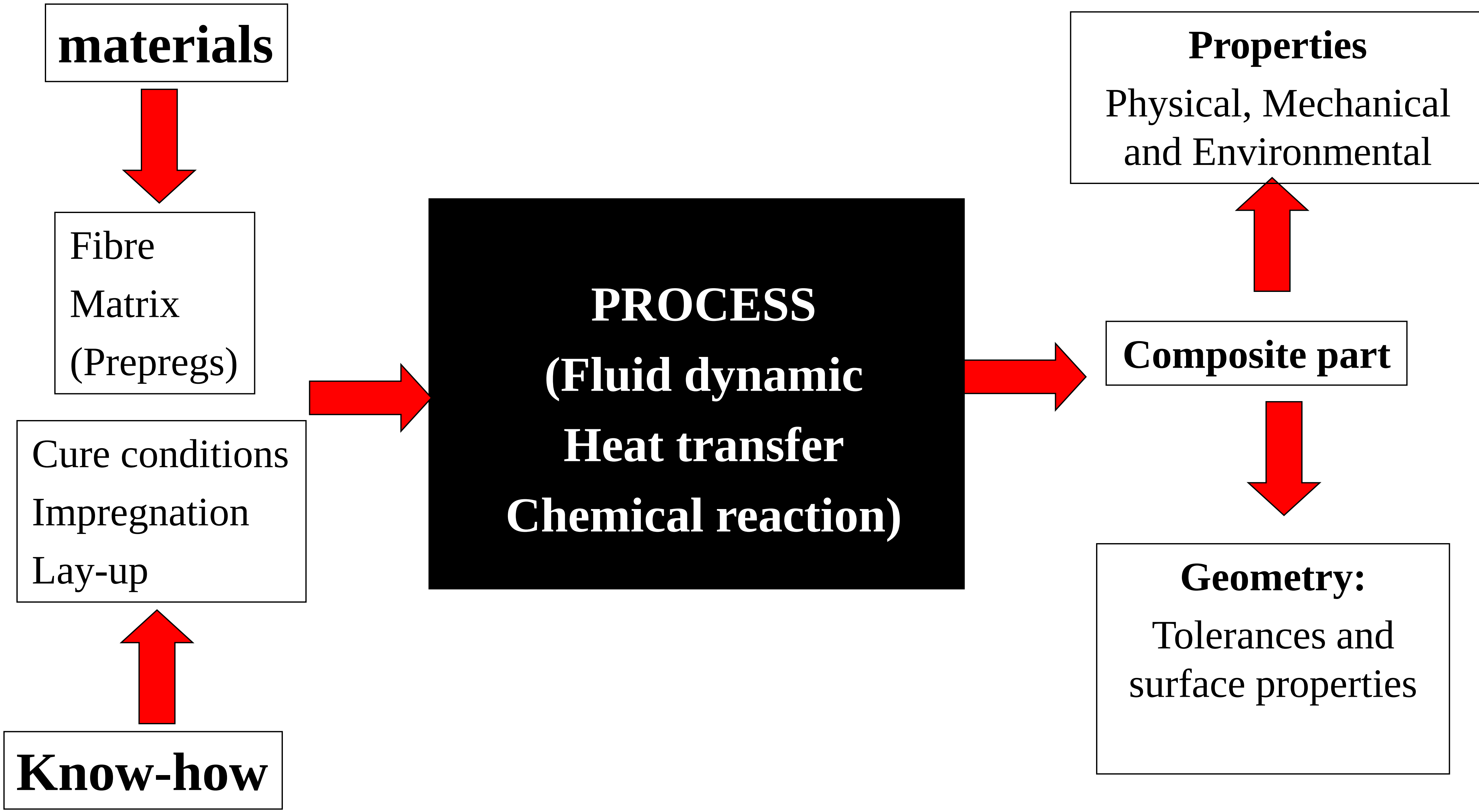
Fabrication processes of **thermosetting matrix** composite materials

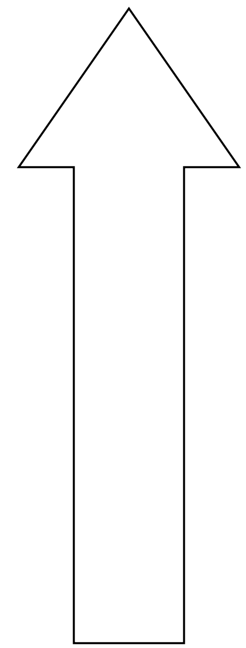


Fabrication processes of composite materials

(Additive manufacturing processes)

- Autoclave lamination
- Filament winding
- Resin Transfer Moulding, Pultrusion
- VARI, Resin infusion
- Hand lay-up and SMC
- spray-up and BMC (discontinuous fibers)

High performances

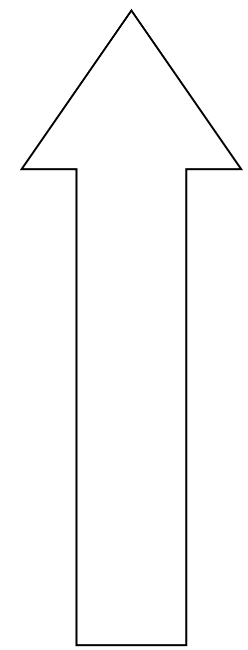


Low Performances

Fabrication processes of composite materials

(Additive manufacturing processes)

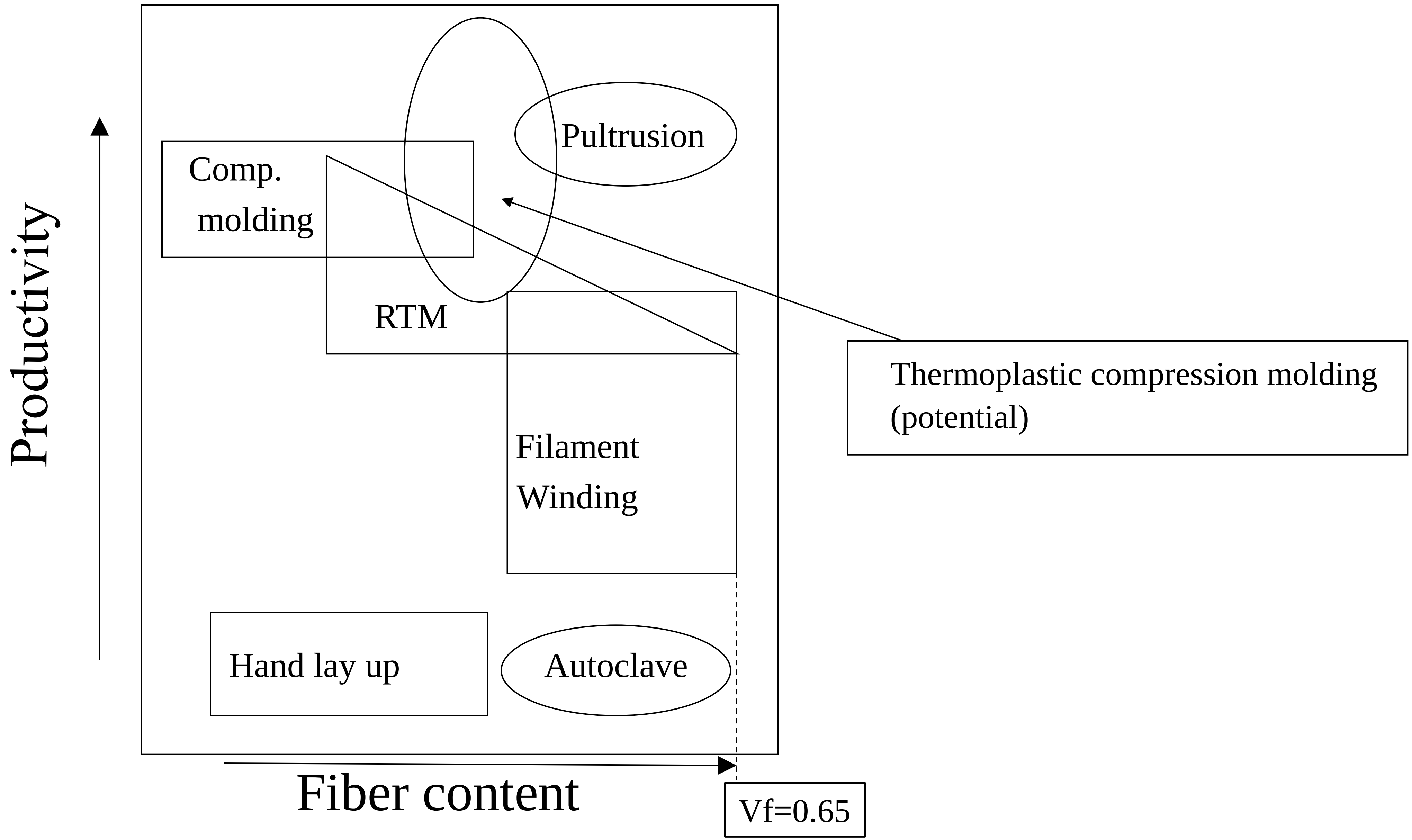
High costs



Low costs

- Autoclave lamination
- Filament winding
- Resin Transfer Moulding, Pultrusion
- VARI, Resin infusion
- Hand lay-up and SMC
- spray-up and BMC (discontinuous fibers)

Manufacturing of fiber reinforced plastic



Chemical and physical phenomena occurring in all technologies

Fibre Impregnation → Fluid dynamics

Heating and curing → Heat transfer and cure kinetics

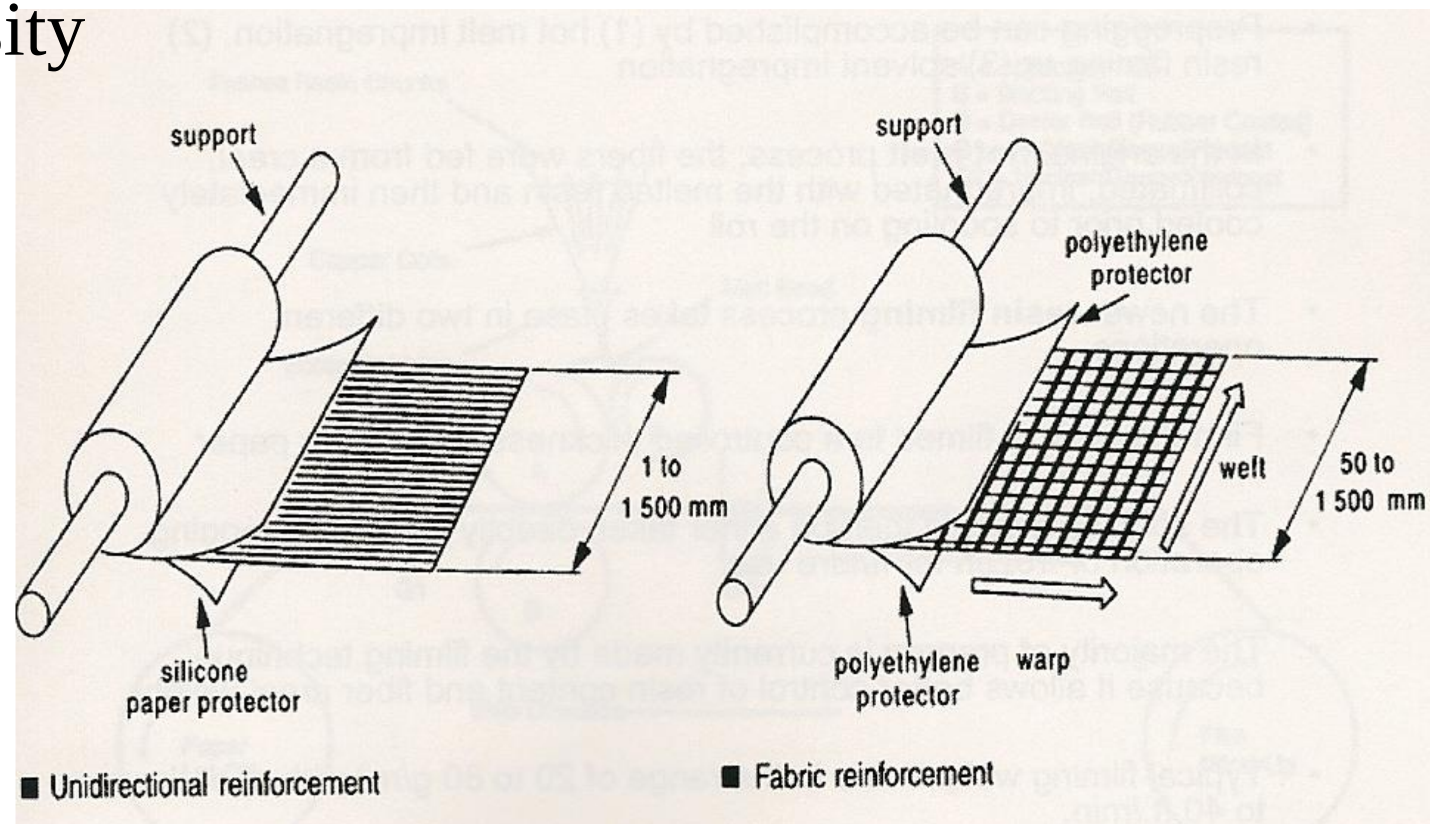
Residual stresses → Mechanics of materials and viscoelasticity

Autoclave lamination

- Lamination= manual or automated stacking layer by layer of UD (or fabric) laminae, using uncured resin.
- The so-called “prepregs” are used
- Autoclave = an oven in which it is possible to control temperature and pressure (8 bar)
- The curing cycle consists of a program of temperature and pressure devoted to polymerization of resin and reduction of defects (voids, tolerances, etc.) below a threshold depending on the component
- It is mainly used to produce advanced composite with carbon and Kevlar fibers and with epoxy resins

