INSTITUTO DE
PESQUISAS
TECNOLÓGICAS

SAMPE 2022

DEVELOPMENT AND MANUFACTURING OF STRUCTURAL COMPOSITE PARTS

Wellington Mello

August/2022

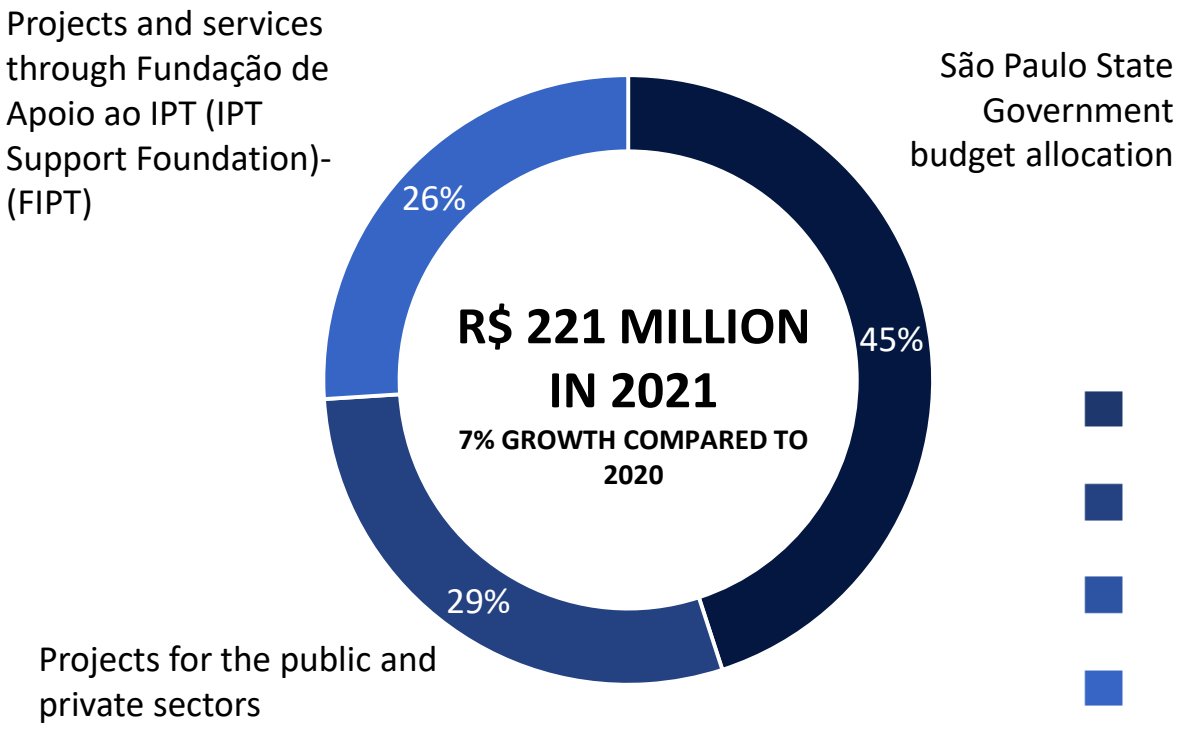
AGENDA

- IPT overview
- Fiber-reinforced polymer composites and mobility industry
- Design process of a composite part
- Manufacturing processes
- Material selection
- Material behavior
- Compression Molding overview
- Defects in compression molded parts
- Final remarks

WHAT IS IPT?

WE PROVIDE TECHNOLOGICAL SOLUTIONS FOR INDUSTRY, GOVERNMENTS AND SOCIETY, ENABLING THEM TO OVERCOME THE CHALLENGES OF OUR TIME

REVENUES



OUR NUMBERS (2022)

123 YEARS OF CONTRIBUTIONS TO SOCIETY

> 1000 EMPLOYEES AND PARTNERS

37% REVENUE IN INNOVATION PROJECTS

> 3450 CUSTOMERS SERVED

SATISFIED CUSTOMERS NPS 81 (LEVEL OF EXCELLENCE)

> 17.000 TECHNICAL DOCUMENTS ISSUED

> 2000 TESTING AND ANALYSIS PROCEDURES IN THE PORTFOLIO

WHAT WE DO?

RESEARCH, DEVELOPMENT AND INNOVATION

- PRODUCTS AND PROCESSES
- SOFTWARES
- FROM BENCH TO PILOT
- INCENTIVE SUPPORT
- EMBRAPII

TESTS, TRIALS AND ANALYSIS

- TECHNICAL STATEMENTS
- PRODUCT EVALUATION
- PRODUCT CERTIFICATION

INSPECTION AND MONITORING

- CONSTRUCTION AND SCTRUCTURES
- MACHINERY AND EQUIPMENT
- ACCREDITED INSPECTION BODY

METROLOGICAL DEVELOPMENT, MEASUREMENTS AND CALIBRATIONS

- PROFICIENCY PROGRAMS
- STANDARDS DEVELOPMENT
- ADVANCED METROLOGY
- DA

CERTIFIED REFERENCE MATERIALS

- METALS
- CERAMIC
- MINERAL
- VISCOSITY
- NORMAL SAND

TECHNOLOGICAL EDUCATION

- PROFESSIONAL MASTER
- EXTENSION COURSES
- COURSES ON DEMAND

BUSINESS UNITS

BIONANOMANUFACTURING
Biotechnology, Nanotechnology,Micro-manufacturing, Chemistry and PPEs

CITIES, INFRASTRUCTURE AND ENVIRONMENT
Territorial Planning , Civil Works, Risks, Water Resources, Forests

ENERGY
Generation, Infrastructure, Efficiency, Clean energy

BUILDING AND HOUSING
Generation, Performance, Safety, Materials, Sustainability

ADVANCED MATERIALS
Metallic, Polymeric, Composite, Cellulosic, Corrosion

DIGITAL TECHNOLOGIES
IoT, Embedded Systems, Transport Systems, IA, Analytics

NORMATIVE AND METROLOGICAL TECHNOLOGIES
Mechanics, Electrical, Flow Measurement, Aerodynamics, Chemistry

ADVANCED MATERIALS

CORROSION AND PROTECTION
Corrosion in oil and gas industry
External corrosion, internal corrosion and monitoring
Metallic, organic and nanostructured coatings
High corrosion resistance alloys (CRA)

41 PEOPLE
3 PhDs
9 MScs
9 GRADUATES
20 TECHNICIANS

PULP, PAPER AND PACKAGING
Compliance and performance assessment
Simulation of packaging storage and transportation
Lignocellulosic materials of agroindustrial waste
Recyclability assessments

15 PEOPLE
2 PhDs
1 MScs
7 GRADUATES
5 TECHNICIANS

LIGHTWEIGHT STRUCTURES
Composites and nanocomposites
Multifunctional materials
High strength polymers
Friction stir welding (FSW)

29 PEOPLE
10 PhDs
5 MScs
5 GRADUATES
9 TECHNICIANS

METALLURGICAL PROCESSES
Additive manufacturing
Forming processes
Mineral processing
Pyrometallurgical and electrochemical refining

49 PEOPLE
8 PhDs
6 MScs
17 GRADUATES
18 TECHNICIANS

BACKGROUND INFO

- EMBRAPII UNIT: HIGH PERFORMANCE MATERIALS
- 47% STAFF WITH MASTERS AND DOCTORS
- MULTIDISCIPLINARY TECHNOLOGICAL CAPACITATION
- PHYSICAL AND MATHEMATICAL MODELING
- CONCEPT DEVELOPMENT, PROTOTYPE AND PROCESS SCHEDULING
- PHYSICAL INFRASTRUCTURE IN BENCH AND PILOT SCALE

Oil and gas

Pultruded

- Processing parameters optimization;
- Mathematical simulation to define process parameters;
- Development of new pultruded materials

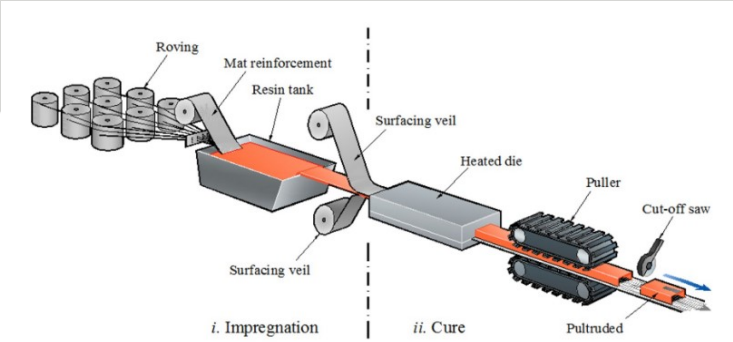
Structural adhesives

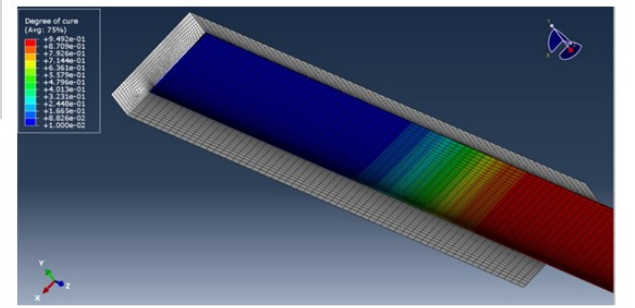
- Development of structural adhesives for offshore applications;
- Representative testing for evaluation of aging of adhesives

Pipe protection System

- Development of rigid pipe protection system

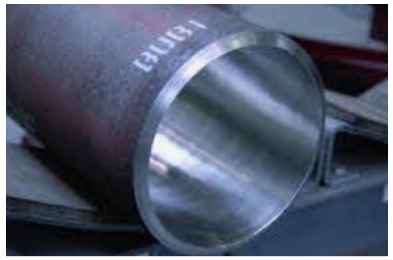
Development of new pultruded materials

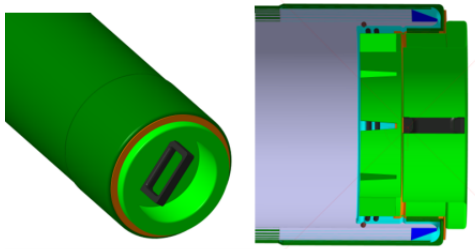




Cure kinectis of pultrusion process

Adhesive evaluation - Creep



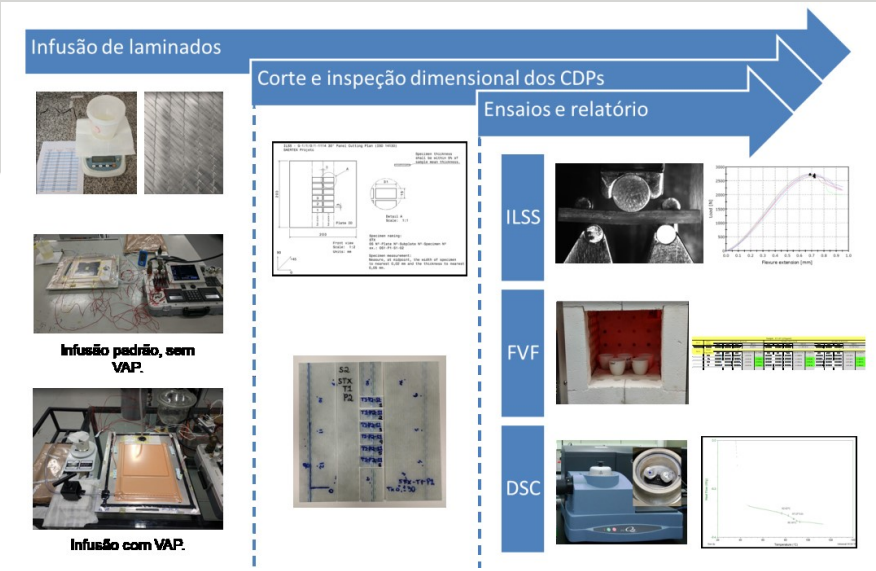


Energy

Material qualification

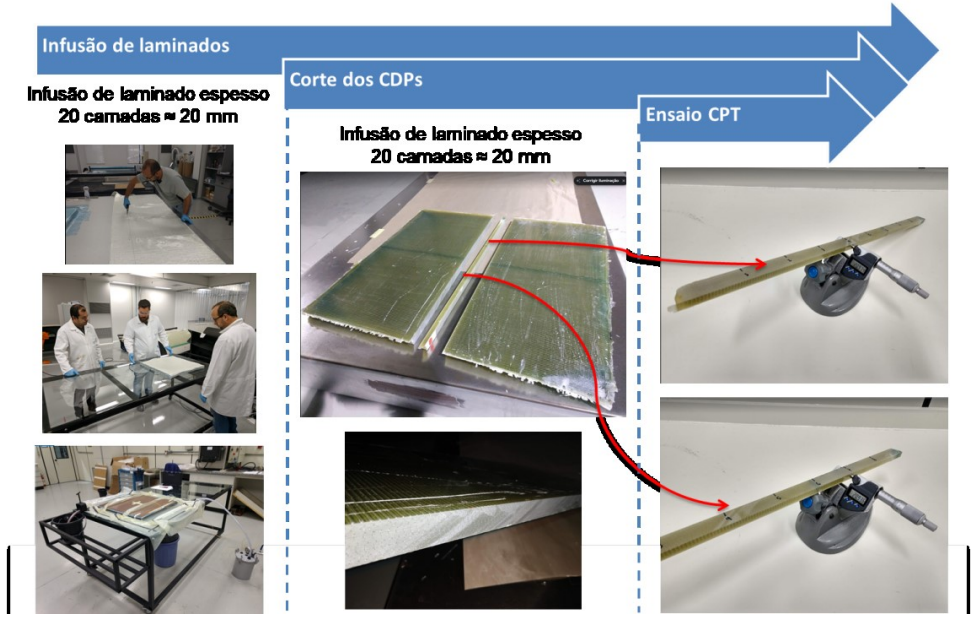
- Processing of glass fiber composites used in wind power industries;
- Representive sample preparation by infusion;
- Dimensional evaluation and sample/component inspection;
- Mechanical testing for wind power industries;
- Assessment of repair techniques in power transmission poles applying composite materials

