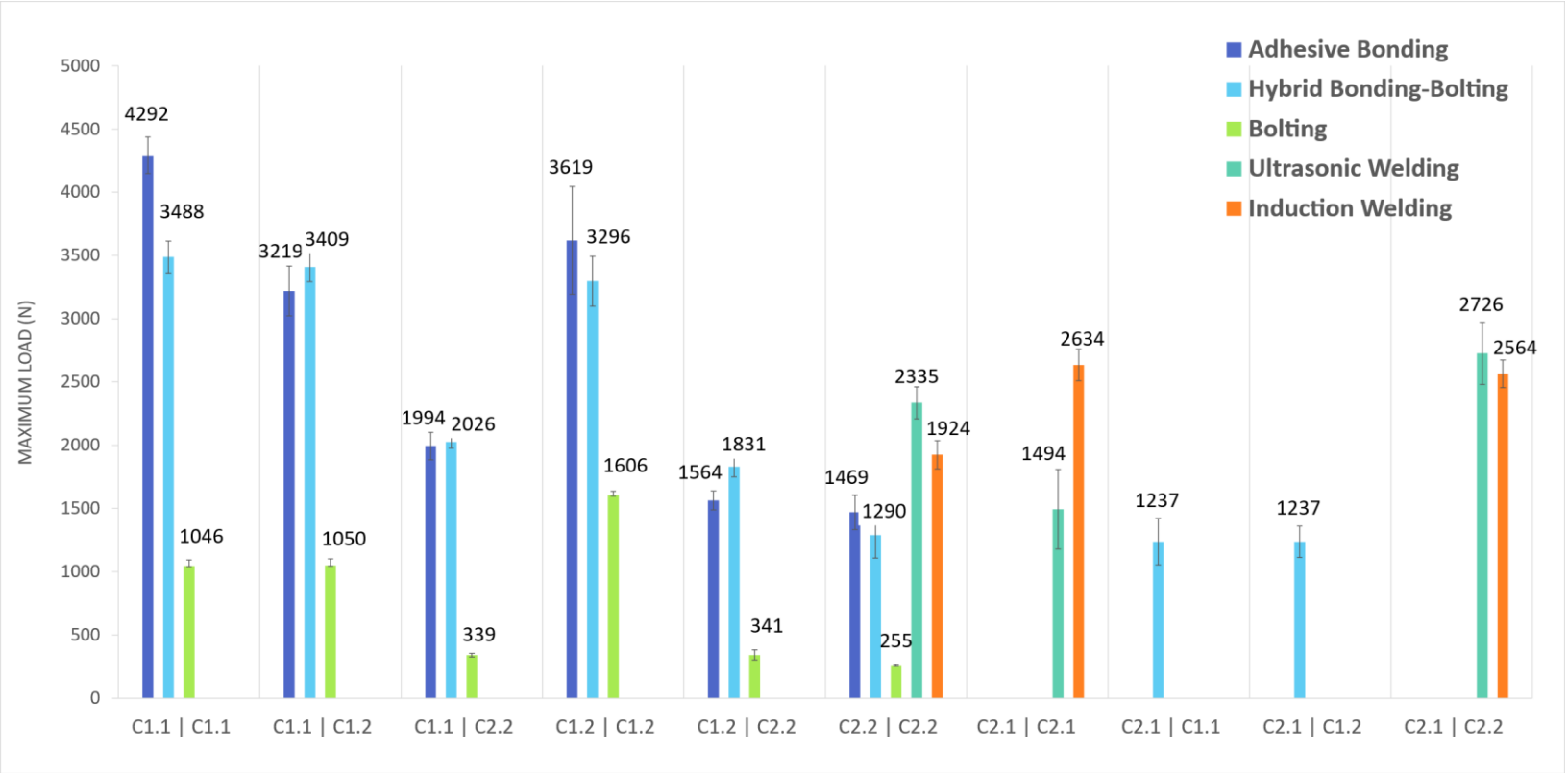
Summary



Summary and Conclusion

Conclusion

The proceeding investigation represents a comprehensive evaluation of common joning 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** > provide **higher strength** rather than other techniques.

Dissimilar thermoset composites: **hybrid joining** > efficient > higher strength rather than adhesive bonding and bolting+ fail-safe mechanism

Joining of thermoplastic materials: significant challenge

Similar thermoplastic materials: welding techniques.

Ultrasonic welding of similar C2.1 - C2.1 (Carbon Fibre Reinforced PP)composites > **high energy absorption of carbon fibres** > using **energy directors** > requires a set of **experimental designs**

Summary and Conclusion

Conclusion

Ultrasonic Welding seems to be **more efficient** and **straightforward** to perform compared with **Induction Welding**.

In order to employ **fusion-based welding** methods for continuous joining application, **further research** is required.

Thermoplastic 3D Printed PP composites: improving the manufacturing and surface finishing quality > Solving cleavage and adhesive failure of experimental designs

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Thank You For Your Attention

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