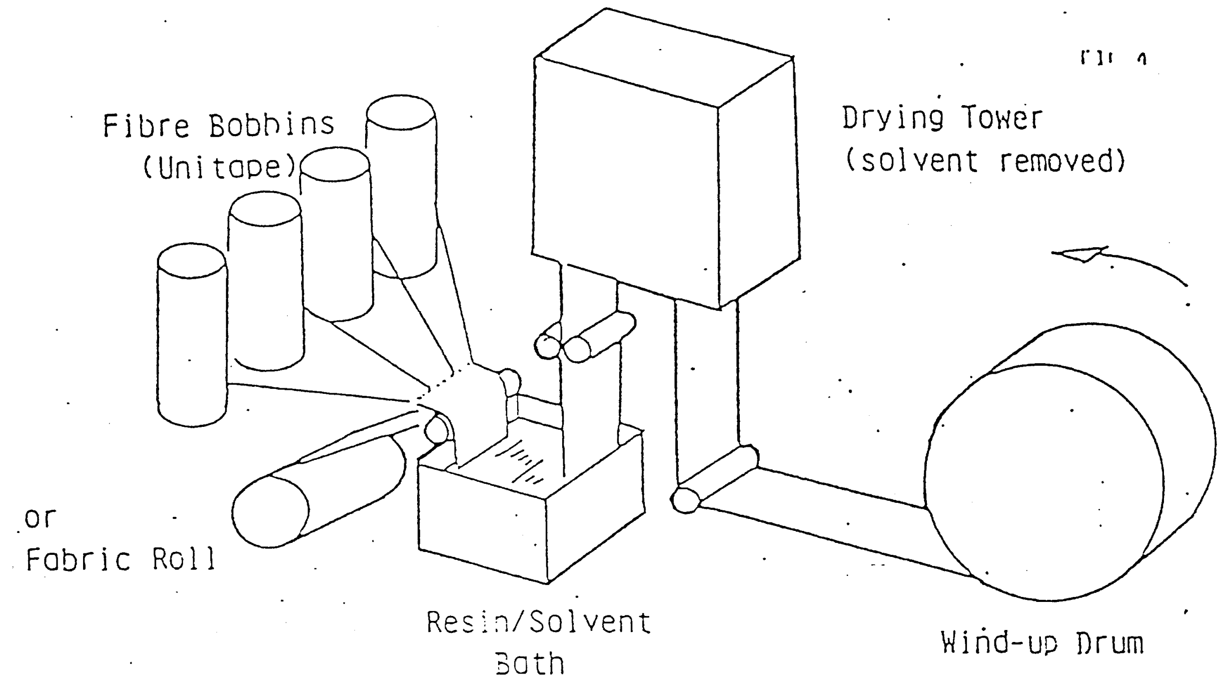
Prepregs

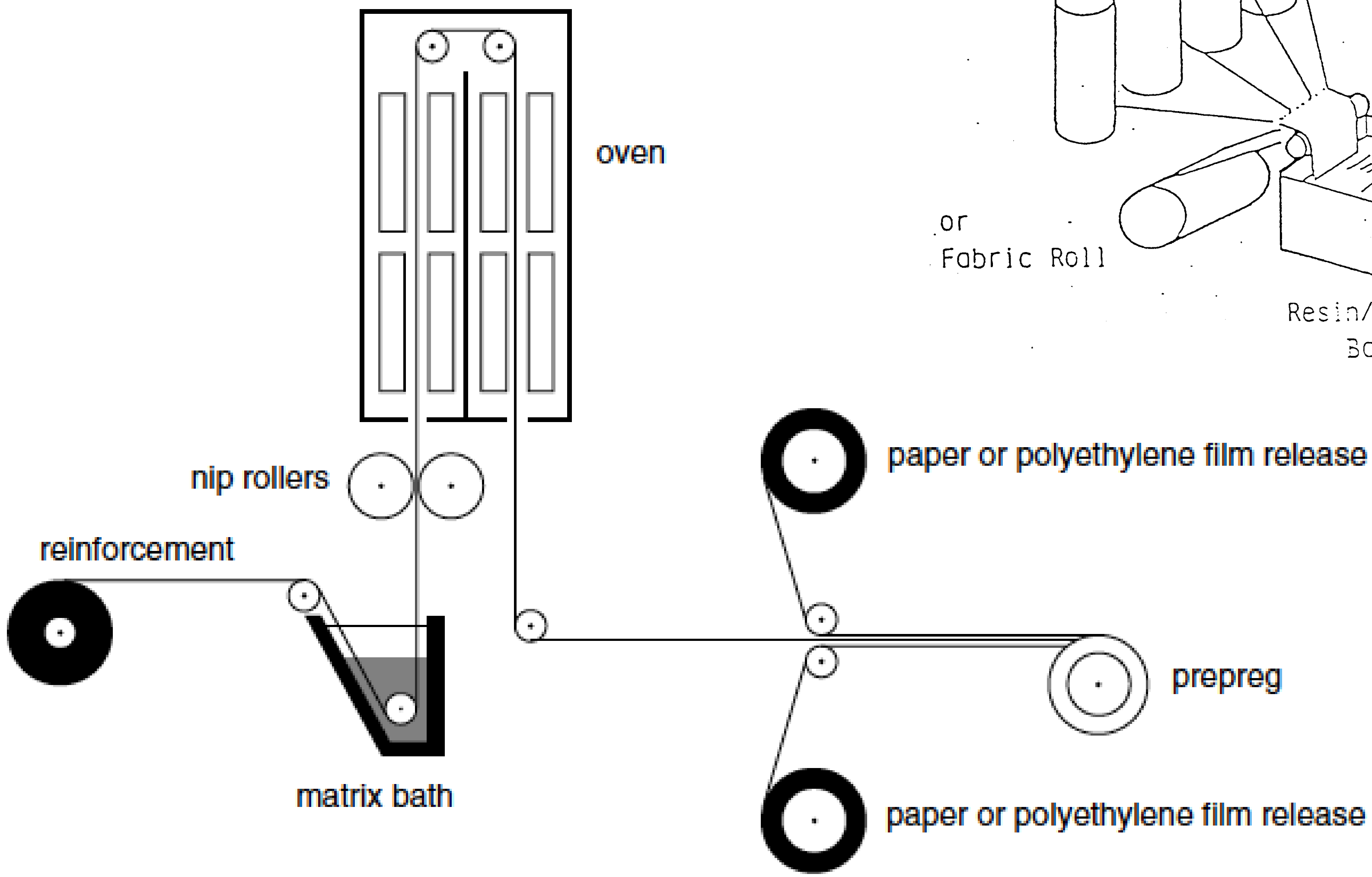
- Laminae made of fibres impregnated with resin (thickness= a few tens of mm, width from 1.25 cm to 150 cm)
- The reinforcement can be unidirectional (tape) or a fabric (woven)
- The resin is characterized at room temperature by a very high viscosity



Prepregs fabrication by solvent impregnation

– The fibers go through a bath where the resin is in solution in a solvent and subsequently between rollers that regulate the amount applied. The solvent is then removed in a dryer



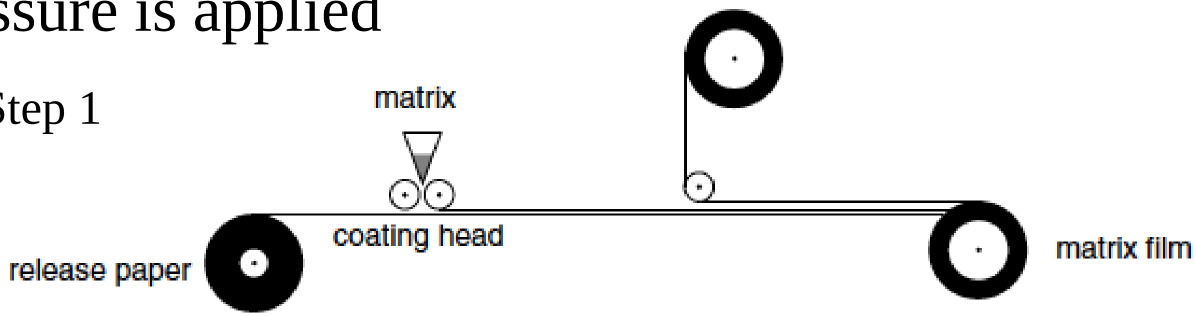


Prepreg fabrication by melt impregnation

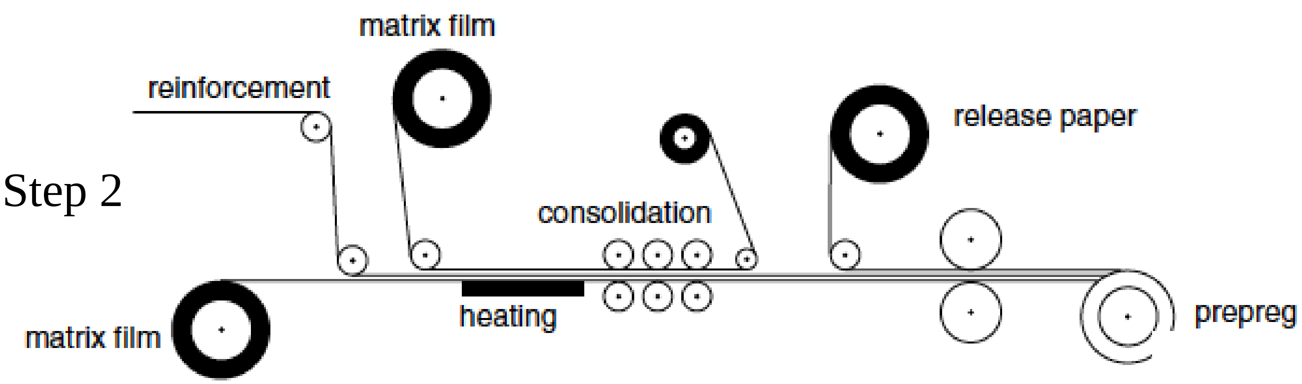
Step 1: a resin film of constant thickness is applied on a release paper.

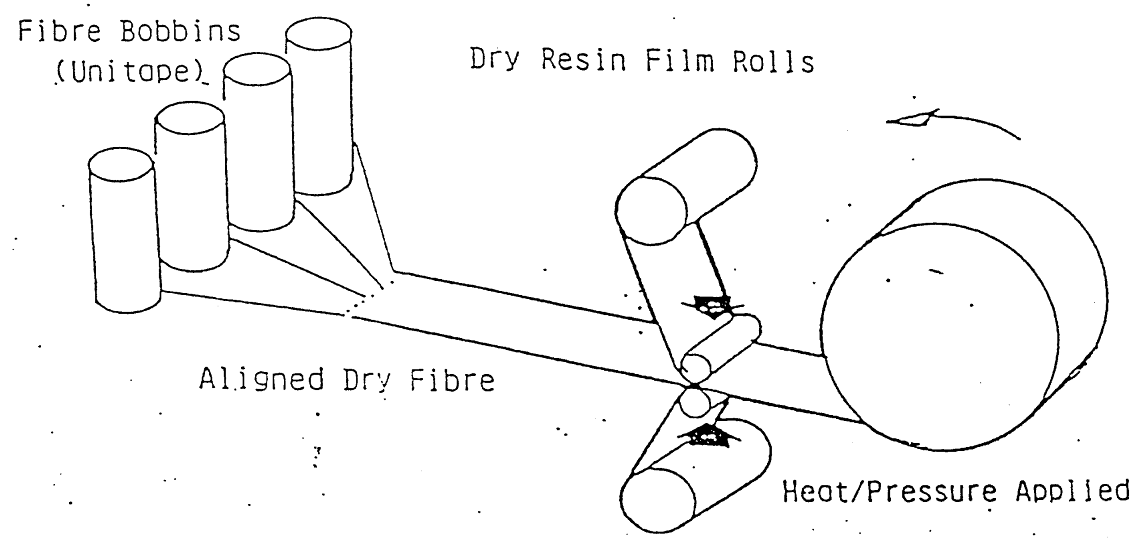
Step 2: is transferred on fibres (fabric or tapes) going through heated rolls where also pressure is applied

Step 1



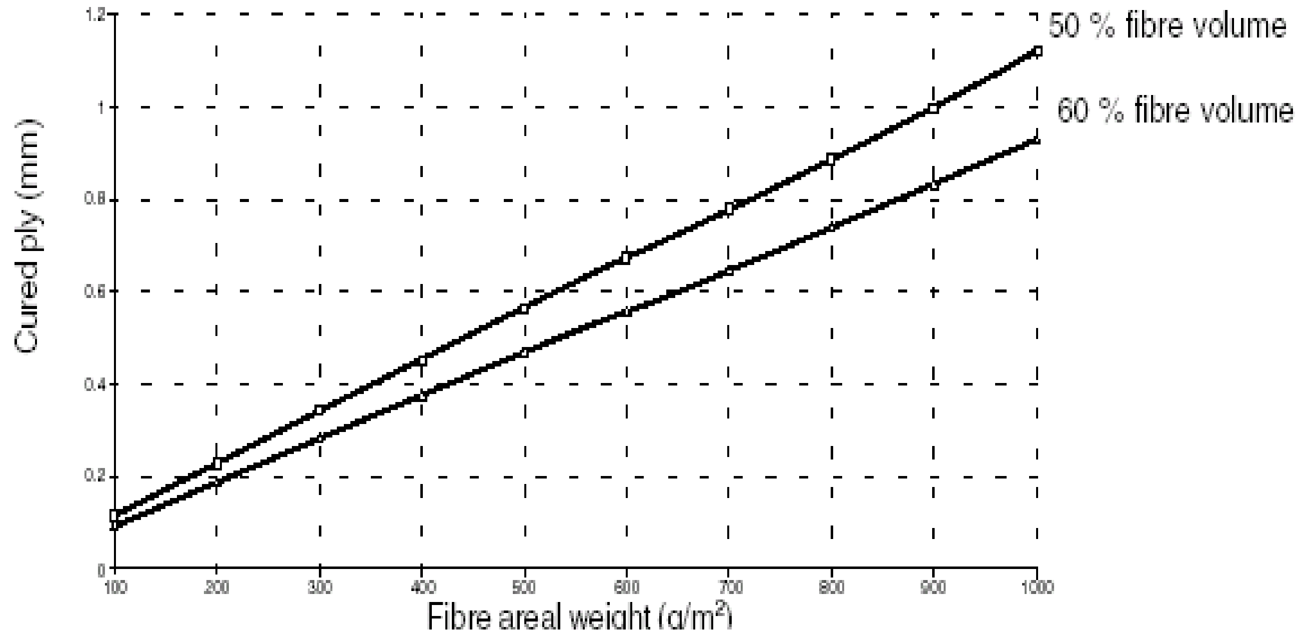
Step 2

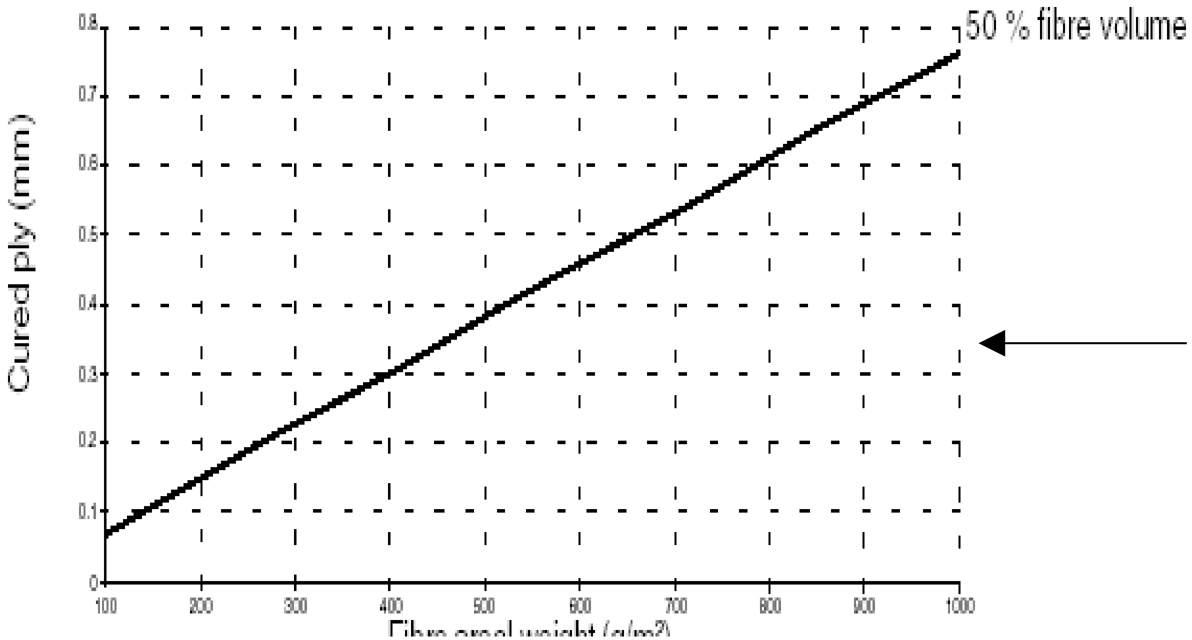




Ply thickness as a function of areal weight (surface density)

Epoxy carbon HS





Epoxy/glass

Why prepregs are used?