Mechanical and thermal testing



Repair techniques - Power transmission poles

Cured ply thickness evaluation



Airspace

Automated manufacturing

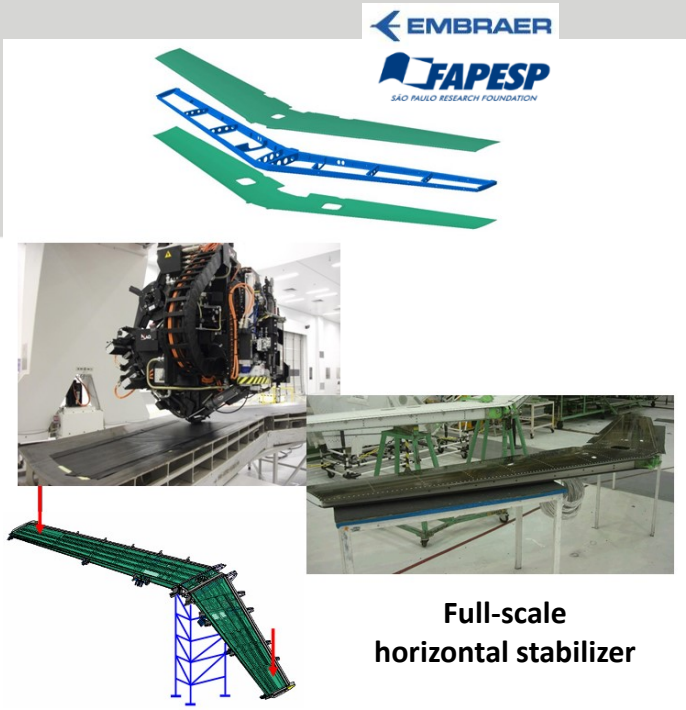
- Design and manufacture of aeronautical and airspace components in composite materials, in real scale;
- Study on the advantages and limitations of replacing metal with composite;

Friction joints

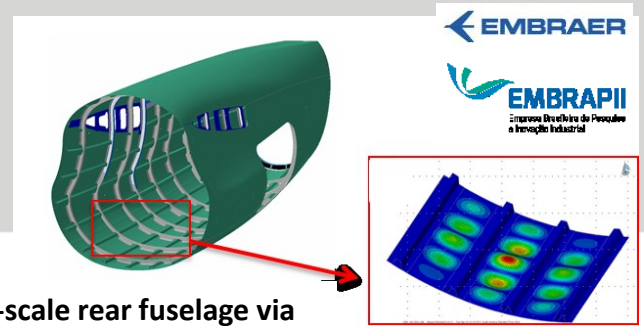
- Friction joining techniques of metallic materials;

Superplastic Forming

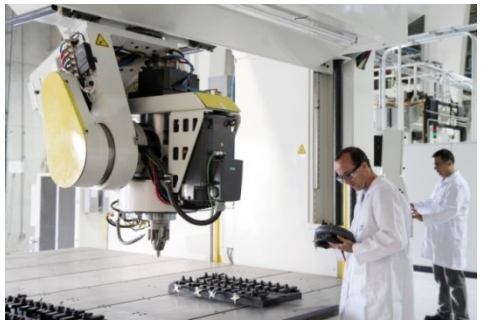
- Superplastic forming for the manufacturing of satellite tanks



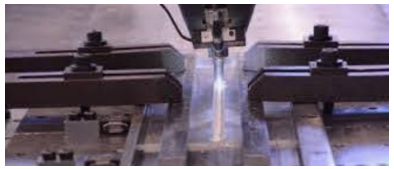
Full-scale horizontal stabilizer

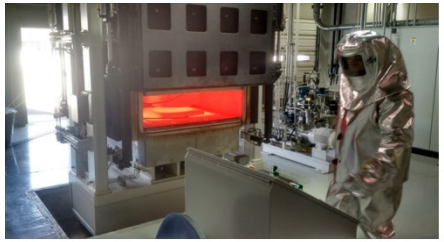


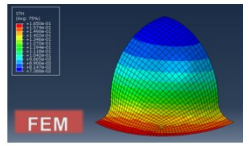
Full-scale rear fuselage via Automated Fiber Placement

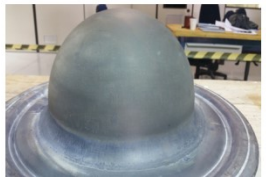


Friction Stir Welding research







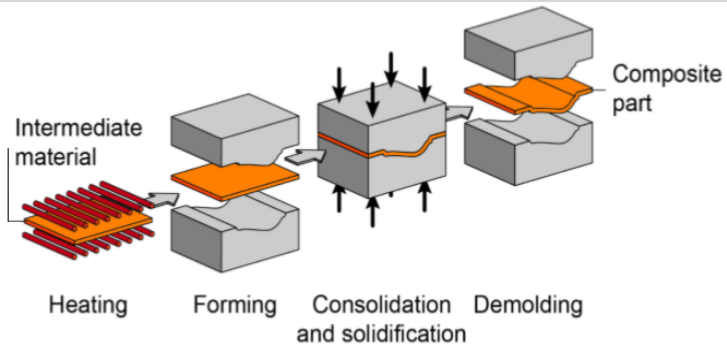


Satellite tank

Automotive

Weight reduction

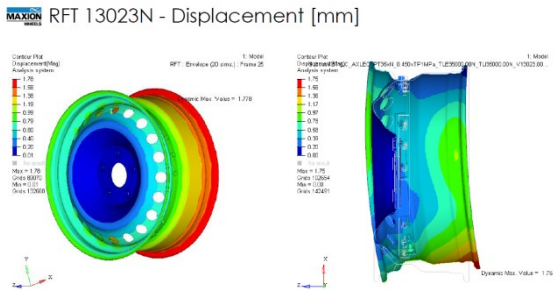
- Qualification of composite materials for structural applications in commercial vehicles;
- Computer simulation for designing composite structural components (FEM, crashworthiness, CFD);
- Simulation of hot forming manufacturing processes (compression molding and stamp forming;
- Evaluation of 3D printing techniques for dissimilar materials;
- Tooling design for composite parts



Development of structural components

MAXION STRUCTURAL COMPONENTS a division of IOCHPE-MAXION

EMBRAPII Empresa Brasileira de Pesquisa e Inovação Industrial



Disco de roda

MAXION WHEELS a division of IOCHPE-MAXION

EMBRAPII Empresa Brasileira de Pesquisa e Inovação Industrial

Tooling design for composite parts

New car generation developments

STOCK TECH

EMBRAPII Empresa Brasileira de Pesquisa e Inovação Industrial

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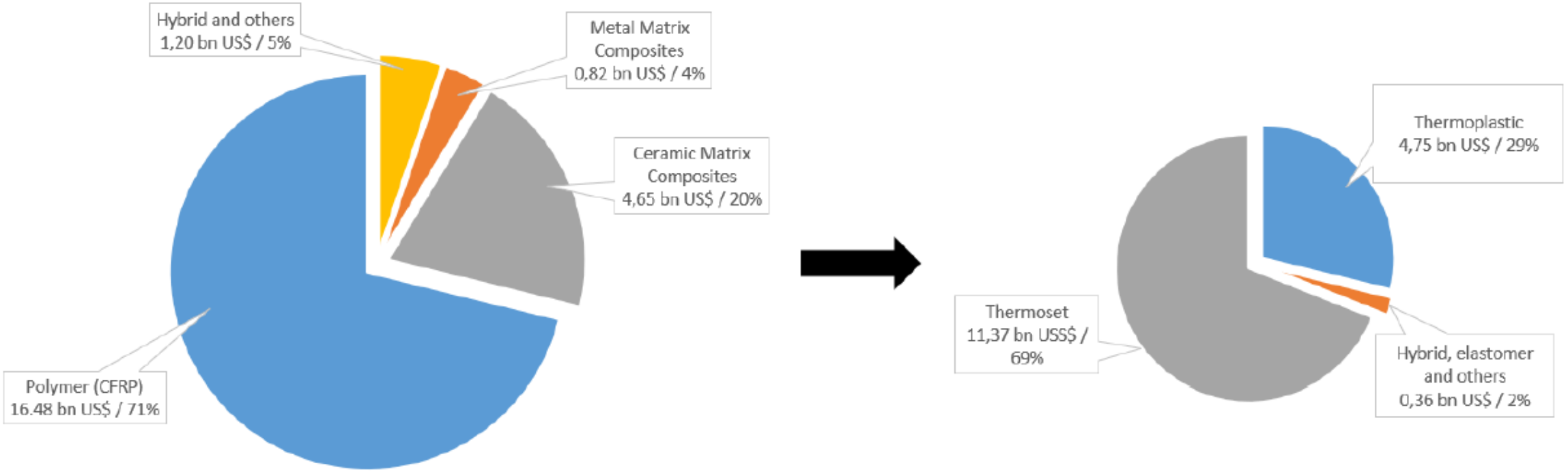
FIBER-REINFORCED POLYMER COMPOSITES

- Studies and application in several industrial sectors: aerospace, automotive and energy
- High strength-to-weight and high stiffness-to-weight ratios
- AVK report:



Source: SAUER, M.; KÜHNEL, M.; ELMAR, W. Report - Composites Market AVK Report 2018 - Market developments, trends, outlook and challenges, 2018.

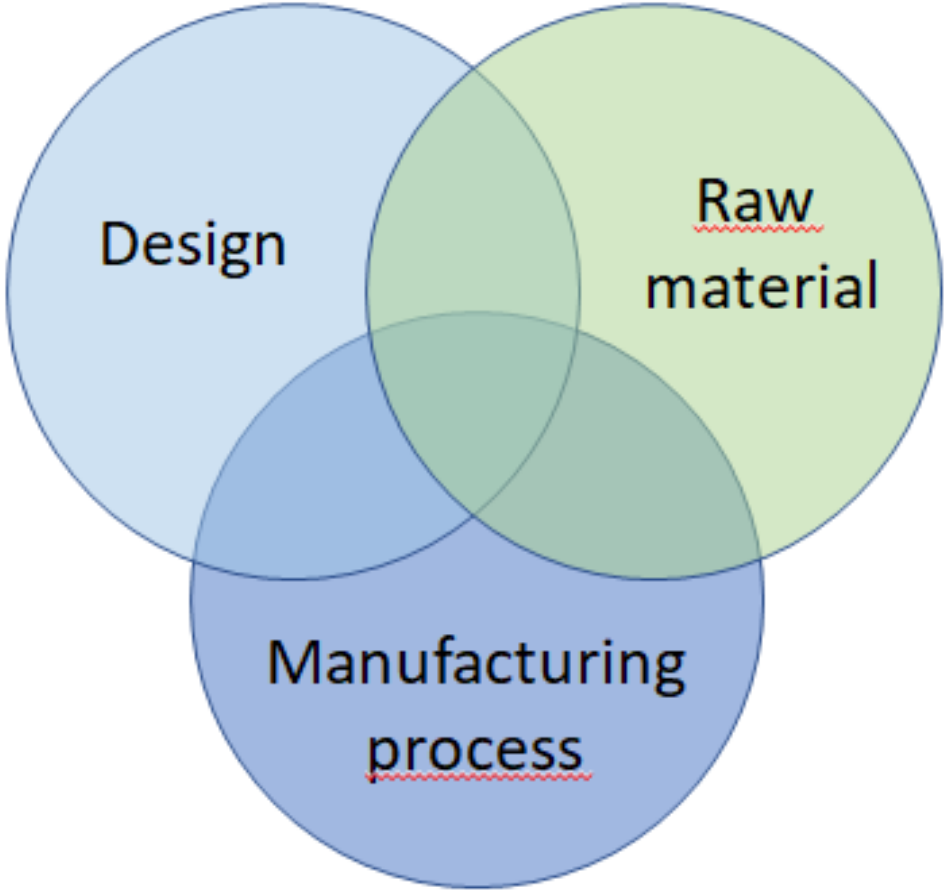
FIBER-REINFORCED POLYMER COMPOSITES

- Mobility and Automotive industries:
  - weight reduction
  - fuel consumption reduction
  - reduction in emission of CO_2
  - vehicle safety
  - electrification: battery pack enclosure
  - mass-production

- Automotive components: potential to 30% gain in fuel efficiency and 20% reduction in CO_2 emissions by replacing steel with Carbon Fiber Reinforced Polymers (CFRP)