- Optimal control on the ratio between resin and hardener
- Uniform resin distribution on the surface and through the thickness
- Lay up with different fiber orientation and complex shapes can be obtained

↓

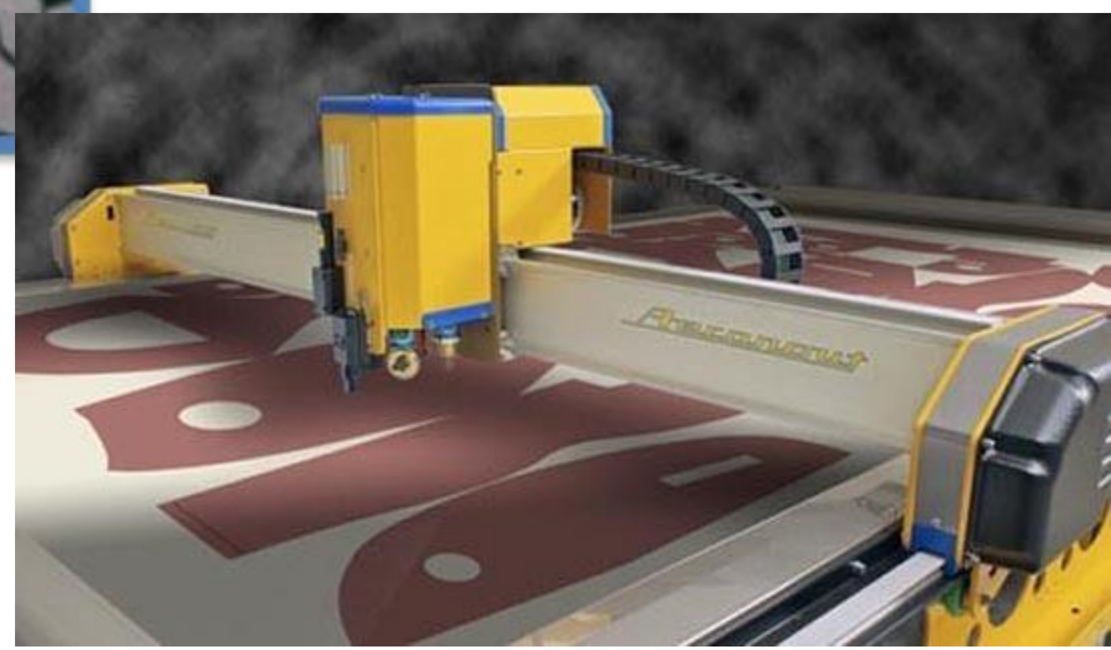
Better control on:

- the final composite properties,
- its homogeneity
- ripetibility of mechanical properties

Lay-up in clean room

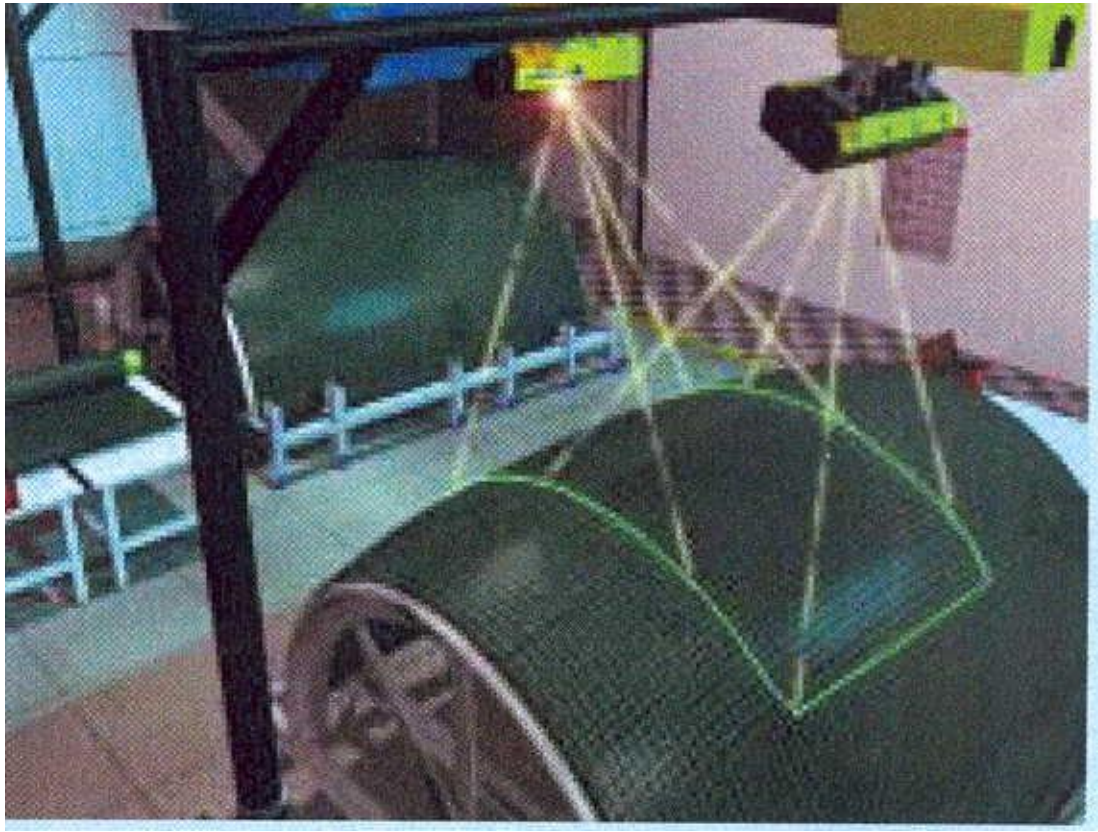
1. The prepregs are stored at about -20 ° C. After extraction they must be kept at room temperature in their packaging films for at least 24 h, so avoiding moisture condensation
2. Prepreg cutting
   - Manual
   - Automatic
   - Fiber placement machine (automatic cutting and lay up)
3. Lay up on tools
4. vacuum bagging → consolidation and void removal are promoted

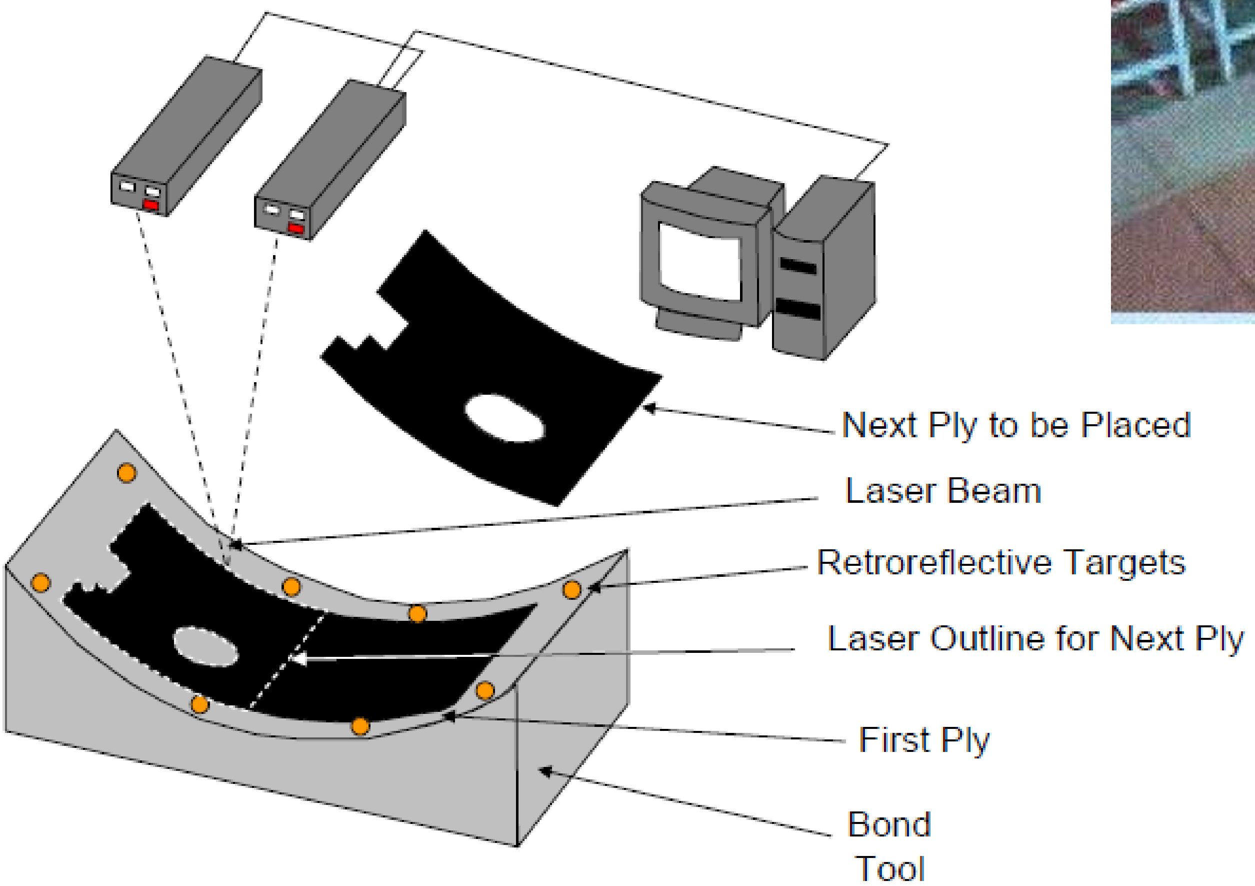
Prepreg cutting



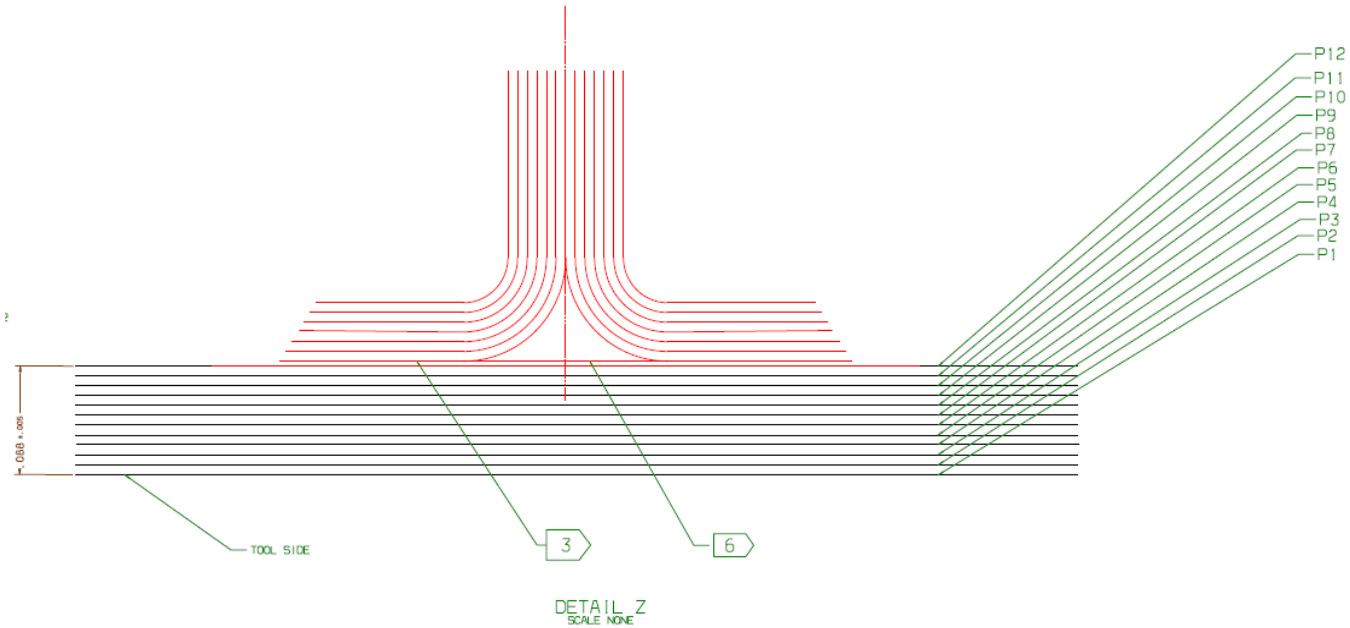
Laser projectors for proper lamina placement on tools

- Accuracy between 0.3 and 1 mm
- Data transferred from CAD
- The ply table provides the stacking sequence



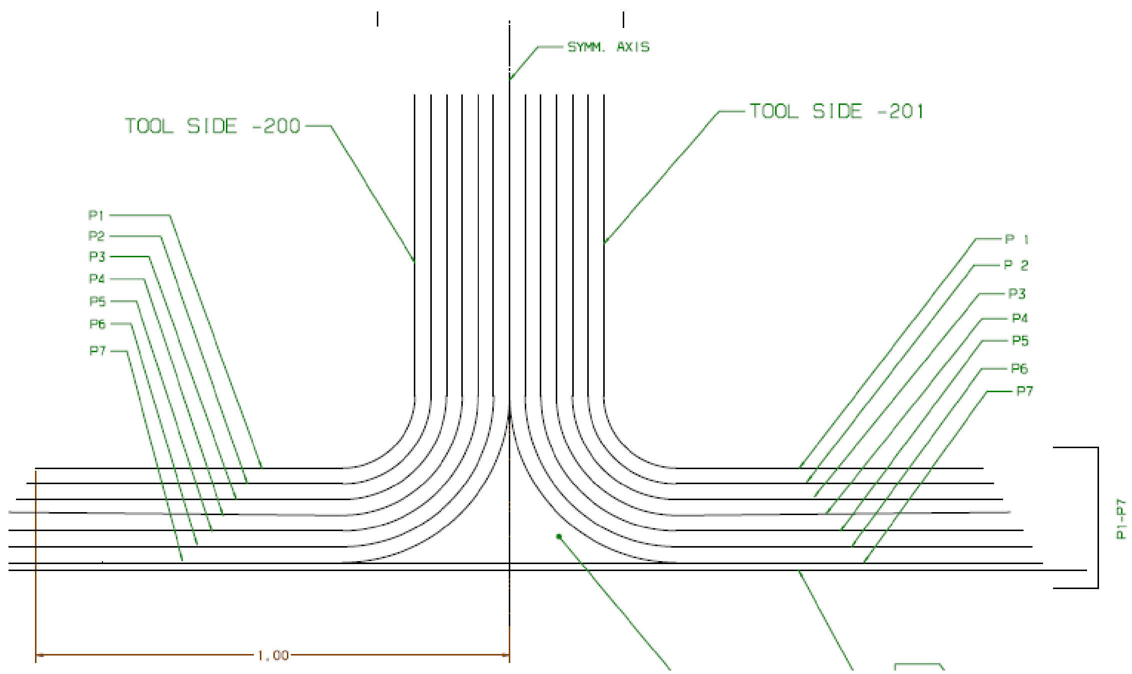


Ply Table



ply table: bottom laminate

COMPOSITE PART OR IDENTIFYING NUMBER	PLY (P) NUMBER OR COMPONENT PART OR IDENTIFYING NUMBER	MARTERIAL	TAPE FIBER ORIENTATION
-200	P1	2	45
	P2		-45
	P3		90
	P4		0
	P5		45
	P6		-45
	P7		-45
	P8		45
	P9		0
	P10		90
	P11		-45
	P12		45



ply table: stringer

COMPOSITE PART OR IDENTIFYING NUMBER	PLY (P) NUMBER OR COMPONENT PART OR IDENTIFYING NUMBER	MARTERIAL	TAPE FIBER ORIENTATION
-200	P1	2	45
	P2		-45
	P3		0
	P4		90
	P5		0
	P6		-45
	P7		45
-201	P1		45
	P2		-45
	P3		0
	P4		90
	P5		0
	P6		-45
	P7		45
-202	5	6	N/A

Hand lay up and automated fiber placement

Hand lay up:
•Limited access to large tools
•Lay up rate: about 1-3 kg/h

fiber placement machine (simultaneous cutting and laying up of prepregs)

Lay up rate: 25 kg/h today, up to 40 kg/h perspective

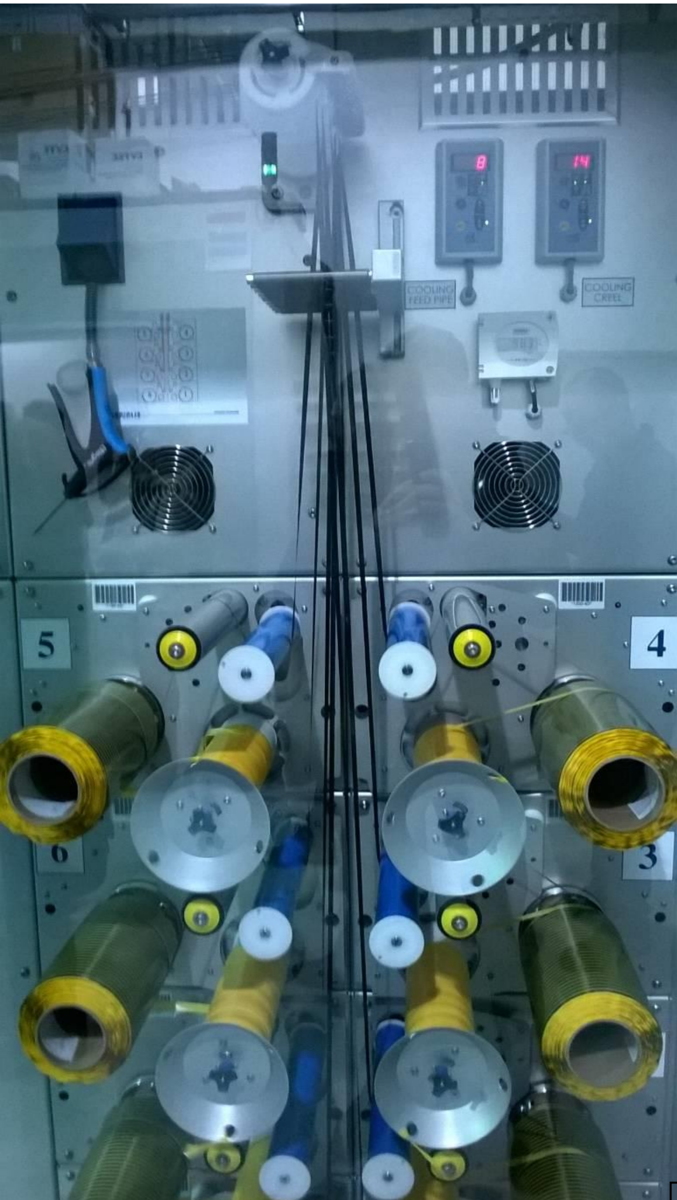

The A380's GLARE fuselage panels are layed up on highly accurate metal tooling as large as 10m by 3m/33 ft x 10 ft. Special transporters suspend workers over the panel.

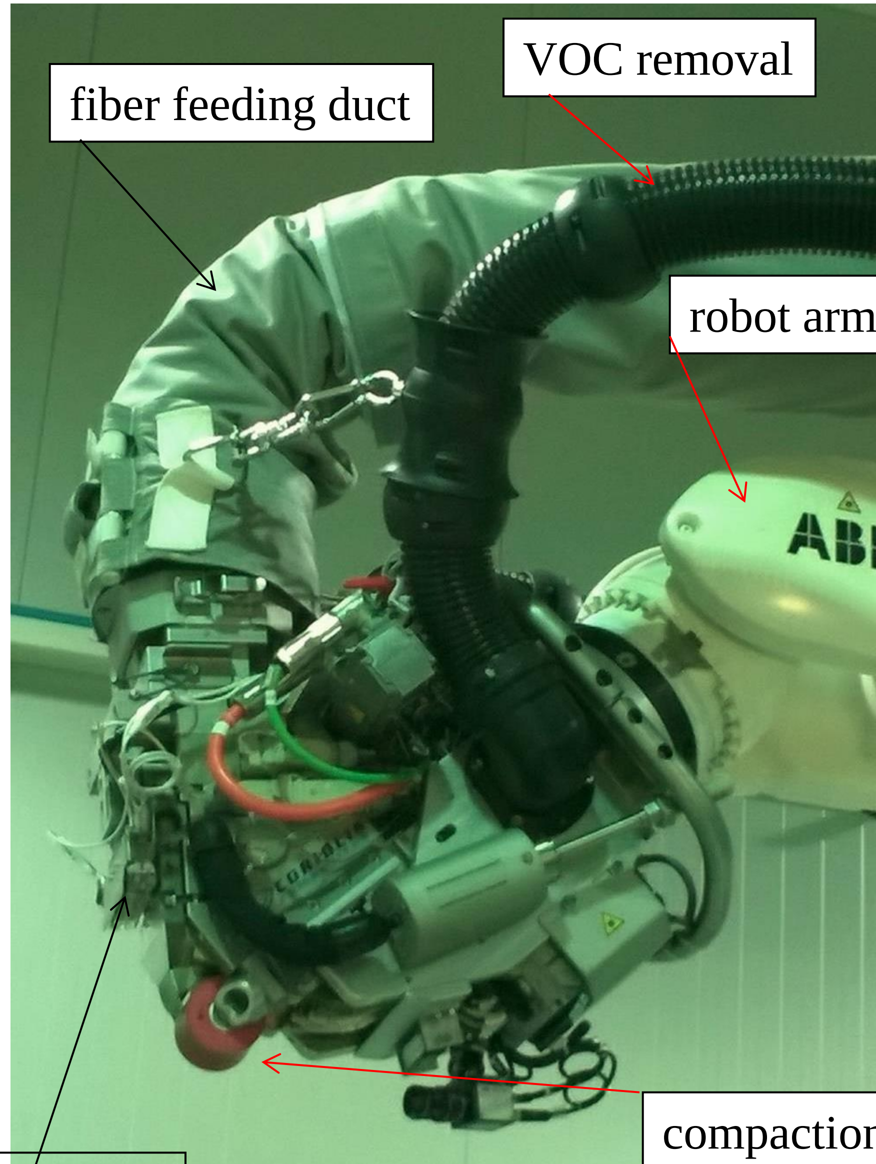
GLAss-REinforced" Fibre Metal Laminate

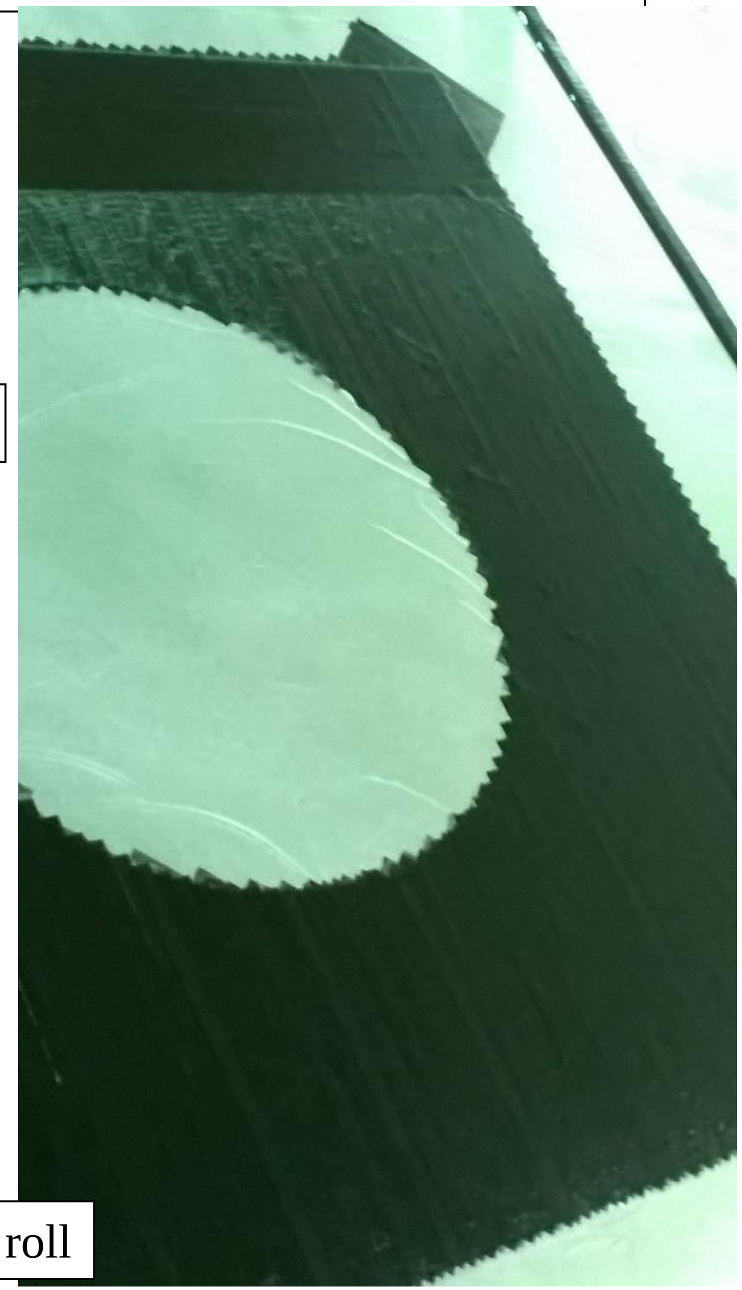
https://www.youtube.com/watch?v=xK4gMDduHgA