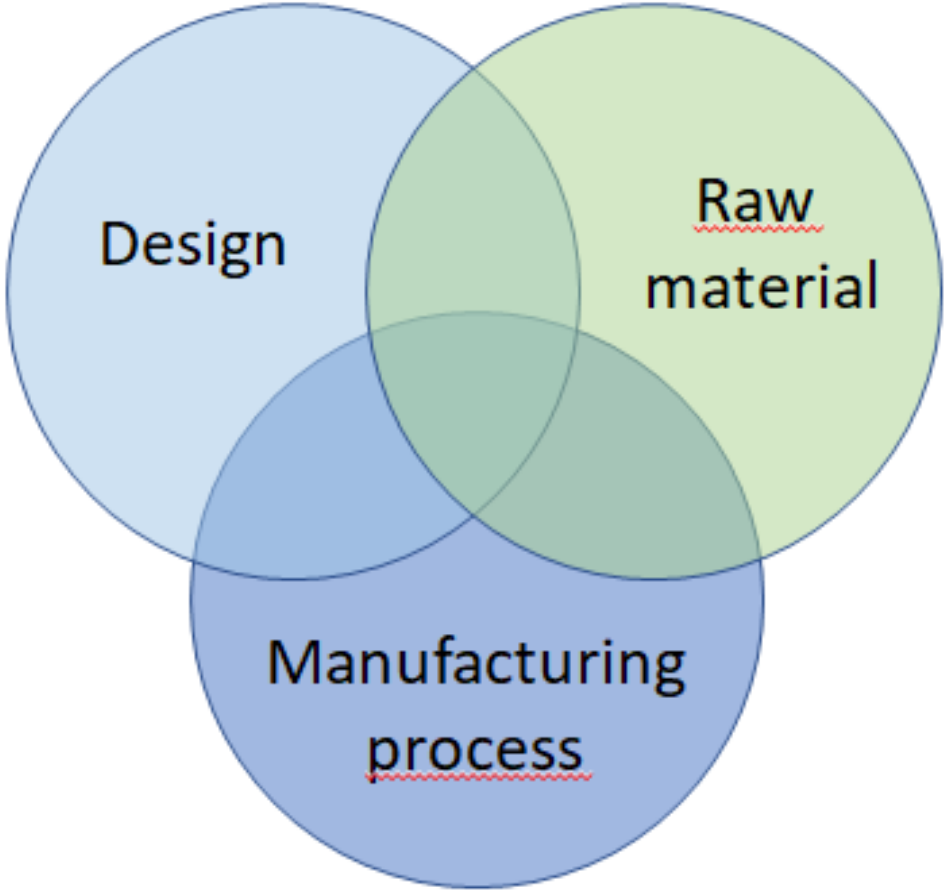
DESIGN OF A COMPOSITE STRUCTURE/PART

- What is involved in the design of a composite structure or part?
  - Given performance requirements
    - load, excitation frequencies, etc.
  - Required:
    - find laminate structural configuration to carry those loads
  - Which is the best material for the component design?
  - Which manufacturing process best suits for that?
- Other design drivers:
  - Structural configuration / Geometry / Shape
  - Weight
  - Costs



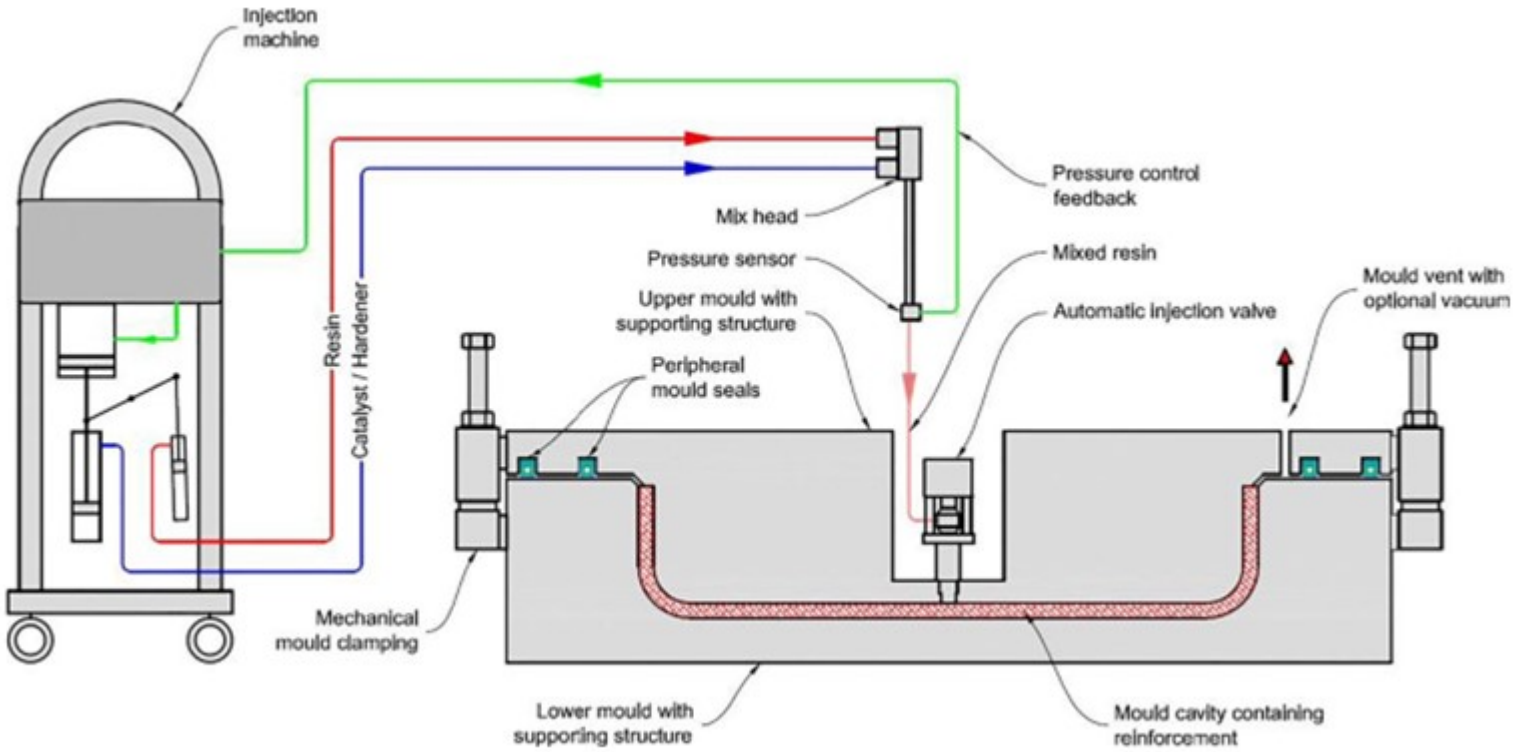
DESIGN OF A COMPOSITE STRUCTURE/PART

- Other design drivers:
  - How the component will be joint to the structure?
  - Design requirements / Failure criteria:
    - Strength (stress or strain limitation)
    - Stiffness (deflection limitation)
    - Life, energy absorption, fatigue, etc.
  - How to evaluate if the design requirements are satisfied?
    - Run different analyses -> FEM, Crash-worthiness, CFD, etc.
    - Analysis is a one-way street
  - Design is an iterative process, with several analyses



MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

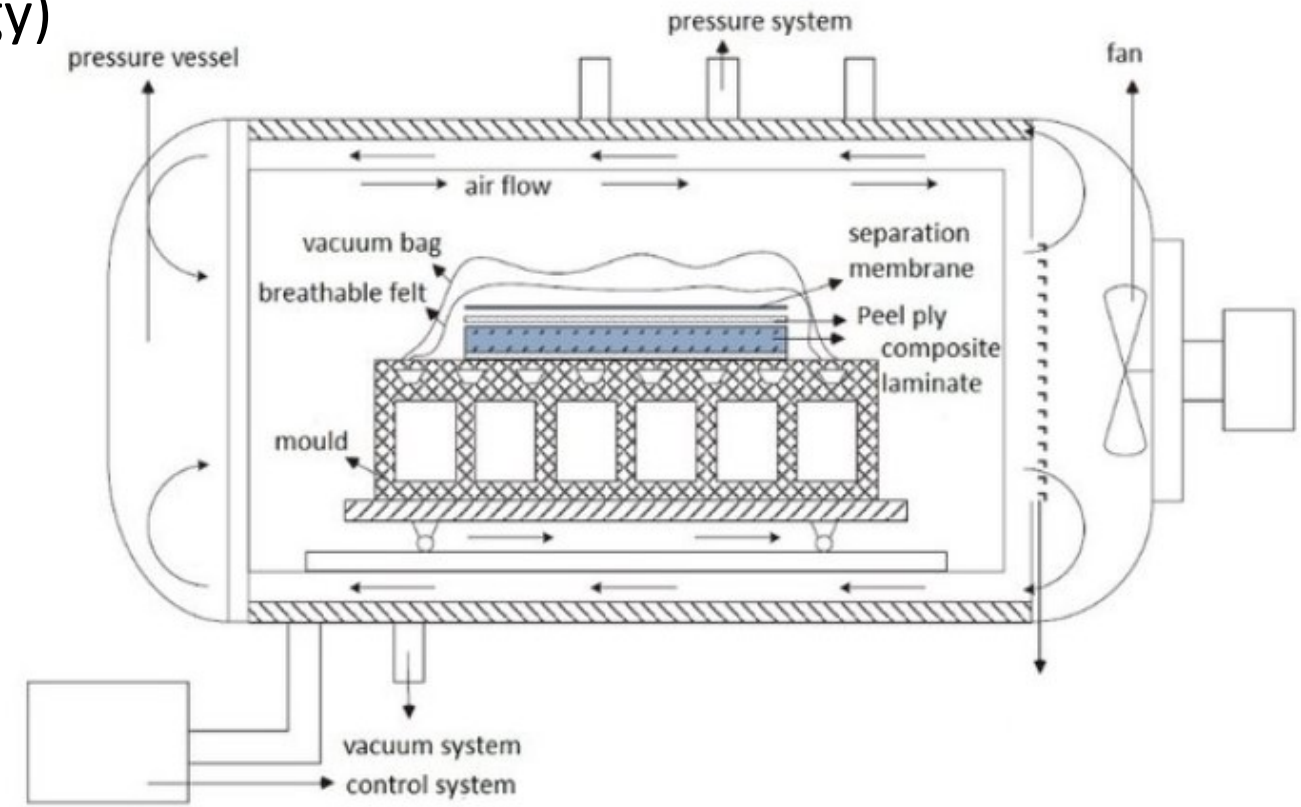
- Thermoset composites for structural parts: Resin Transfer Molding - RTM (low pressure)
  - High cost (tooling system)
  - Long cure cycles
  - Low mass-production
  - Draping to a 3D Preform



Source: Composite Integration - Resin Transfer Molding

MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

- Thermoset composites for structural parts: Autoclave process
  - High cost (tooling, equipment, energy)
  - Long cure cycles
  - Low mass-production
  - High cost of prepreg material
  - Labor cost: manual layup



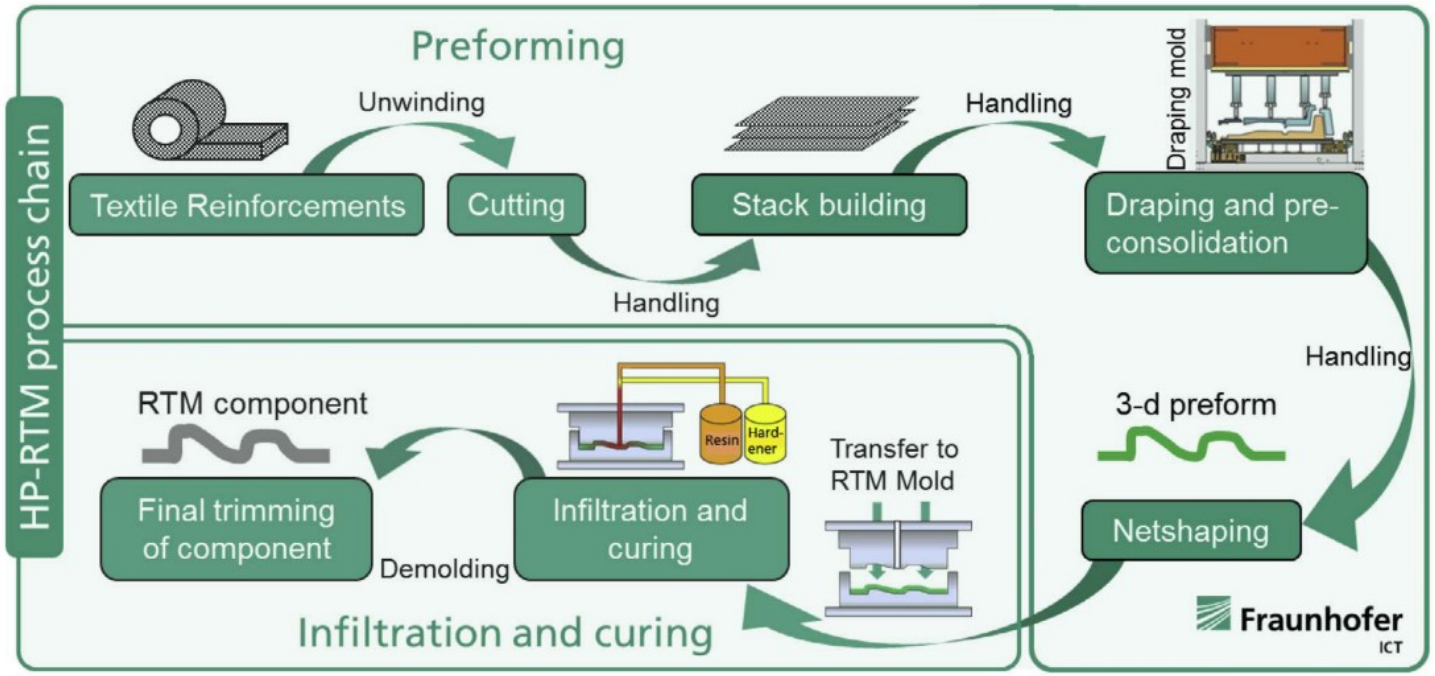
Source: XIANGWEN JU et al. Research on the manufacturing quality of co-cured hat-stiffened composite structure, 2021.

MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

- SNAP CURE materials:
  - Accelerated resin reactivity systems can be applied
    - High Pressure RTM
    - Wet Compression Molding
  - Prepregs
    - Hot Compression Molding
- Increased mass-production – 0.5 to 30 minutes/part
- Reduced manufacturing costs: short cycle-times
- High thickness parts without using autoclave -> lower production costs

MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

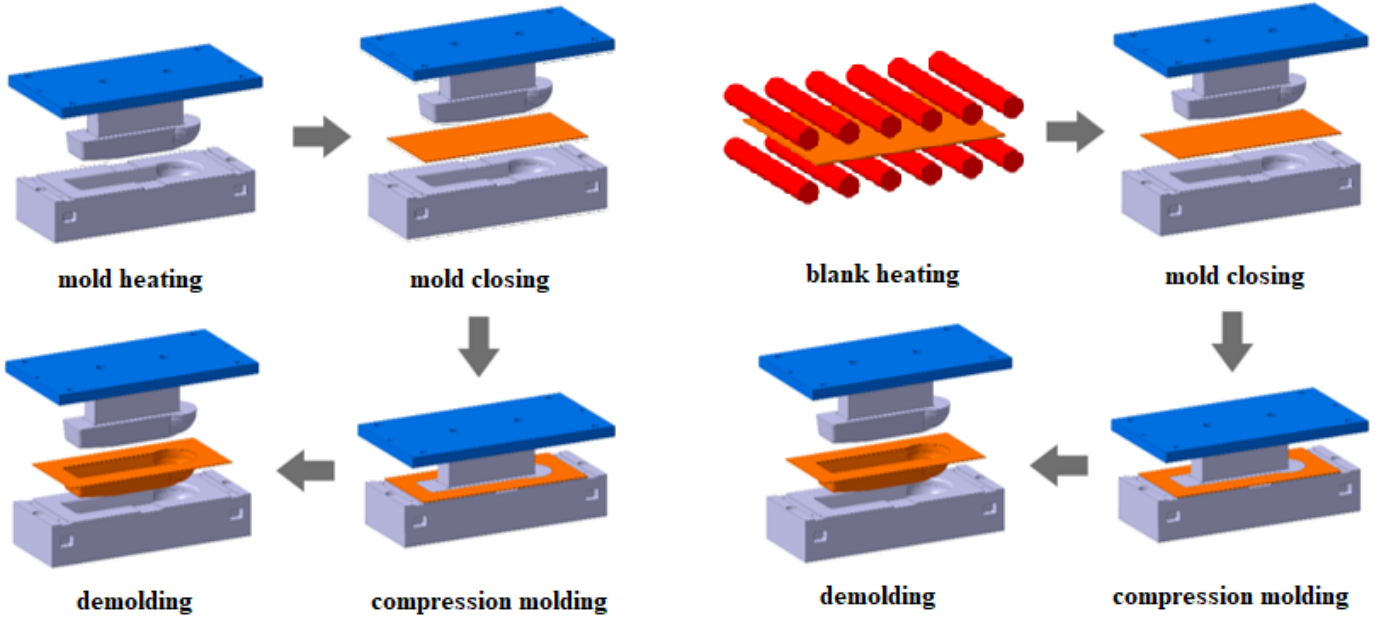
- Thermoset composites for structural parts: High Pressure Resin Transfer Molding (HP-RTM)
  - High cost (tooling system)
  - Draping to a 3D Preform
  - Rapid mold filling
    - Shorter cycle times
  - Accelerated resin reactivity system can be applied
    - Shorter cycle times
  - Increased production capacity



Source: RONDINA et al. Development of full carbon wheels for sport cars with high-volume technology, 2018.

MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

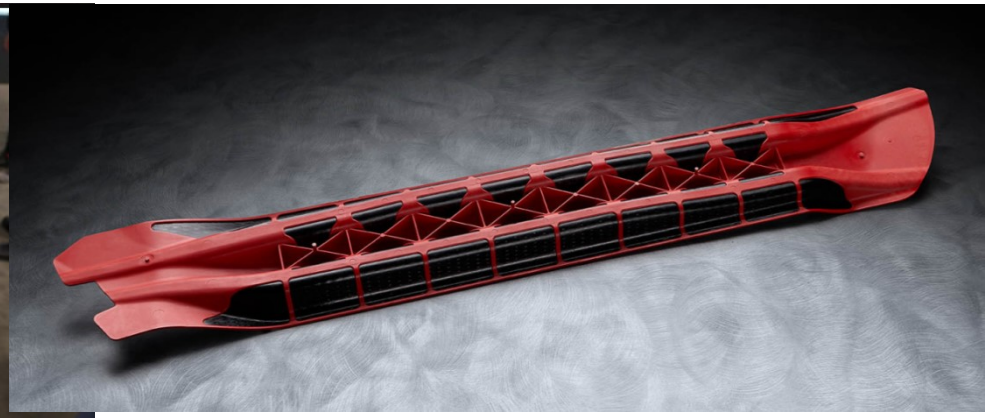
- Thermoset composites for structural parts: Hot Compression Molding
  - High cost (tooling system/equipment/heating system)
  - Hot press or heated tooling
  - Thicker parts: preform heating
  - Blank holder fixture
  - May be vacuum-assisted
  - Snap cure prepreg material
    - Shorter cycle times
  - No need to drape a 3D Preform
  - Increased production capacity



MANUFACTURING PROCESSES FOR STRUCTURAL PARTS

- Thermoplastic composites parts: Stamping forming + Overmolding
  - High cost (tooling system/equipment/heating system/cooling system)
  - Sheet heating system
  - Press or tooling cooling system
  - Overmolding process
    - Added stiffness
    - Enhanced part integration
  - Weight reduction
  - Improved strength
  - Improved crash-worthiness
  - Improved recyclability

Source: Engel, JEC Composites Paris 2022.



Source: DuPont Vizilon Thermoplastic Composite.

MATERIAL SELECTION

- Main market players: thermosseting epoxy resin / carbon fiber fast cure prepregs

Supplier	Prepreg	Reinforcement	% Resin mass content	Theoretical Cured Ply Thickness (mm)	Storage condition
Toray	E732	CF - Twill 2x2 3k 205 g/m²	42	0.210 (0.838 before cure)	6 months (-18 °C) 21 days (18 °C)
Toray	2700	CF - Plain weave T700S - 12KC 190 g/m²	42	0.210	24 months (-12 °C) 28 days (-12 to 30 °C)
Teijin	Q183	CF - Twill 2x2 / E IMS65 E23 24k / 196 g/m²	38	0.221	12 months (-18 °C) 30 days (23 °C)
Solvay	Solvalite 714	CF - Twill 2x2 3k SM / 245 g/m²	40	0.270	12 months (-18 °C) 30 days (21 °C)

Source: Supplier's datasheets.

MATERIAL SELECTION

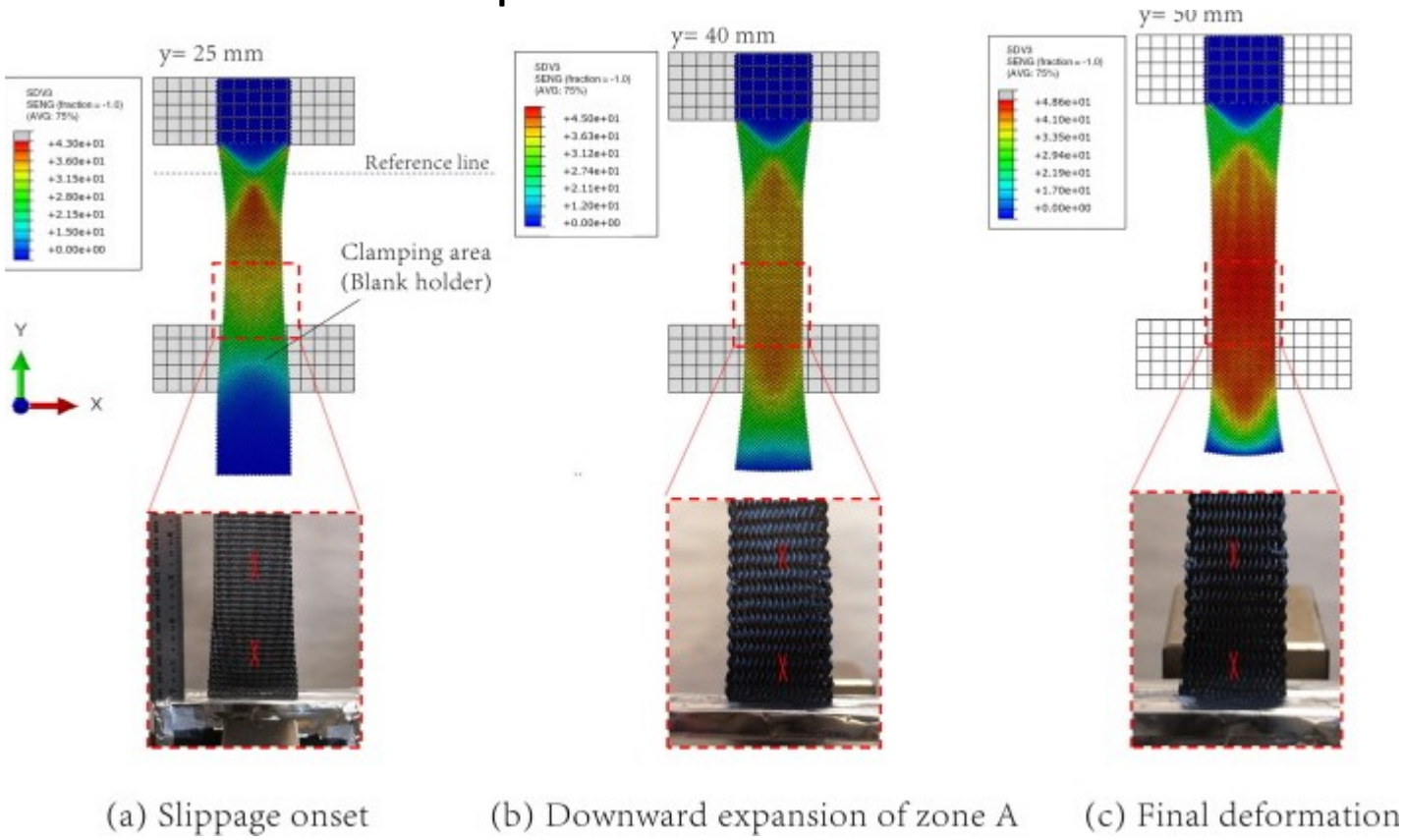
- Main market players: thermosseting epoxy resin / carbon fiber fast cure prepregs

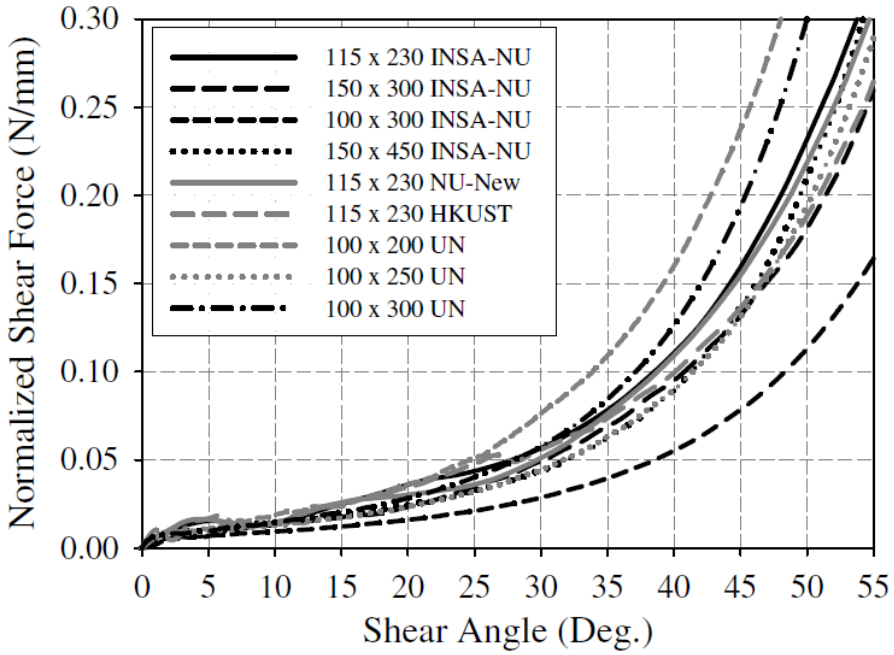
Supplier	Prepreg	T_g by DMA	Gel time	Compression Molding Processing
Toray	E732	Onset: 170 °C Peak: 190 °C	41 min (50 to 115 °C - 2 °C/min)	120 to 160 °C 20 to 4 min Pressure: 45 psi
Toray	2700	Onset: 163 °C	54 min (22 to 132 °C - 1.7 °C/min)	150 °C 5 min Pressure: -
Teijin	Q183	Onset: 182 °C	7 to 9 min	160 °C 20 min Pressure: 145 - 290 psi
Solvay	Solvalite 714	Onset: 165 °C	-	150 °C 10 min Pressure: 300 to 600 psi

Source: Supplier's datasheets.