https://www.youtube.com/watch?v=ulv50nbap5k

automated fiber placement







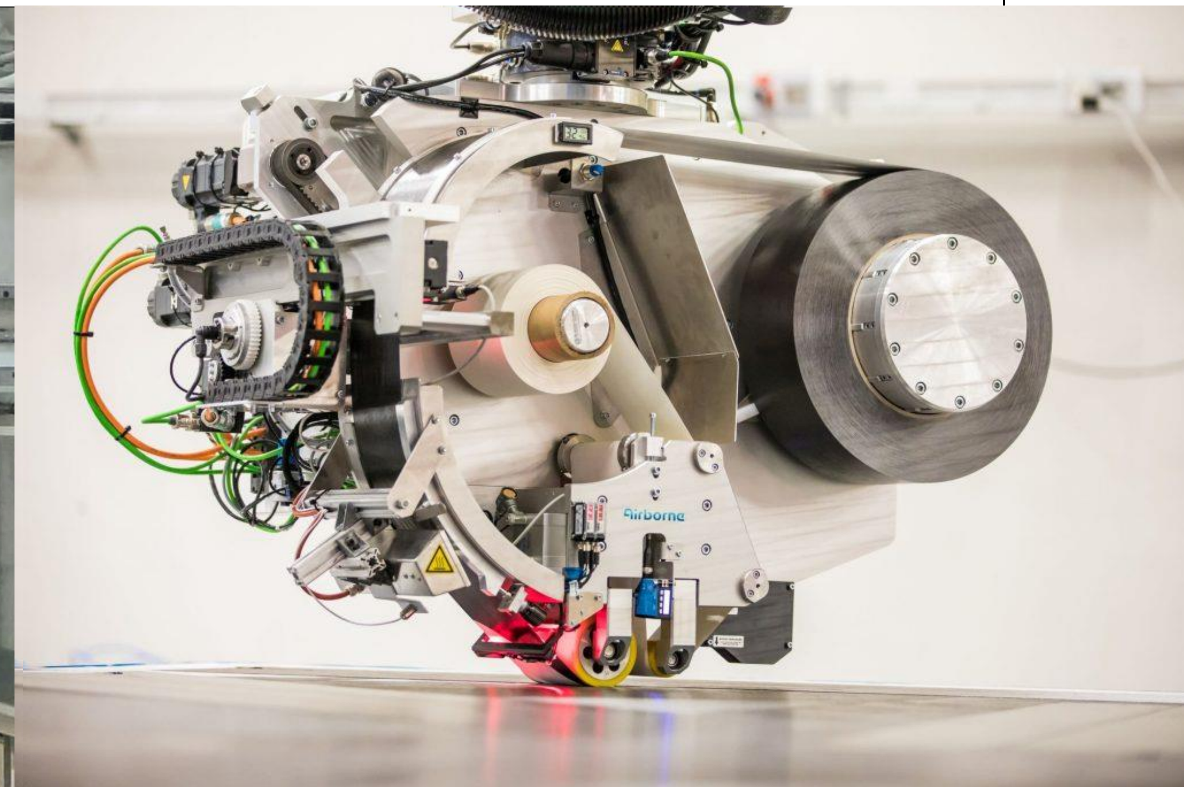
prepreg tape bobins

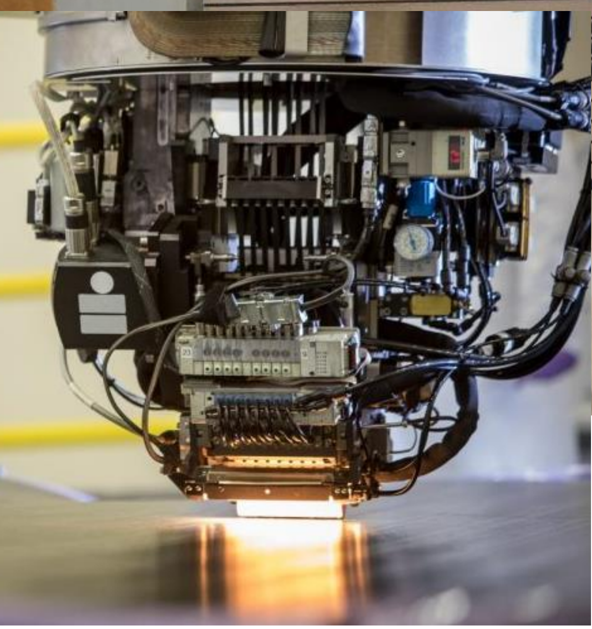
Deposition head

A shape with cutting signs around curve boundaries

Automated tape laying (ATL)

Ingersoll: Leonardo helicopters

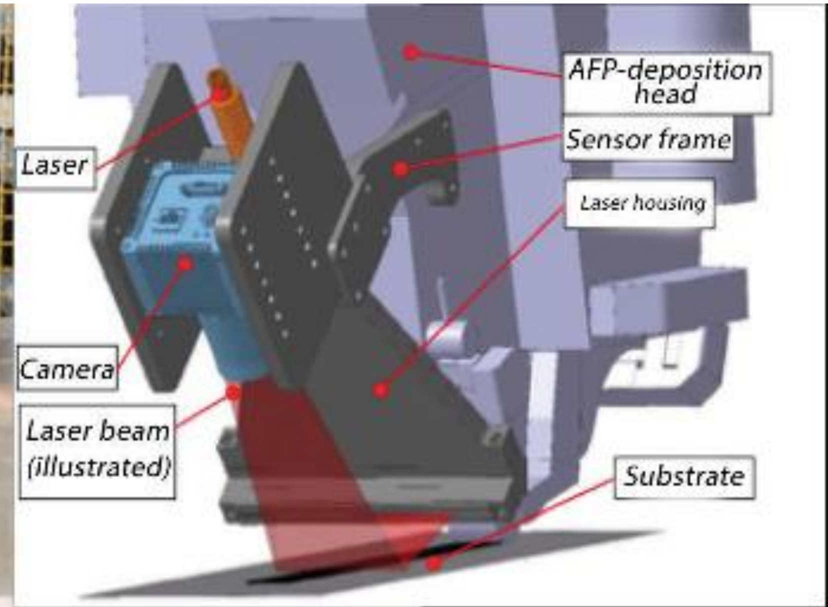




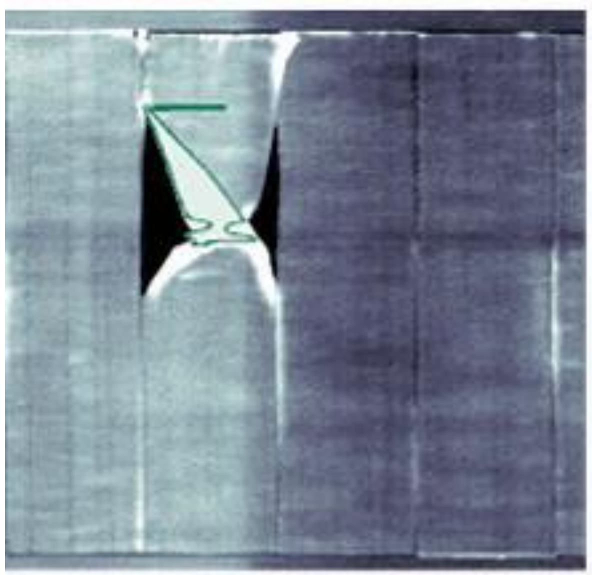
Electroimpact: B777X wing skins

On line inspection under implementation

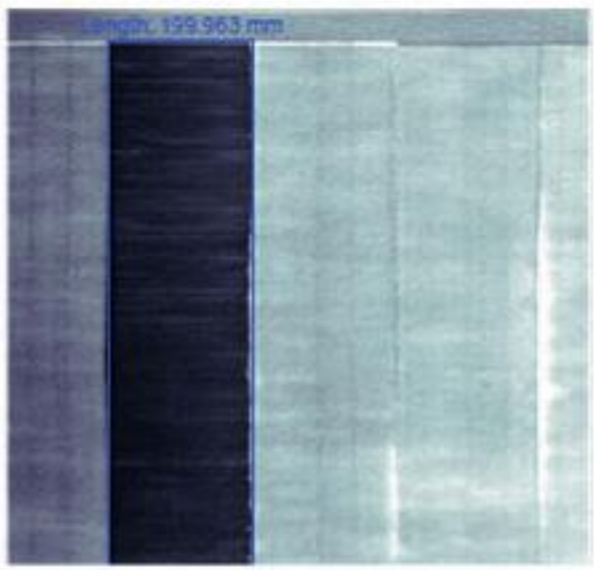
AFP: On-line defect detection



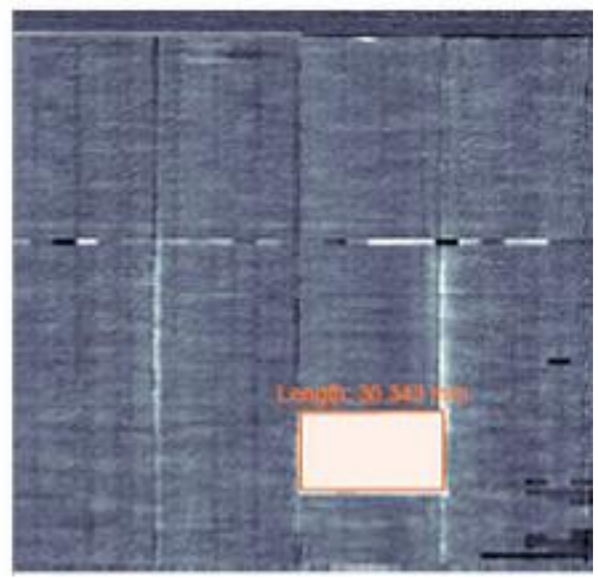
Images of typical defects, taken with an on-line camera



Twist



Missing tow



Gap

JEC composites July 2018

Prepreg characterization

Beside resin and fiber type, a prepreg is characterized by

- Gel time
- Tack level
- Drape
- Resin viscosity and “flow”
- Resin content
- Resin to hardener ratio (FTIR, HPLC)
- Resin reactivity and glass transition temperature (DSC)

Key properties are also the shelf life and the mechanical life

Prepreg characterization

- Gel time:
  - At a given temperature (usually curing Temp), it represents the time to reach gelation
- Tack level and drape:
  - Qualitative parameters that describe the ability of a prepreg plies to bond each other during stacking and to adapt to complex mold shapes, respectively. They can change during storage

Qualitative tack level	**Definition/Description**
5	Sticks to hand, but no residual left
4	Sticks to untreated tool indefinitely in vertical configuration
3	Sticks to untreated tool for about 30 s in vertical configuration
2	Falls off untreated tool immediately in vertical configuration
1	No tack

- In AFP the placement parameters (Infrared heating, roller pressure, lay-up speed) for the first ply may be expected to differ from the rest of lay-up.
- To adhere the first ply laid by AFP to the tool a" tackifier" or a first ply are hand laid up

Prepreg characterization

- Resin viscosity and flow
  - The resin viscosity is measured either as a control on the prepreg batch either as a control on the aging resulting form prolonged storage.
  - Sometimes the technological parameter named "flow" is performed: a prepreg disc is pressed at the curing temperature and amount of squeezed resin is measured
- Resin content
  - It is usually a little bit higher than the amount that should remain in the composite after curing. It comprises the resin that is lost during curing in order to remove volatiles
  - Typical values:
    - 35%-45% by volume expected in the cured in the composite + an excess of a few %

Volatiles are ususally: Solvent residues, absorbed water, Reactive monomers or any low moecular weight compound that results from former synthesis of monomers

Prepreg characterization

- DSC
  - It is used to measure the Tg of the reactive mixture (T_{go}) to check if it was properly stored. It is used to measure the Tg of cured resin
  - It is used to measure the reactivity through the exothermal effects associated to the reactions (exothermal reaction peak shape and position).
- FTIR
  - It is used as acceptance control to check if the ratio between epoxy and amine groups is that expected. The ratio between the height of epoxy and amine absorption peaks is measured.
- Shelf life: the time the resin (and the prepreg) can be stored at low temperature, usually -20 ° C (usually about 1 year)
- Mechanical life: the time the resin (and the prepreg) can remain at room temperature before curing in autoclave (usually a few hundreds of hours)

Prepreg characteriztion
AGATE (Advanced General Aviation Transport Experiments
FAA qual. Procedure da MIL-HDBK-17

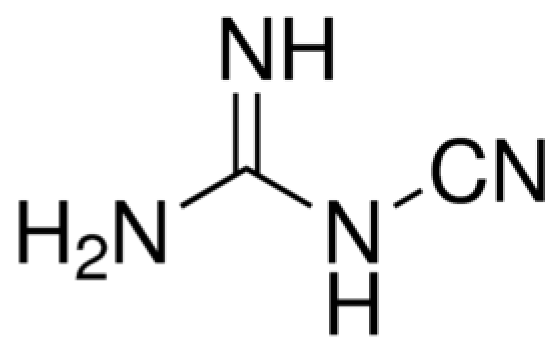
TABLE 1. RECOMMENDED PHYSICAL AND CHEMICAL PROPERTY TESTS TO BE PERFORMED BY MATERIAL VENDOR

No.	Test Property	Test Method(s)		No. of Replicates per Batch
		ASTM	SACMA	
1	RESIN CONTENT	D 3529, C 613, D 5300, D3171	RM 23, RM 24	3
2	Volatile Content	D 3530	- - -	3
3	Gel Time	D 3532	RM 19	3
4	Resin Flow	D 3531	RM 22	3
5	Fiber Areal Weight	D 3776	RM 23, RM 24	3
6	IR (Infrared Spectroscopy)	E 1252, E 168	- - -	3
7	HPLC (High Performance Liquid Chromatography)*	- - -	RM 20	3
8	DSC (Differential Scanning Calorimetry)	E 1356	RM 25	3

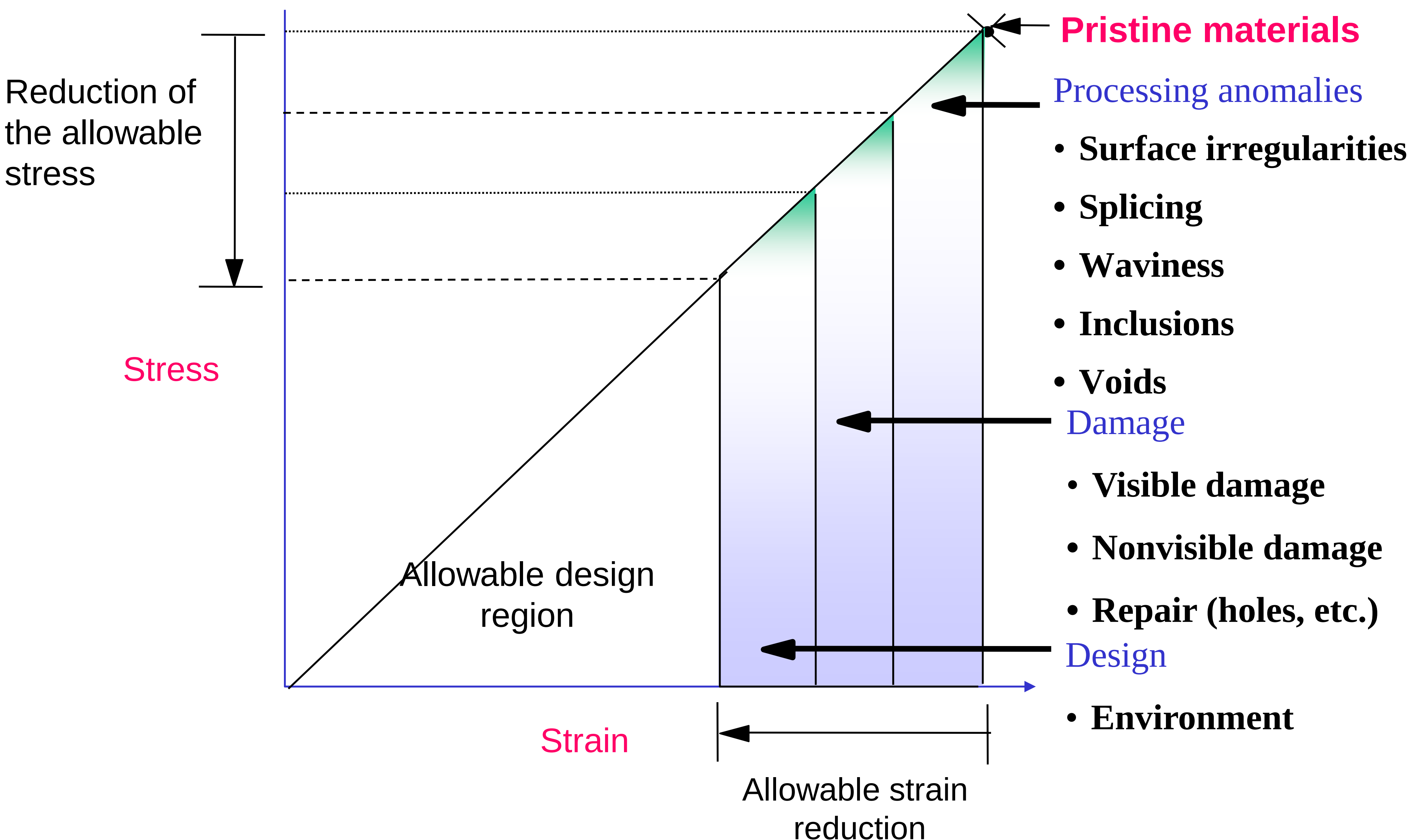
Properties of resins for prepregs

- High viscosity at stratification temperature (room temperature or a little higher): usually > 1000 Pa s
- Low reactivity at room temperature in order to maximize the mechanical life.
- Low reactivity at storage temperatures (- 20 ° C) in order to maximize shelf life.
- High reactivity at curing temperature to minimize curing time.

- Solubility can play a key role. For instance, dicyandiamide is a solid powder poorly soluble at mixing and room temperatures.
- This strongly limits reactivity. Then only at curing temperature (about 125 ° C) the dissolution of the amine in the resin can occur, so activating the reaction.

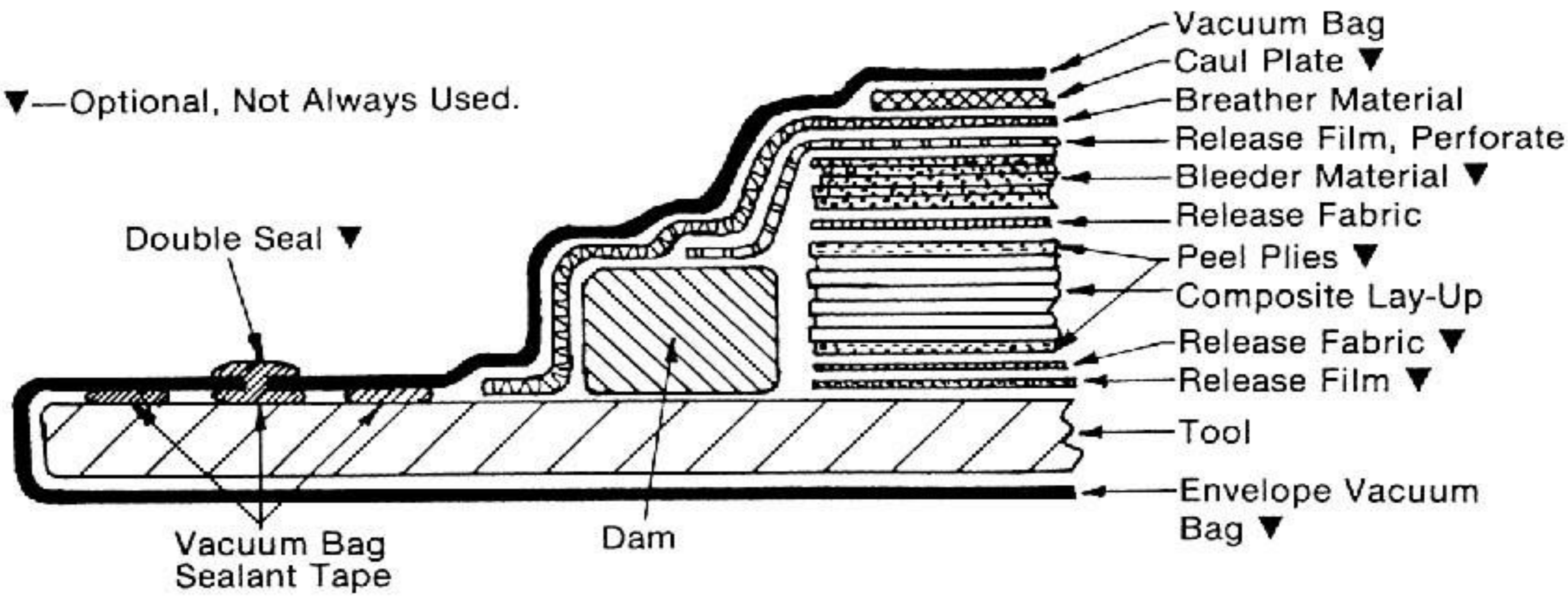


Static Strength Reduction of Composites Comes From Many Sources



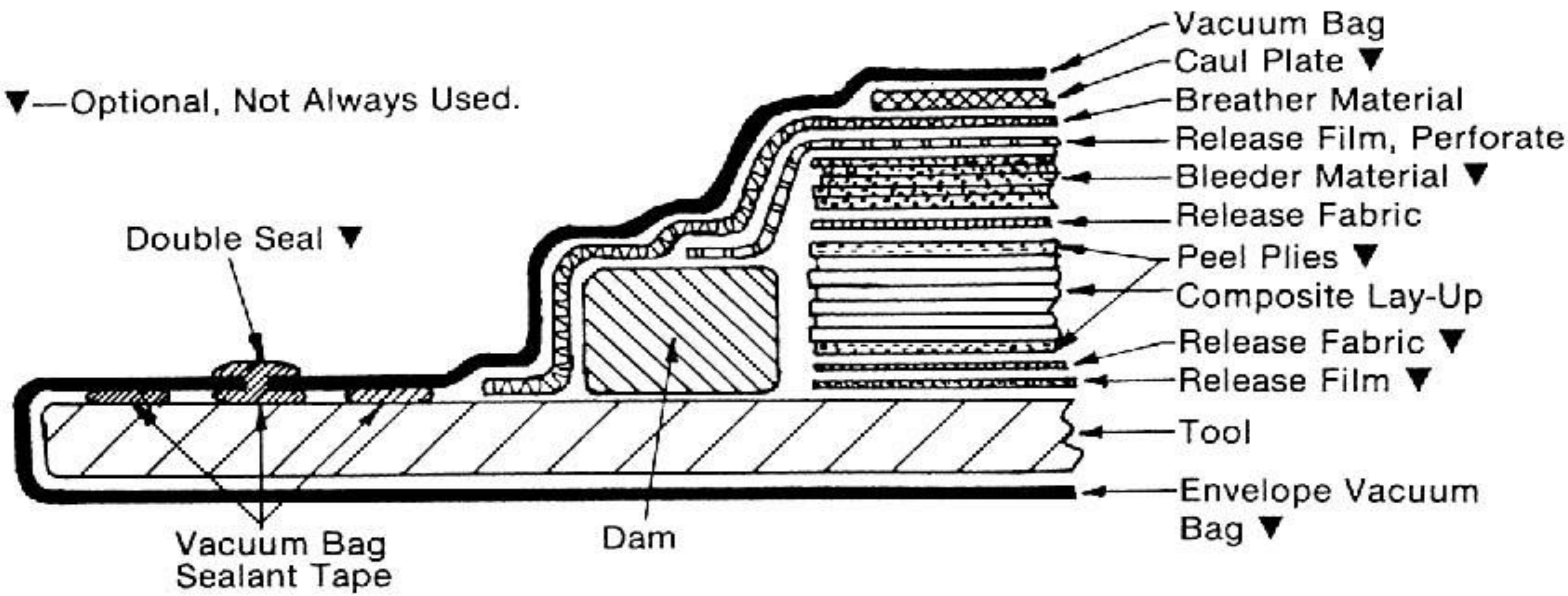
vacuum bagging

- Vacuum bag: a film (usually polyamide) characterized by a high stretching properties also at high temperatures (cure temperature).
- Sealant tape: a bi-adhesive thick tape use to seal the vacuum bag
- Release film or fabric: a release layer in some cases perforrated or porous to allow resin flow and volatiles extraction.

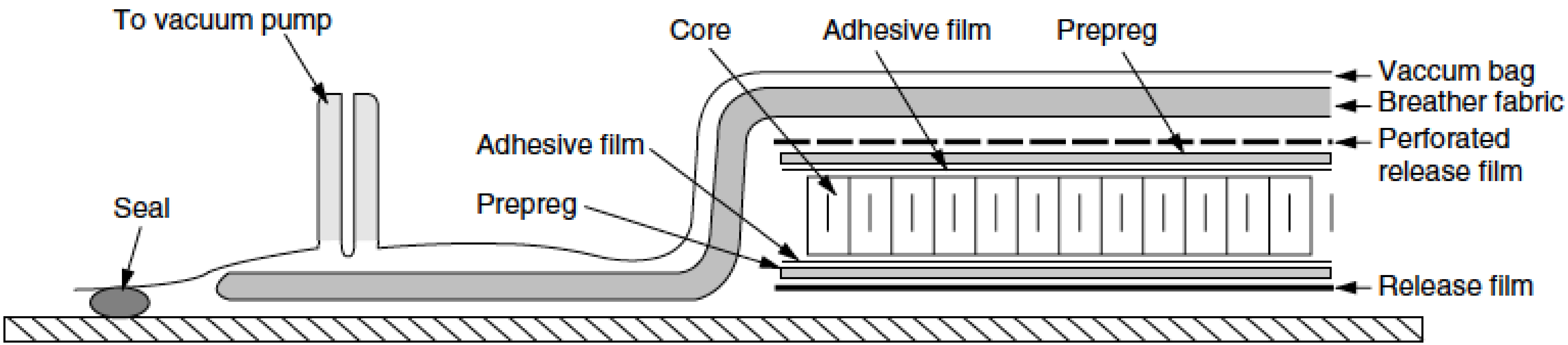


Vacuum bagging

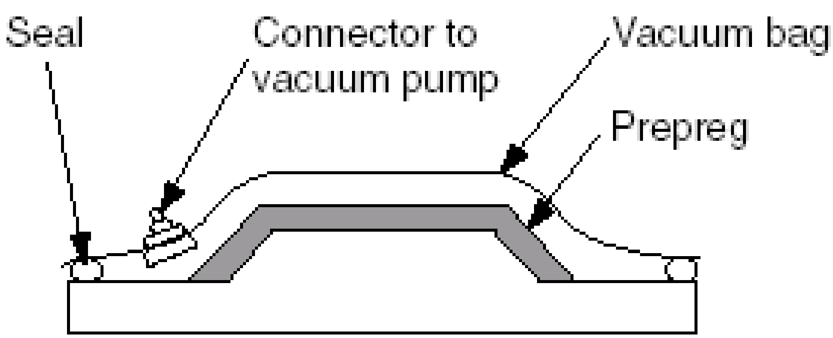
- Breather: always present, is a porous mat deputed to allow air extraction on the entire surface of the tool. It allows the extraction of volatiles. In some cases a single layer acts as breather/bleeder.
- Bleeder: a porous mat deputed to the absorption of the resin in excess lost the laminate surface
- Peel ply: a thin fabric added as last layer on the prepreg stack in order to protect the laminate surface or to produce surface roughness for further adhesive bonding. In some cases used as breather.



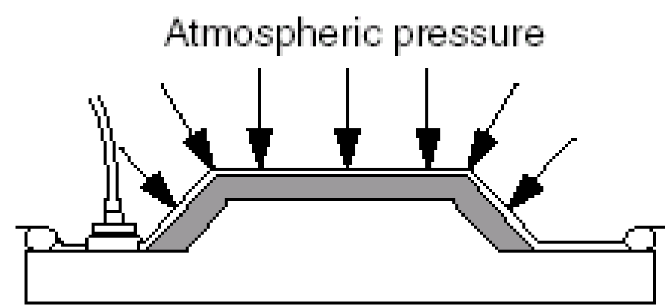
Sandwich panel: minimum required auxiliary materials for vacuum bagging



Vacuum bagging



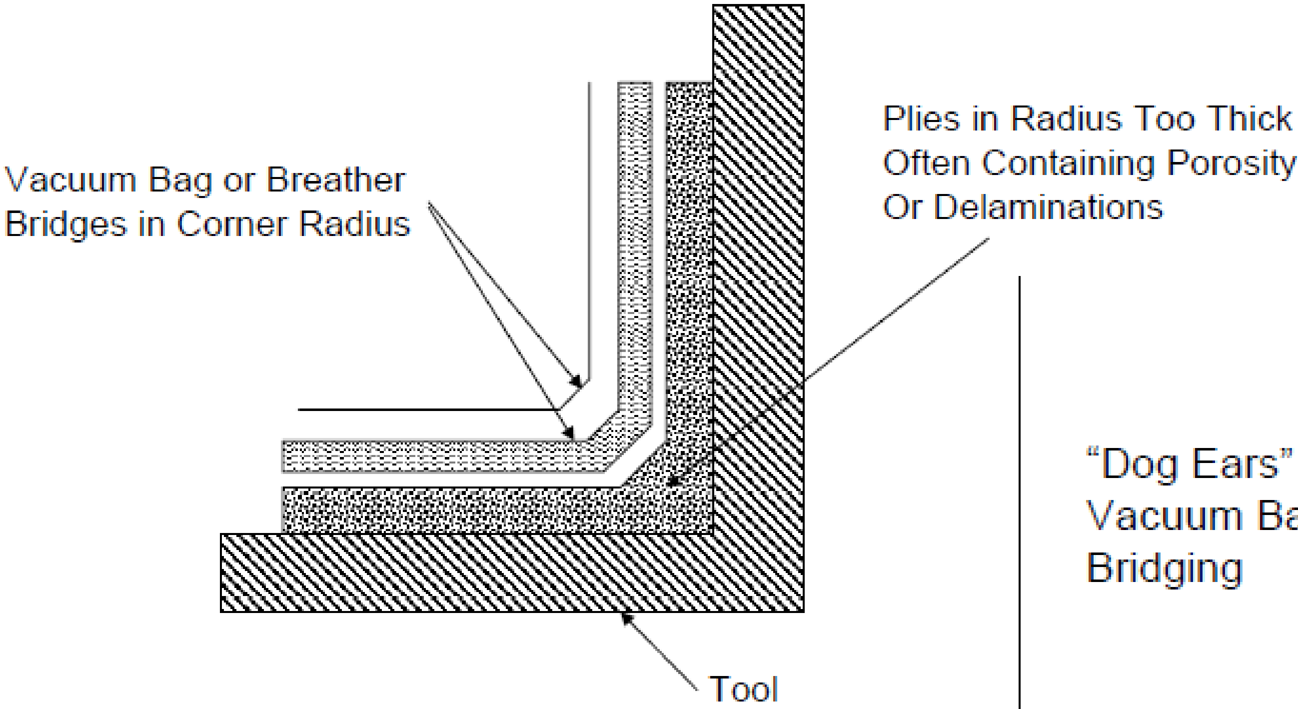
■ Fig. 1 : sealing flexible bag over lay-up