MATERIAL BEHAVIOR CHARACTERIZATION

- Bias-extension test -> fabric specimen with fibers oriented at 45° in order to characterize the nonlinear in-plane shear behavior of the material





Source: CAO et al. Characterization of mechanical behavior of woven fabrics: experimental methods and benchmark results, 2008.

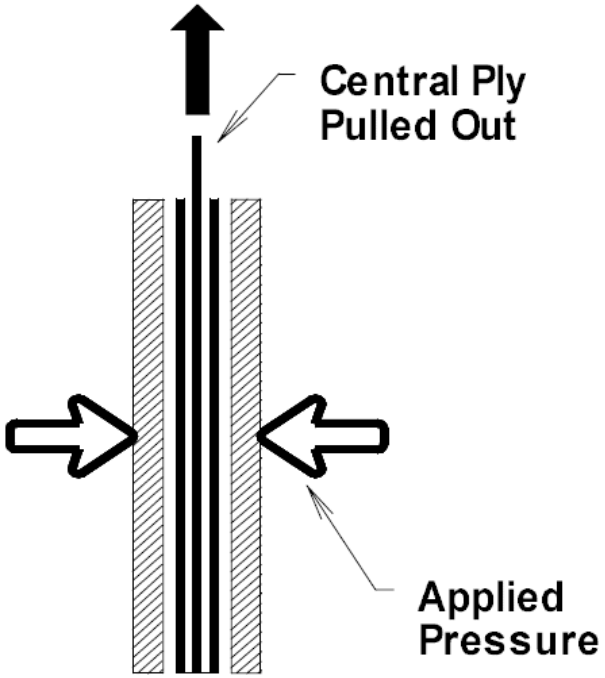
Source: RASHIDI A., MONTAZERIAN, H., MILANI, A.S. Slip-bias extension test: A characterization tool for understanding and modeling the effect of clamping conditions in forming of woven fabrics, 2021.

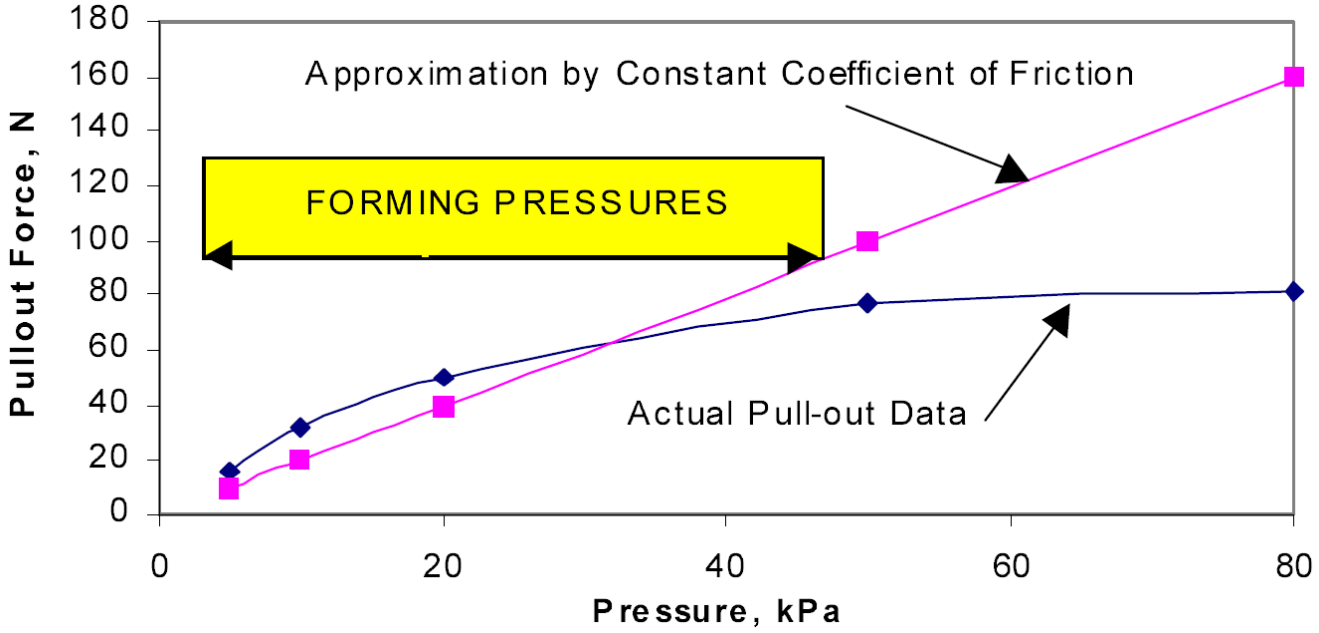
MATERIAL BEHAVIOR CHARACTERIZATION

- Increase the temperature -> reduces resin viscosity -> reduces stress to apply a given deformation during processing
- However, it may result in early curing before proper forming
- Preheating epoxy resins ▲ **60°C to 85°C** → **up to 94% drop in resin viscosity**
- Despite the ease of forming, the drop in resin viscosity can significantly affect the formation of defects such as wrinkling and resin squeeze-out. This factor also influences the shear suffered between the layers and the geometric reliability.

MATERIAL BEHAVIOR CHARACTERIZATION

- Pull-out test -> evaluate coefficient of friction between prepreg plies





Source: CARTWRIGHT et al. Some proposed experimental tests for use in finite element simulation of composite forming, 1999.

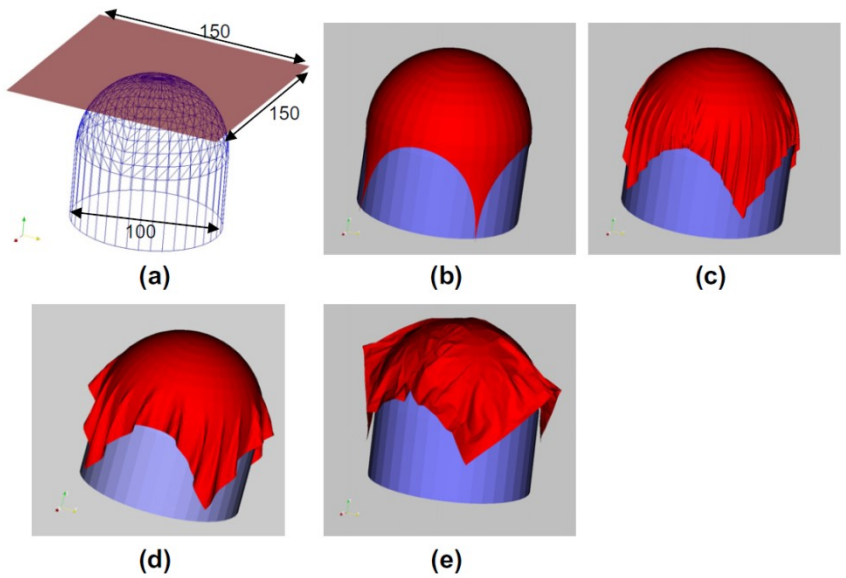
COMPRESSION MOLDING SIMULATION

- Formability and preform final quality result strongly depend on various factors:
  - type of reinforcement (type of fabric, number of layers, orientation);
  - type of process (punch and die, global or sequential stamping, diaphragm);
  - parameter settings (speed, tool, pressure, blank holder);
  - geometry (hemisphere, square, double dome, prism).
- Through simulation, you can perform as many analyses as needed, without consuming material or manufacturing tooling;
- Different material behaviors -> mechanical, chemical and thermal input properties
- Evaluate possible changes in geometry
- Process parameters -> press close speed, dwell times, duration of load application, blank holder optimization, optimum temperature

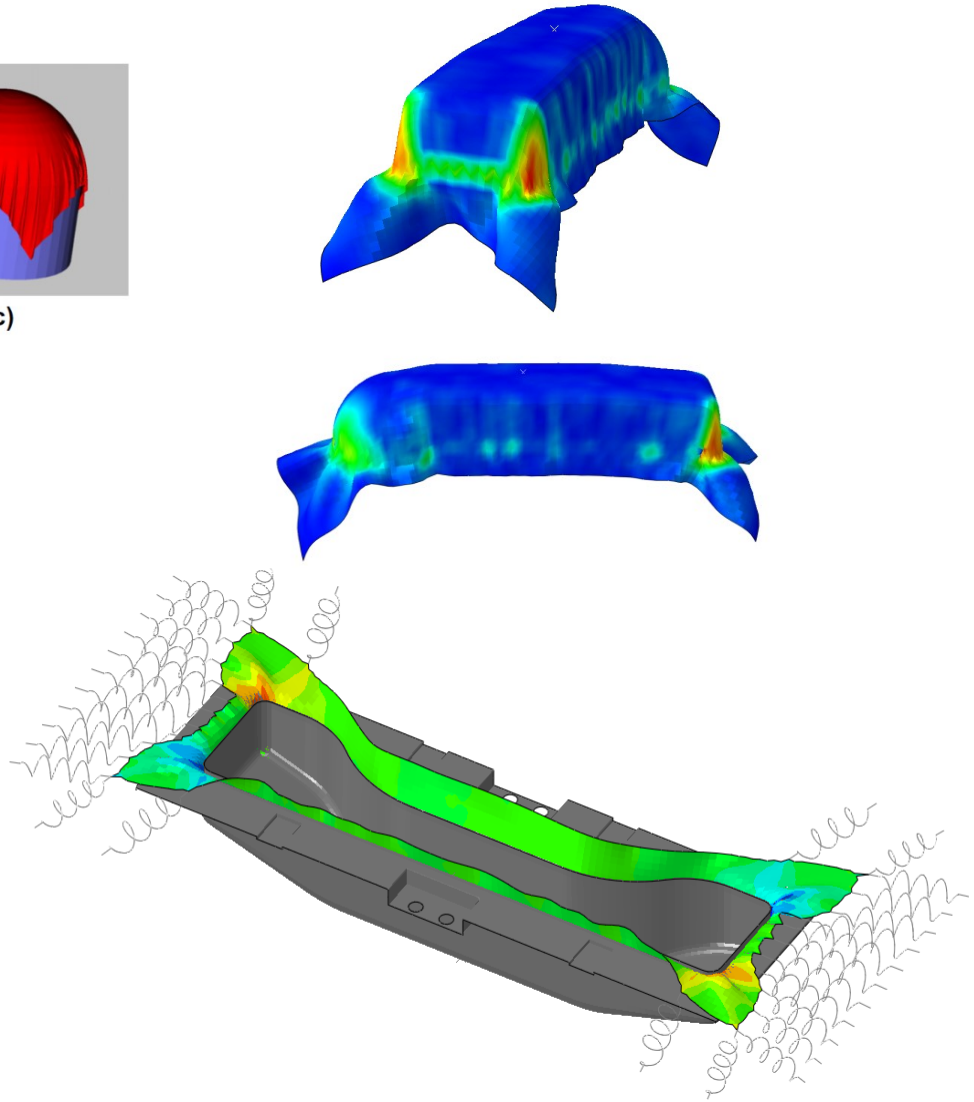
Raw material and tooling costs saving

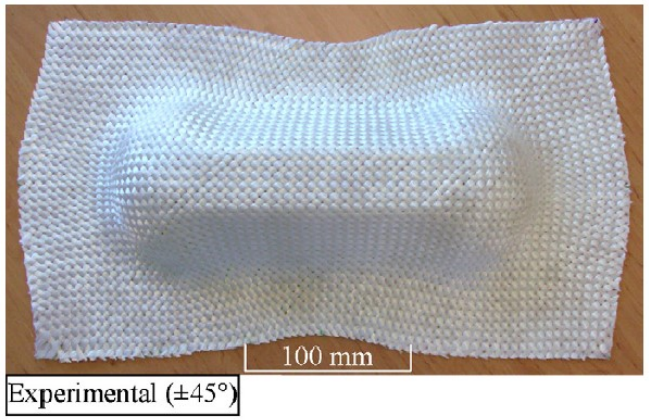
No trial and error – Processing time saving

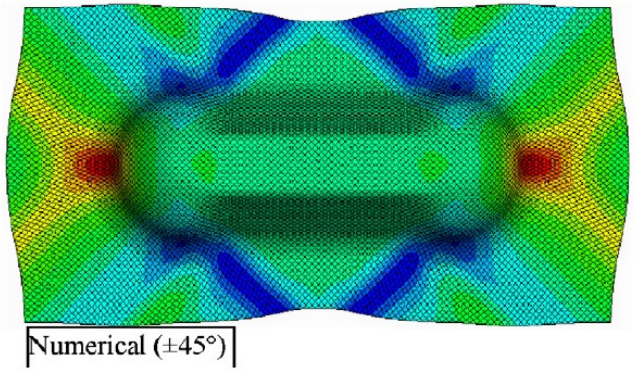
COMPRESSION MOLDING SIMULATION



Source: KHAN et al. Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark., 2010.