■ Fig. 2 : applying vacuum to the system

https://www.youtube.com/watch?v=t22vJLHWxYA

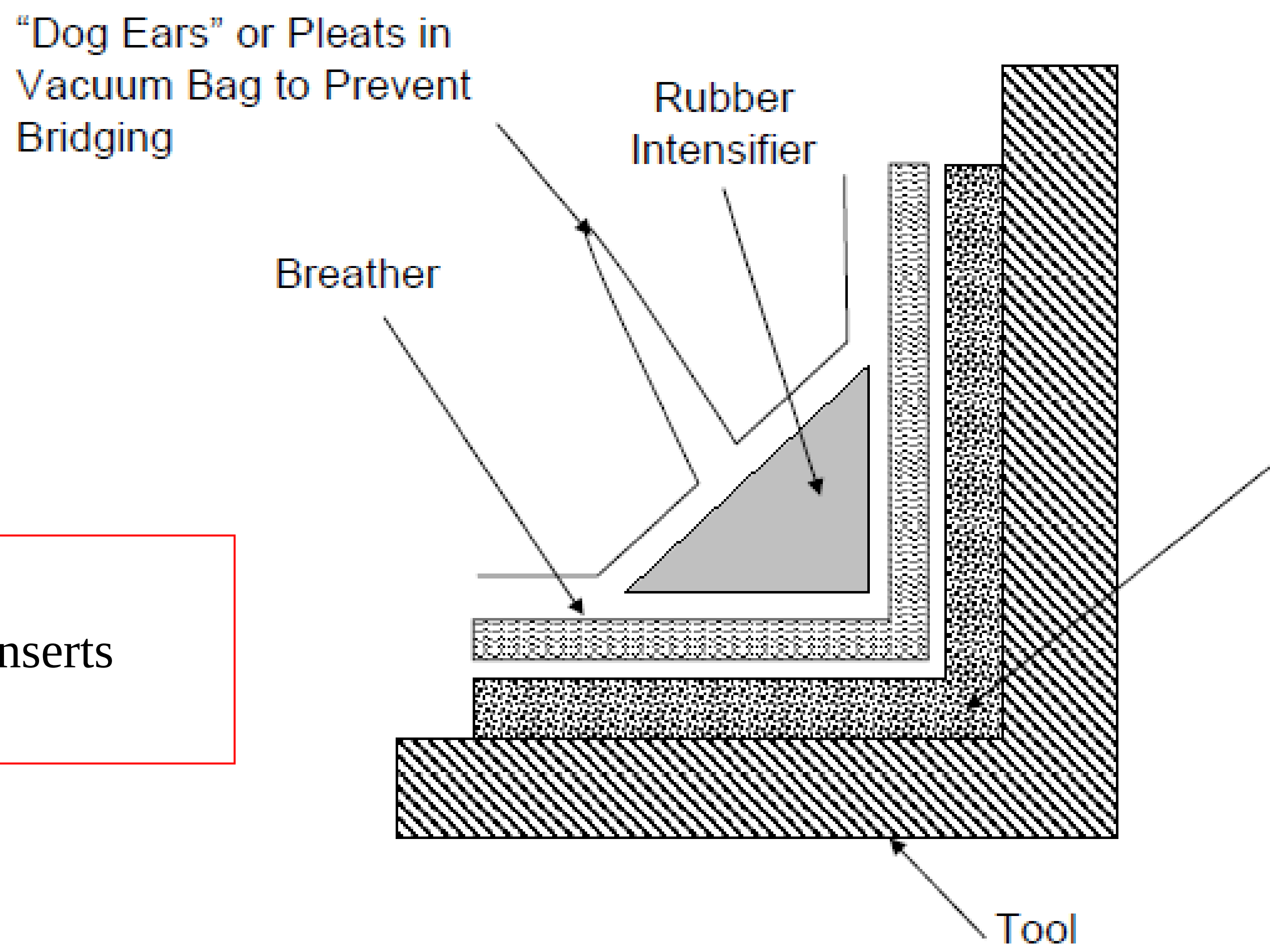
Corner Bridging



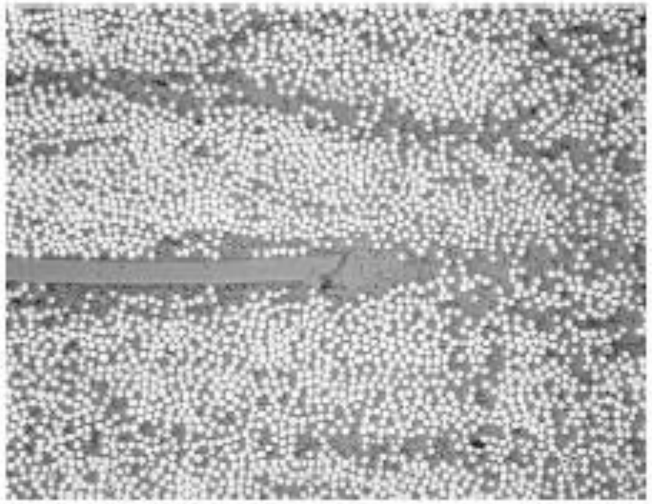
SOLUTION

•Pressure intensifiers: rubber inserts

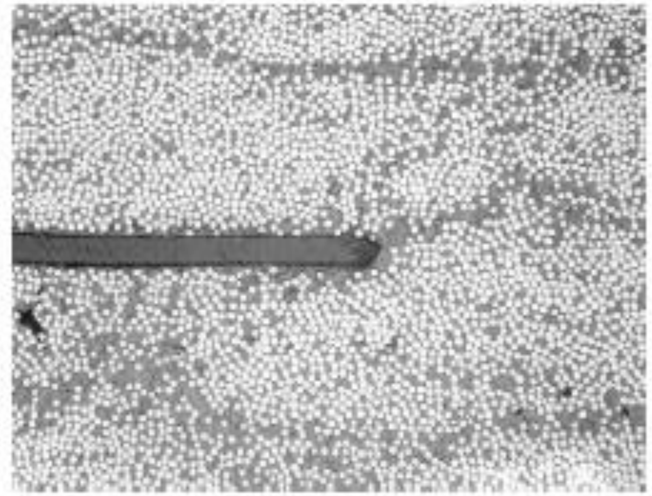
•Dog ears on the bag



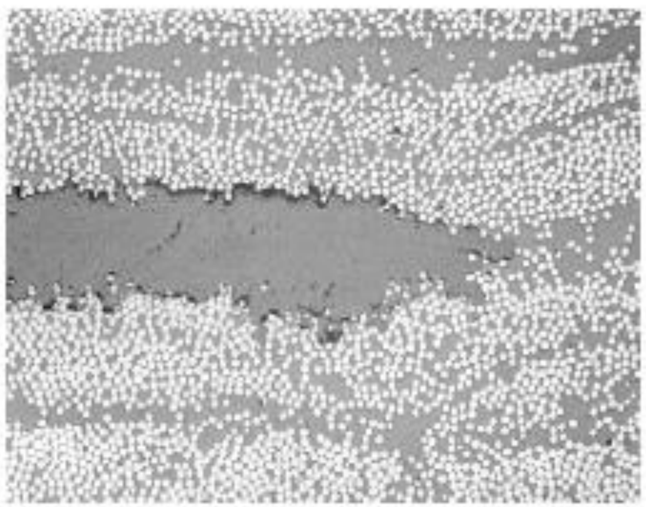
Defects-Foreign Objects



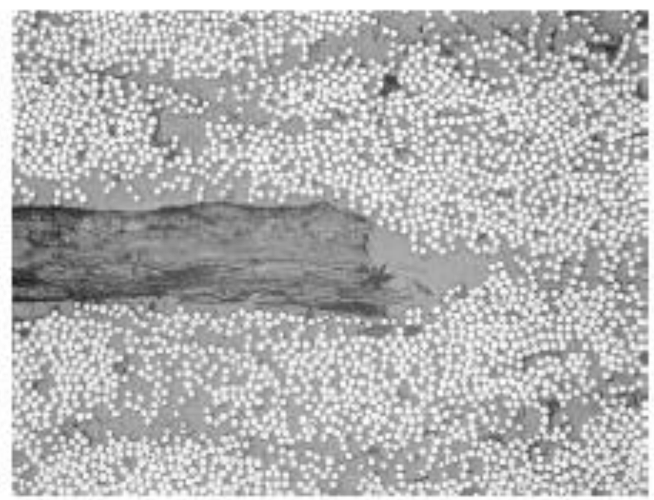
Mylar Film



Teflon Film



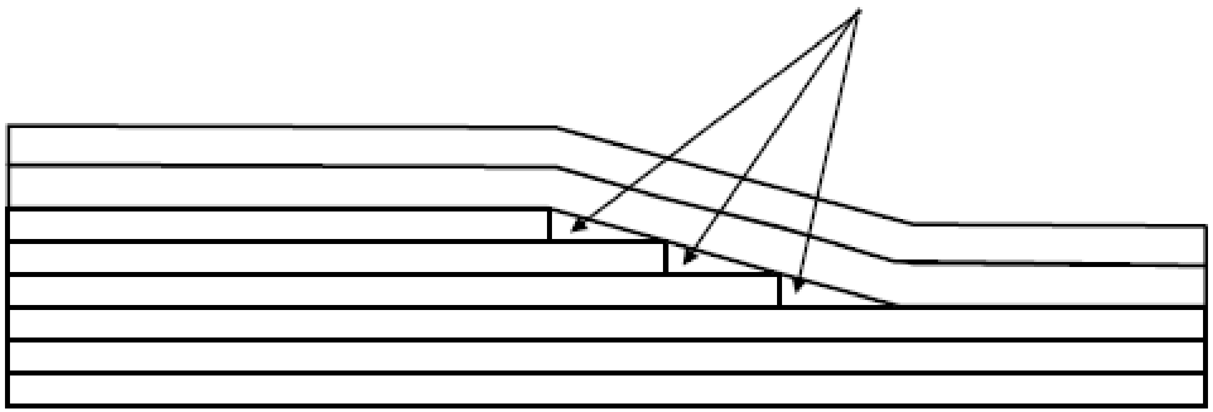
Adhesive Backing Film



Prepreg Release Paper

Ply drop-off a way to change the thickness of a laminate

If drop-off areas are further covered by continuous plies (internal ply drop-off), void can occur



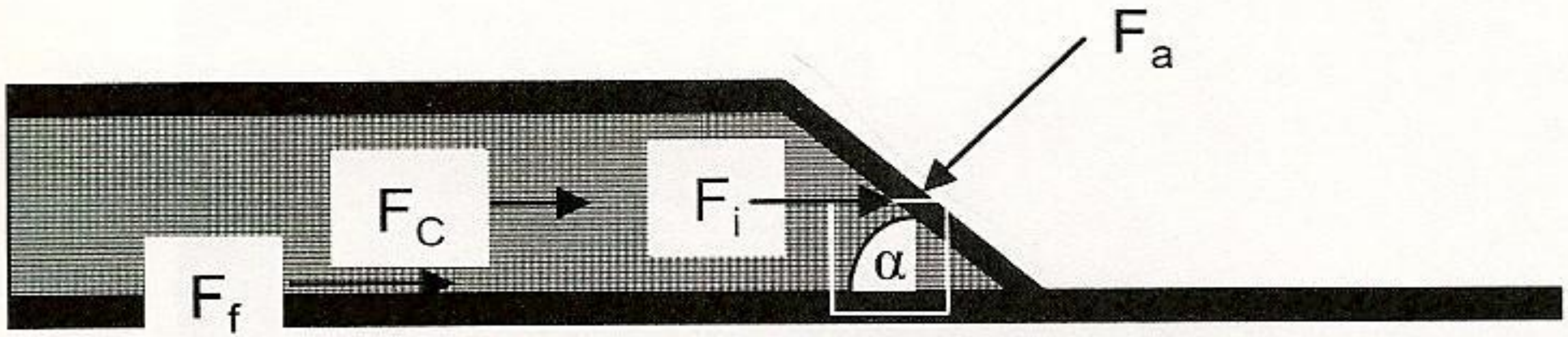
Debulking

The lay-up should be vacuum debulked every 3 to 5 plies, or more often if the shape is complex.

Vacuum debulking consists of covering the lay-up with a layer of porous release material, applying several layers of breather material, applying a temporary vacuum bag and pulling a vacuum for a few minutes.