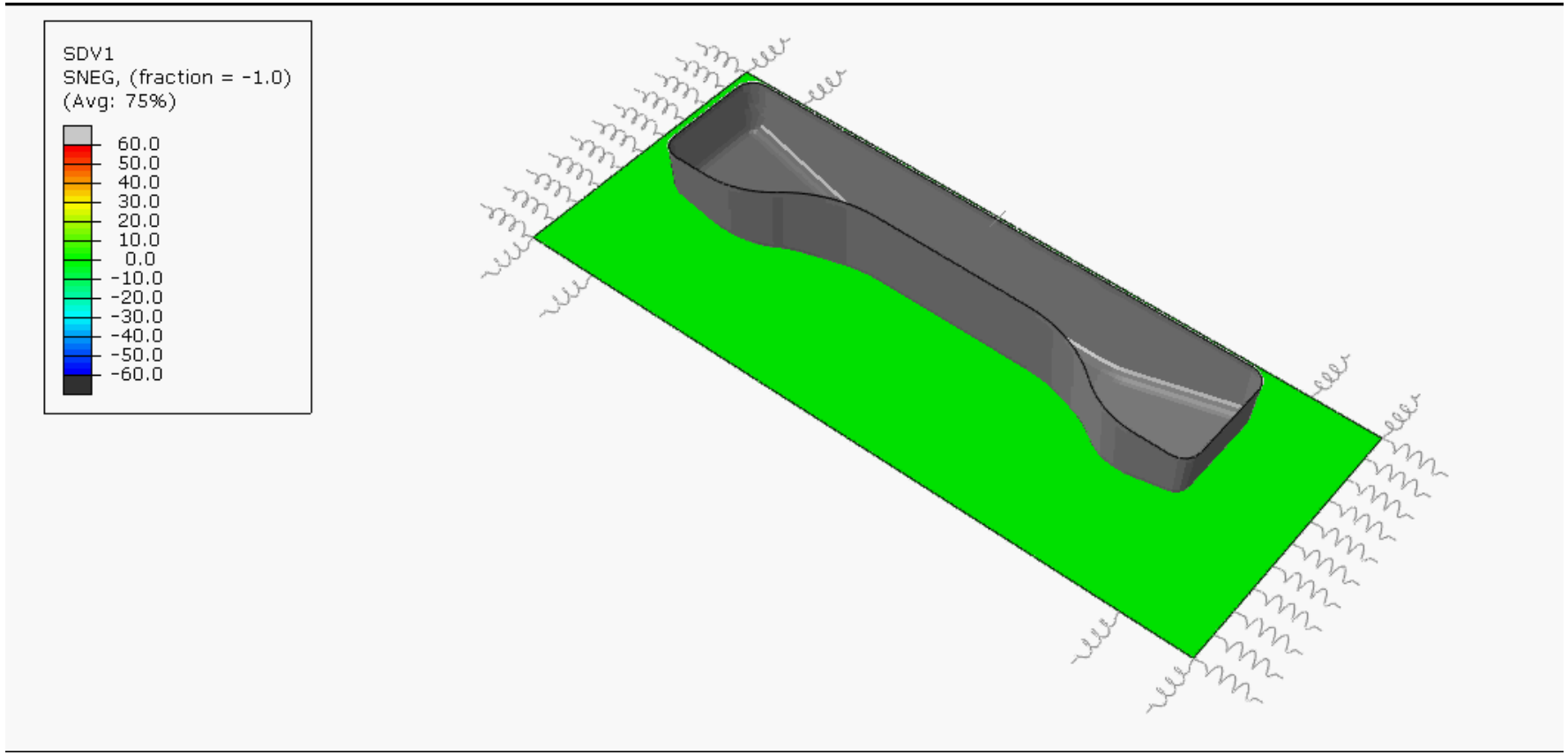






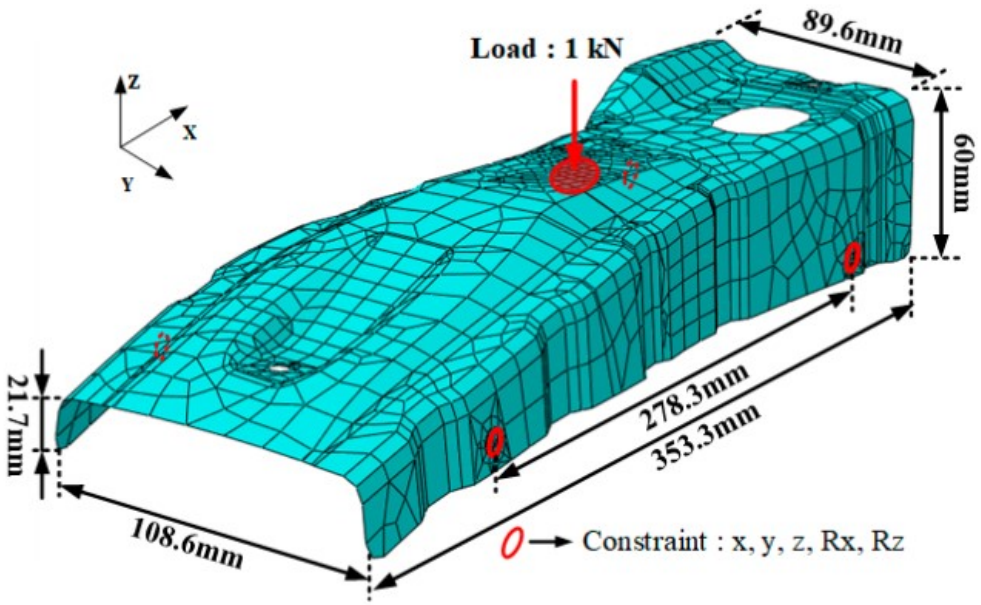
Source: BOISSE et al. Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffnesses, 2011.

EXAMPLE – PROCESS SIMULATION



STRUCUTRAL SIMULATION

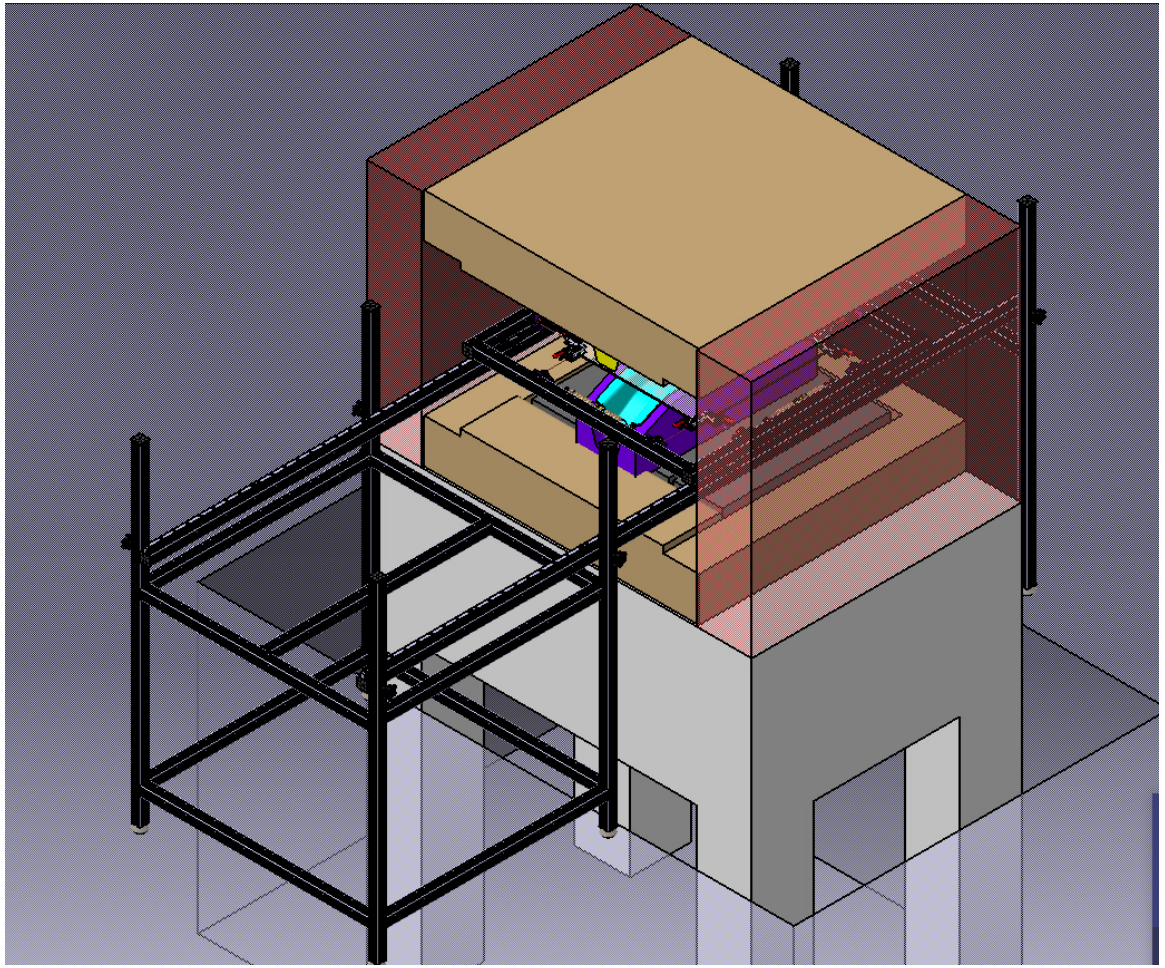
- Structural simulation:
  - load requirements
  - performance requirements
    - Strength (stress or strain limitation)
    - Stiffness (deflection limitation)
    - Life, energy absorption, fatigue, etc.
  - Boundary conditions / constraints
  - Failure criteria



Source: JEONG-MIN LEE et al. Design of lightweight CFRP automotive part as an alternative for steel part by thickness and lay-up optimization, 2019.

PRESS CONFIGURATION

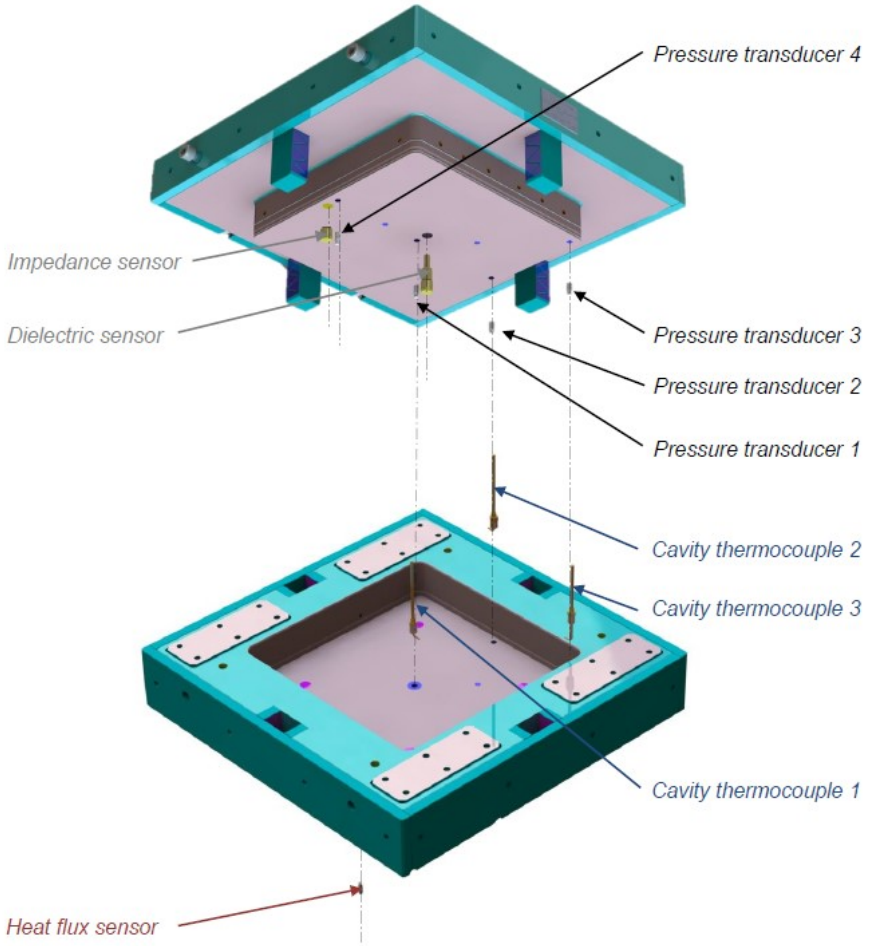
- Hydraulic, servo-mechanical, etc.
- Tonnelage range
- Temperature homogeneity / Heat distribution
- Fixing guides
- Thermal insulation
- Sensors: thermocouples / pressure transducers
- Heating system
- Cooling system
- Process control



PRESS CONFIGURATION

COMPRESSION MOLDING TOOLING

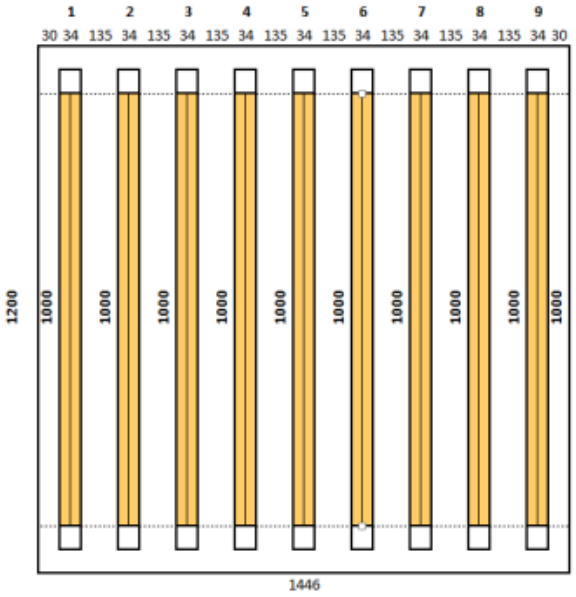
- Fixing configuration
- Temperature homogeneity / Heat distribution
- Pin and guides (match dies alignment)
- Stops (final part thickness guarantee)
- Sensors: thermocouples / pressure transducers
- Heating system
- Cooling system
- Blank holder fixture



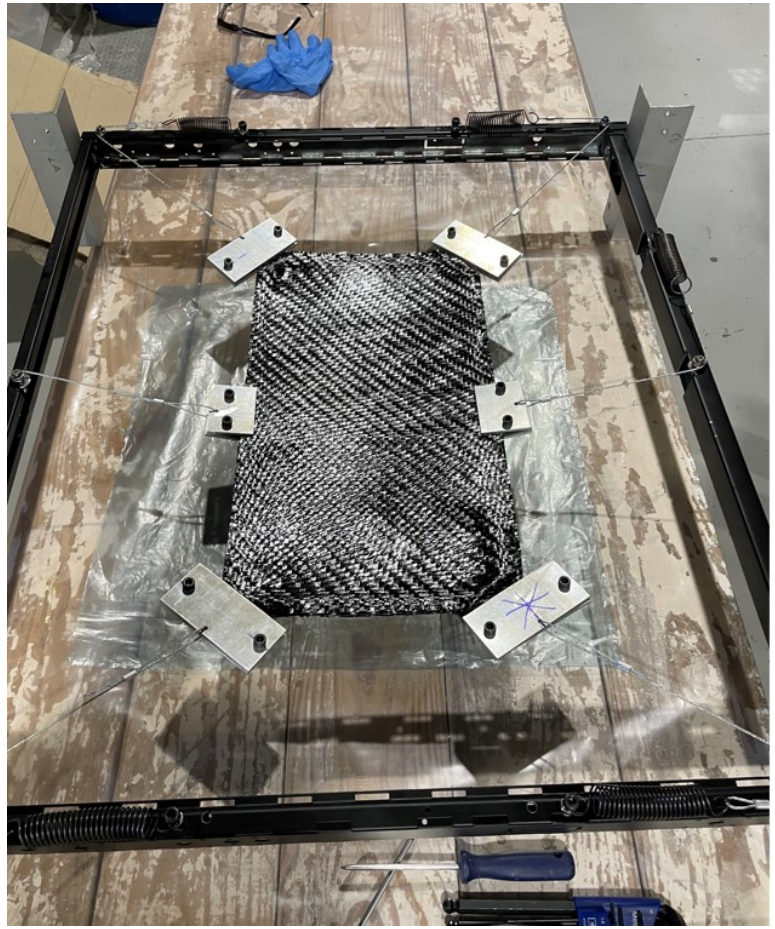
Source: PASCO AND KENDALL. Characterisation of the thermoset prepreg compression moulding process, 2016.

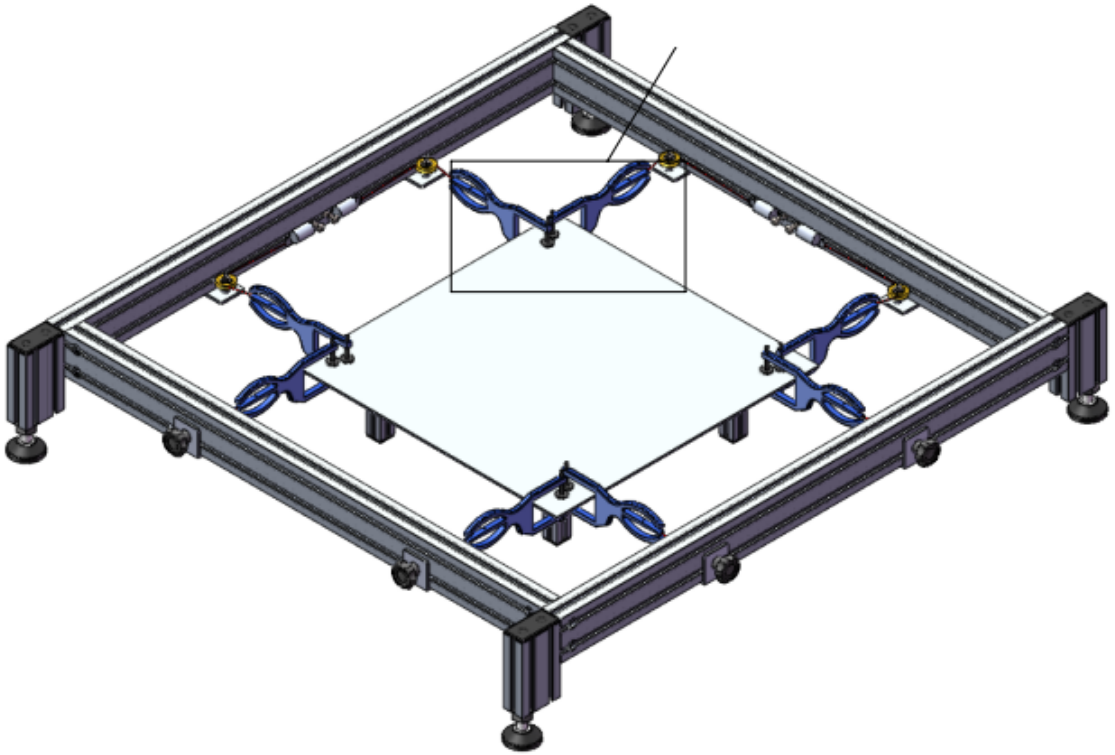
MATERIAL PREHEATING SYSTEM

- The greater the thickness of the blank, the more recommendable preheating it

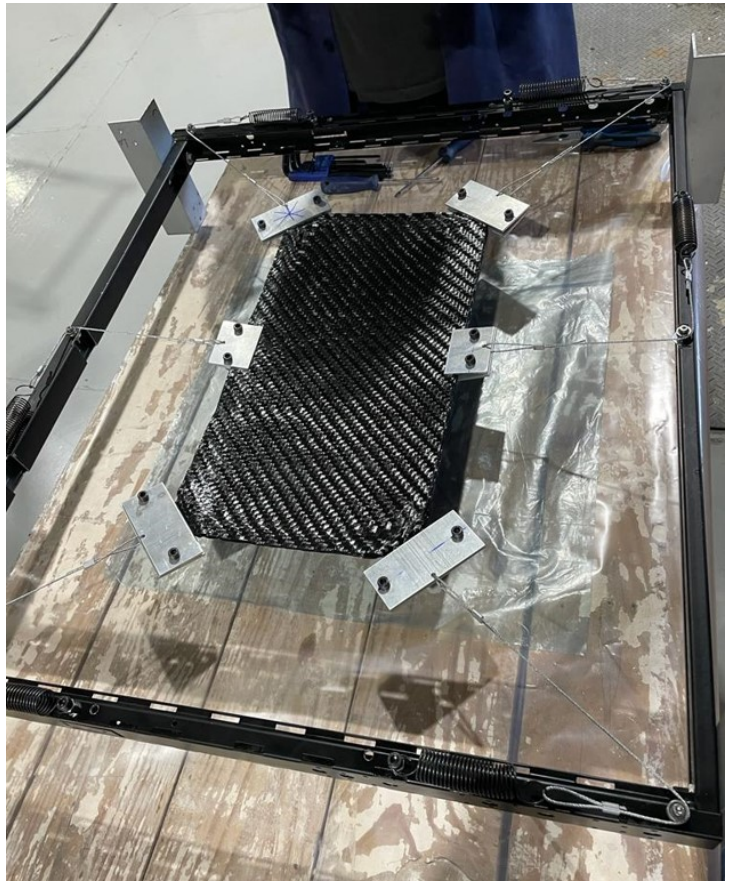


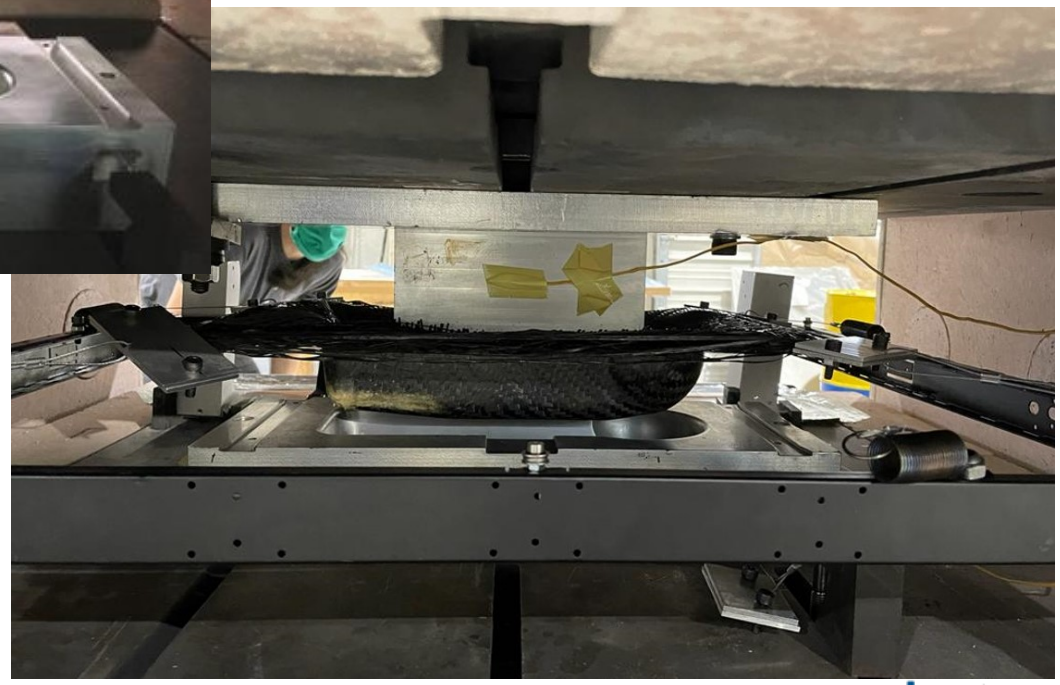
BLANK HOLDER FIXTURE





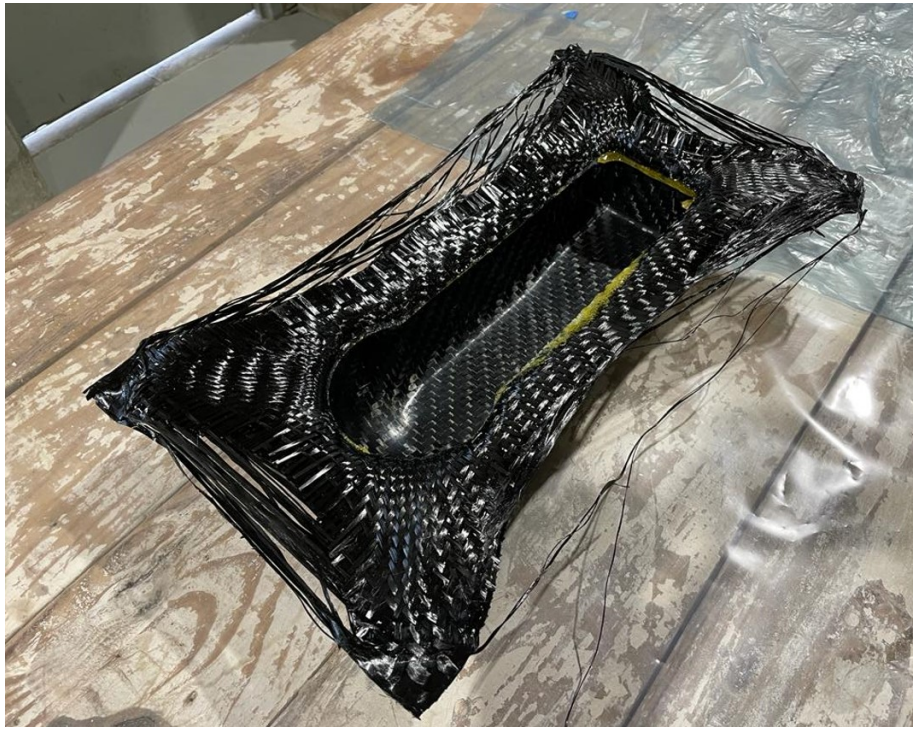
PROCESS STUDY - EXPERIMENTAL TRYOUT





PROCESS STUDY - EXPERIMENTAL TRYOUT

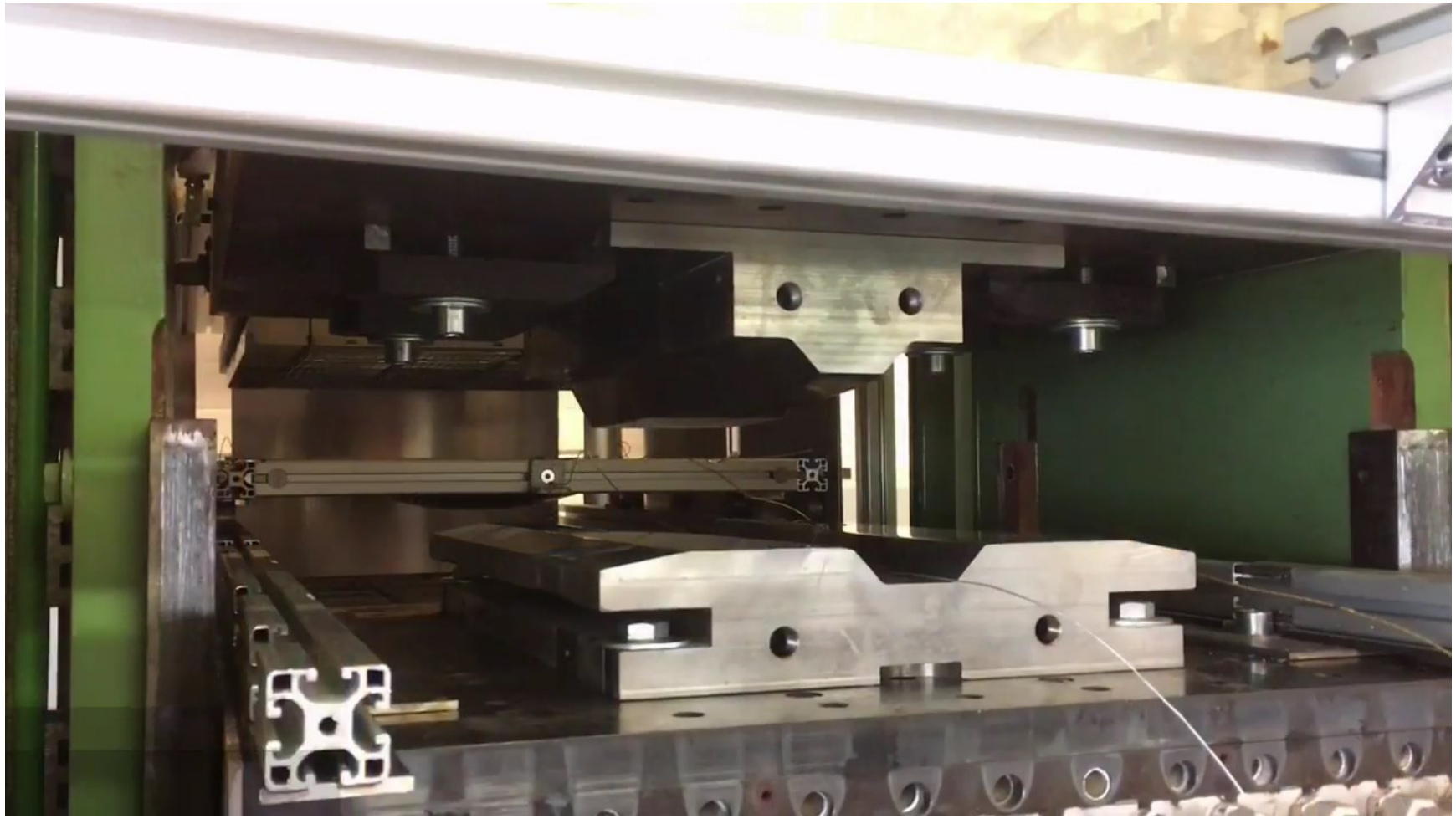
Resin squeezing



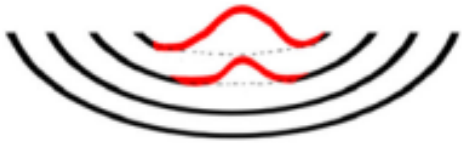
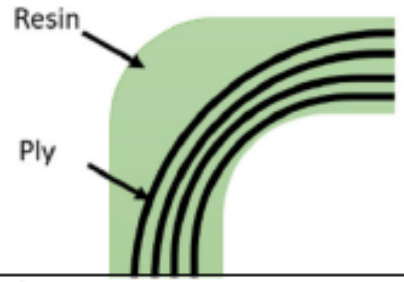
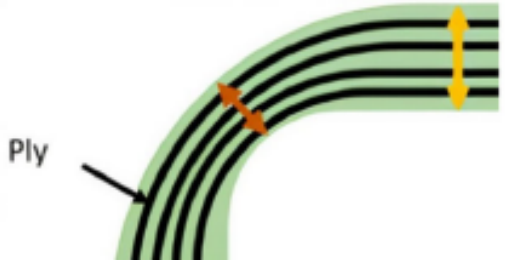
Wrinkles

14 plies (0.4 mm per ply) – Final part 5.6 mm

COMPRESSION MOLDING PROCESS

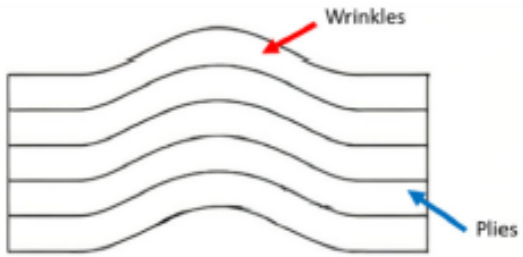
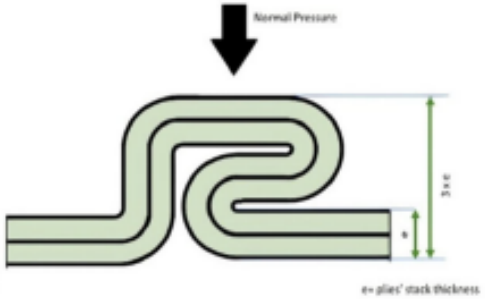
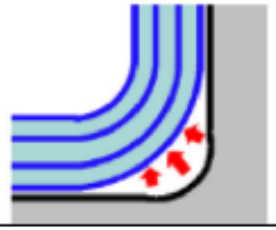


COMPRESSION MOLDED PART DEFECTS

Multi-layer defects			
Defect definition / description		**Terms used**	**Illustrations +Generalized term suggested**
Out of plane deformation			
Corner defects :	Having different radii between the interlayers and the outer layer at the corner resulting in the inner layer buckling to cope with the compressive force.	Buckling [66, 70]; Wrinkles[20, 67, 108]; Misalignment or misorientation [30]	Wrinkles 
	Different radii induce tensile forces on the outer layers forcing them to move to the internal layer and squeezing the resin out. So, we have fabric piling at the inter part and resin-rich are at the outer part.	Resin squeezing [70][71]	Resin squeezing 
	The thickness is at its minimum at the corner tip due to the interlayer friction making it difficult for the plies to inter slip.	Thickness reduction [75, 76]	Thickness reduction 

Source: AZZOUZ et al. Composite preforming defects: a review and a classification, 2021.

COMPRESSION MOLDED PART DEFECTS

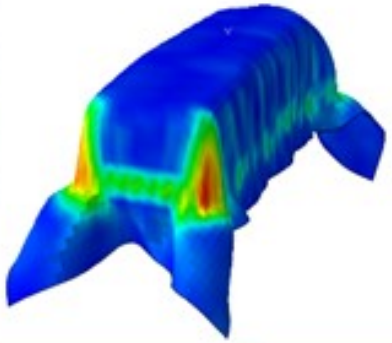
Multi-layer defects		
Defect definition / description	**Terms used**	**Illustrations +Generalized term suggested**
The stack of the fabric changes its shape to an out-of-plane curve. This deformation can affect all the layers or only a certain group and not the rest of the plies.	Wrinkles[3, 5, 9–12, 57, 78, 84, 88][109]; Waviness ; Shear buckling[90]	Wrinkles: The most frequented use of the term 
After the curve of the wrinkles is formed, normal forces applied on the stack of layers can result in the curve sides collapsing on the other, multiplying the thickness of the local area depending on the number of layers folded.	Folds [44] [81]	Folds 
When the group of plies retreat or resist the forming of the angle to obtain a part where the radius is bigger than the geometry desired.	Bridging [109][30][106][50]	Bridging 

Source: AZZOUZ et al. Composite preforming defects: a review and a classification, 2021.

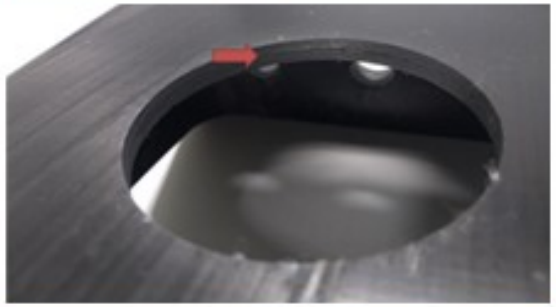
COMPRESSION MOLDED PART DEFECTS

Fibre distortion and wrinkling

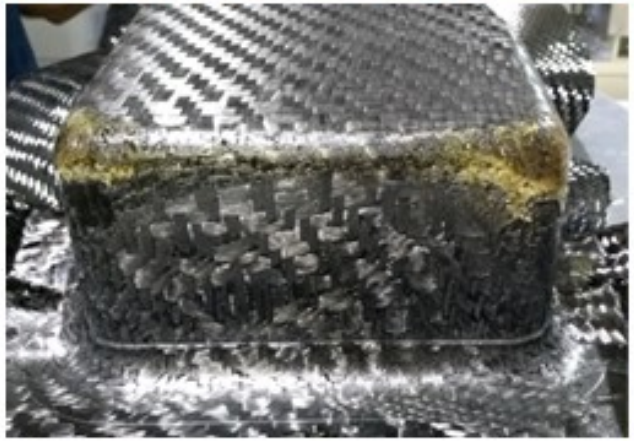
Fibre rupture and distortion angle



Delamination through a hole

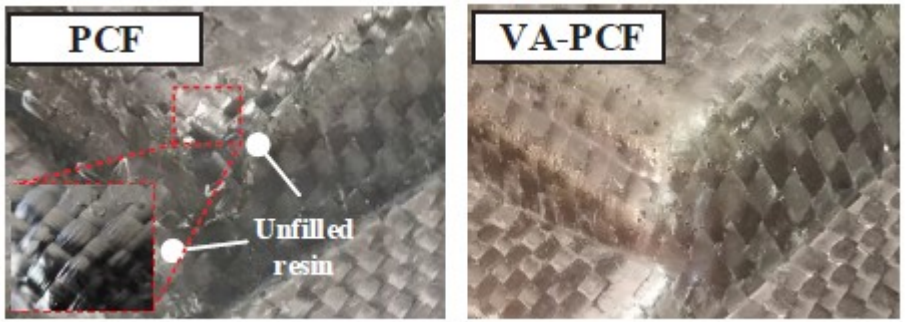


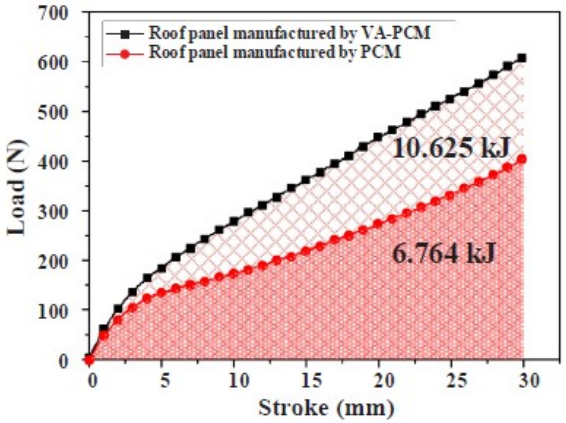
Low material compaction/cure and resin rich region

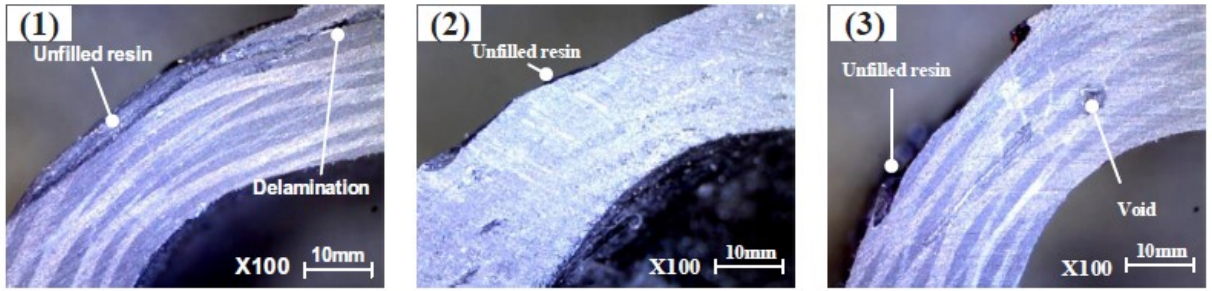


High curvature regions with resin accumulation

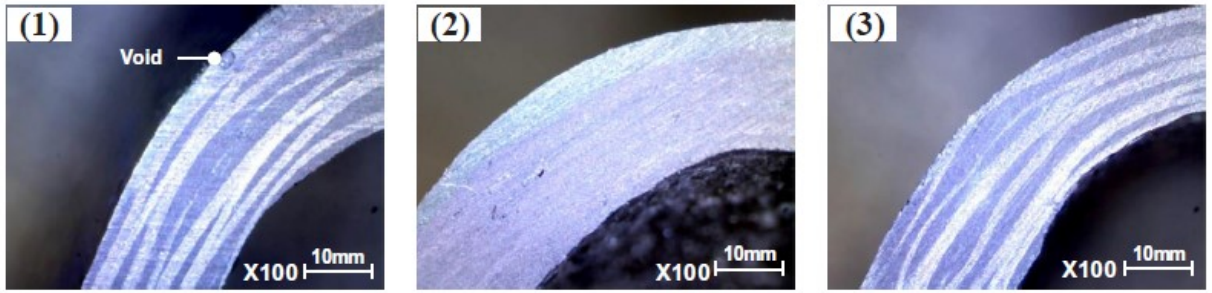
VACUUM ASSISTED COMPRESSION MOLDING







(a) Roof panel manufactured by PCM process



(b) Roof panel manufactured by VA-PCM process

Source: JEONG-MIN LEE et al. Development of vacuum-assisted prepreg compression molding for production of automotive roof panels, 2019.

FINAL REMARKS

- Final remarks

Thank you for your attention!

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