Honeycomb: core crush

Core Crush Due to Core Migration During Cure



$$F_{net} = F_a \sin\alpha - F_i - F_c - F_f$$

Where:

F_{net} = Positive- Core Crushes / Negative- Core Does Not Crush

α = Core Angle

F_a = Force Exerted by Autoclave Gas Pressure

F_i = Force Due to Internal Gas Pressure in Core

F_c = Force Due to Inherent Core Strength

F_f = Force Due to Friction of Prepreg or Adhesive

Ribs and fillers

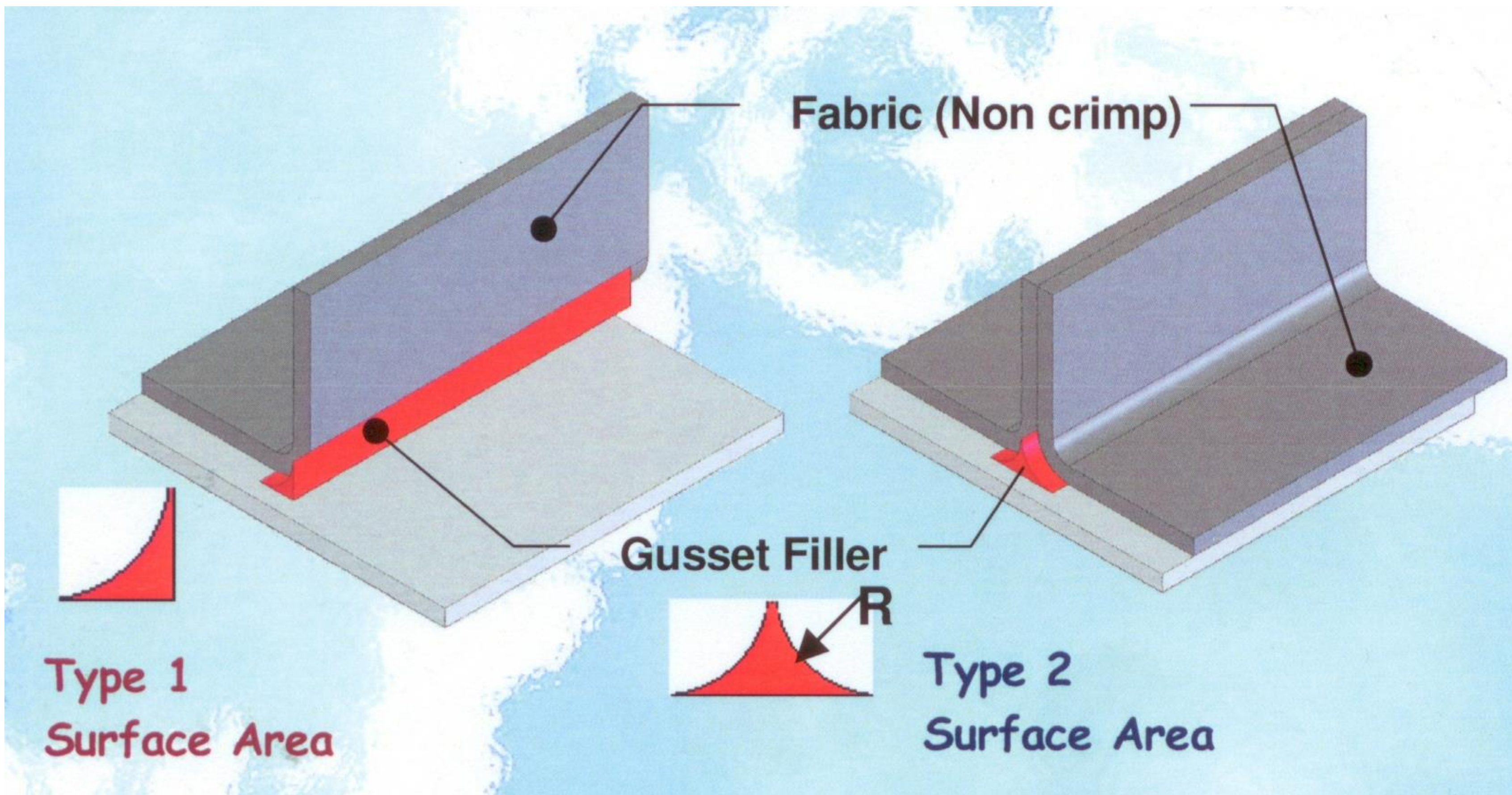
•Ribs can be co cured on a laminate using proper tools

• Fillers are usually needed

• Fillers can be pre-shaped assuming proper triangular sections with the aid of additional tools.

•Fillers can be also used simply rolling UD or fabric prepregs

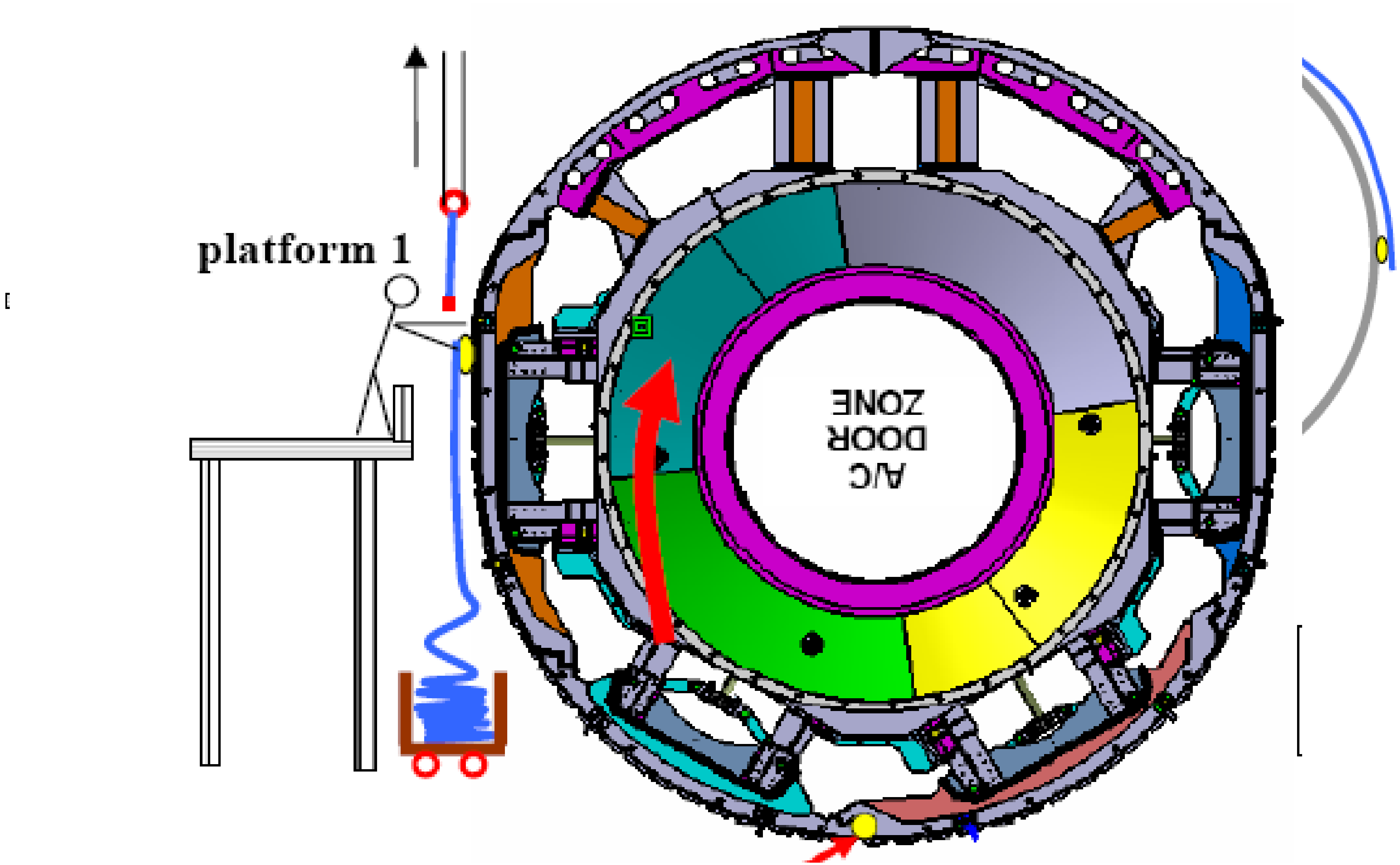
•In some cases fillers are pre-cured and used as solid composite parts



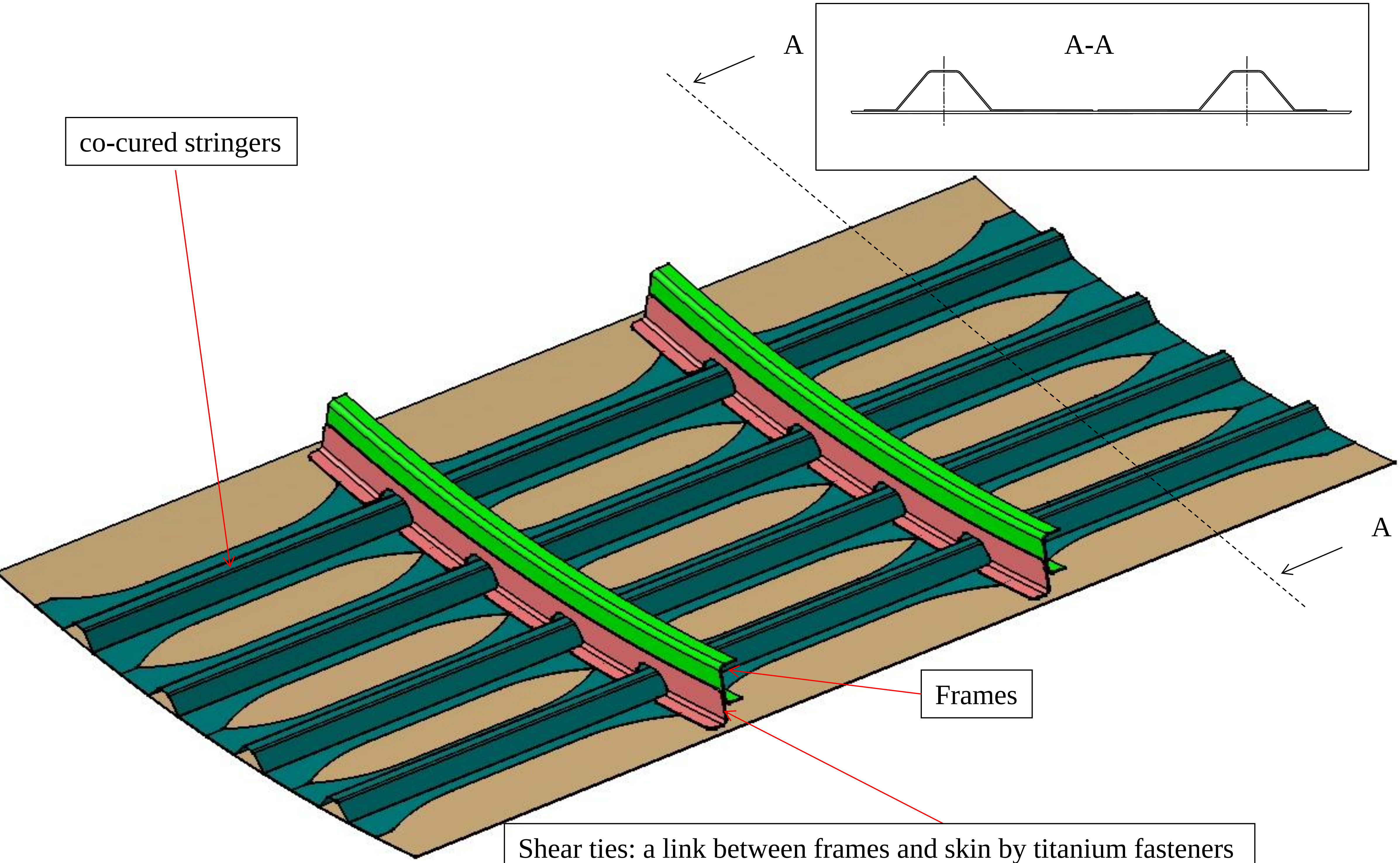
Vacuum bagging: section 46 B787

Vacuum bagging: section 44 B787

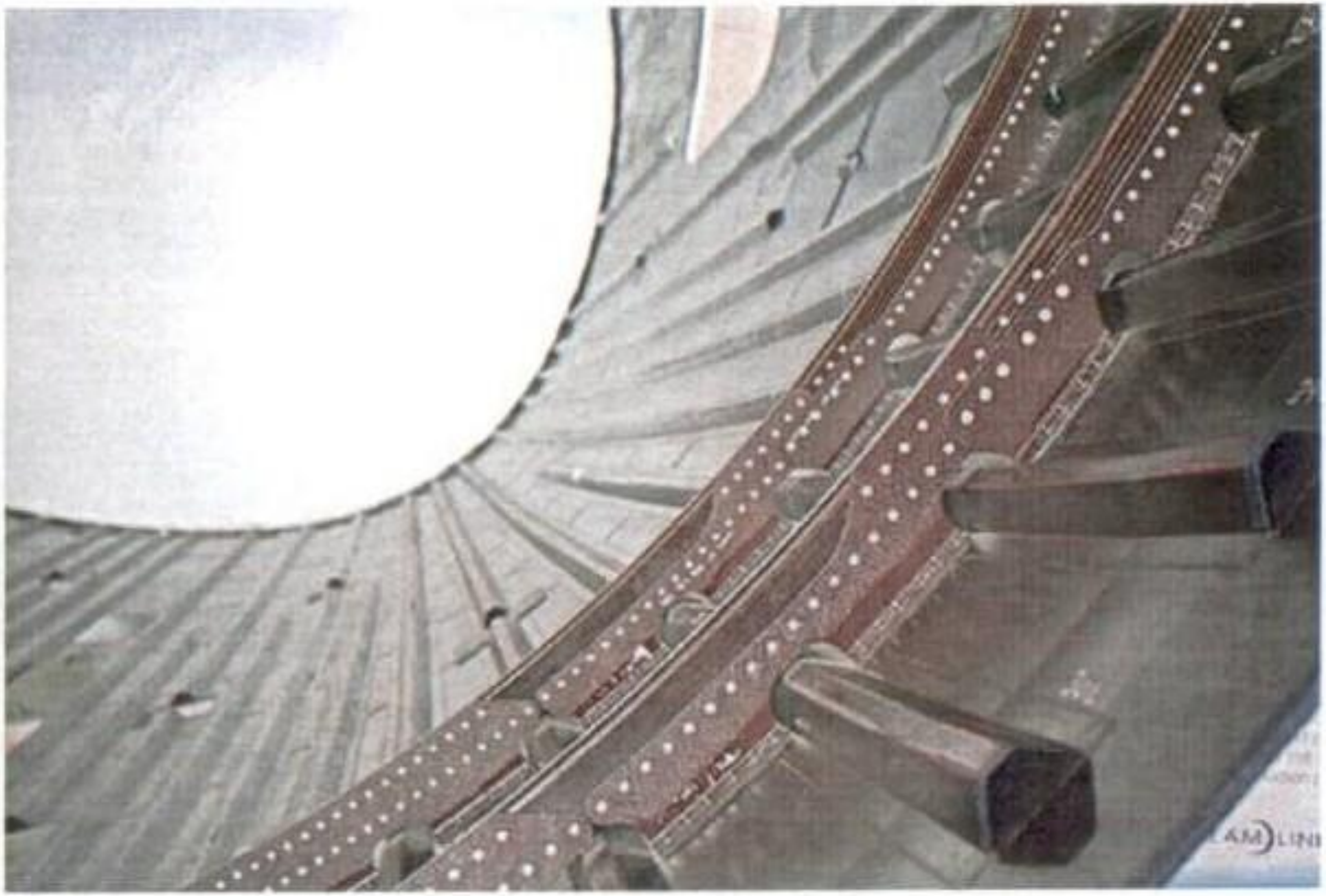
Vacuum bagging: sections 44 and 46 B787



Boeing 787: fuselage structure

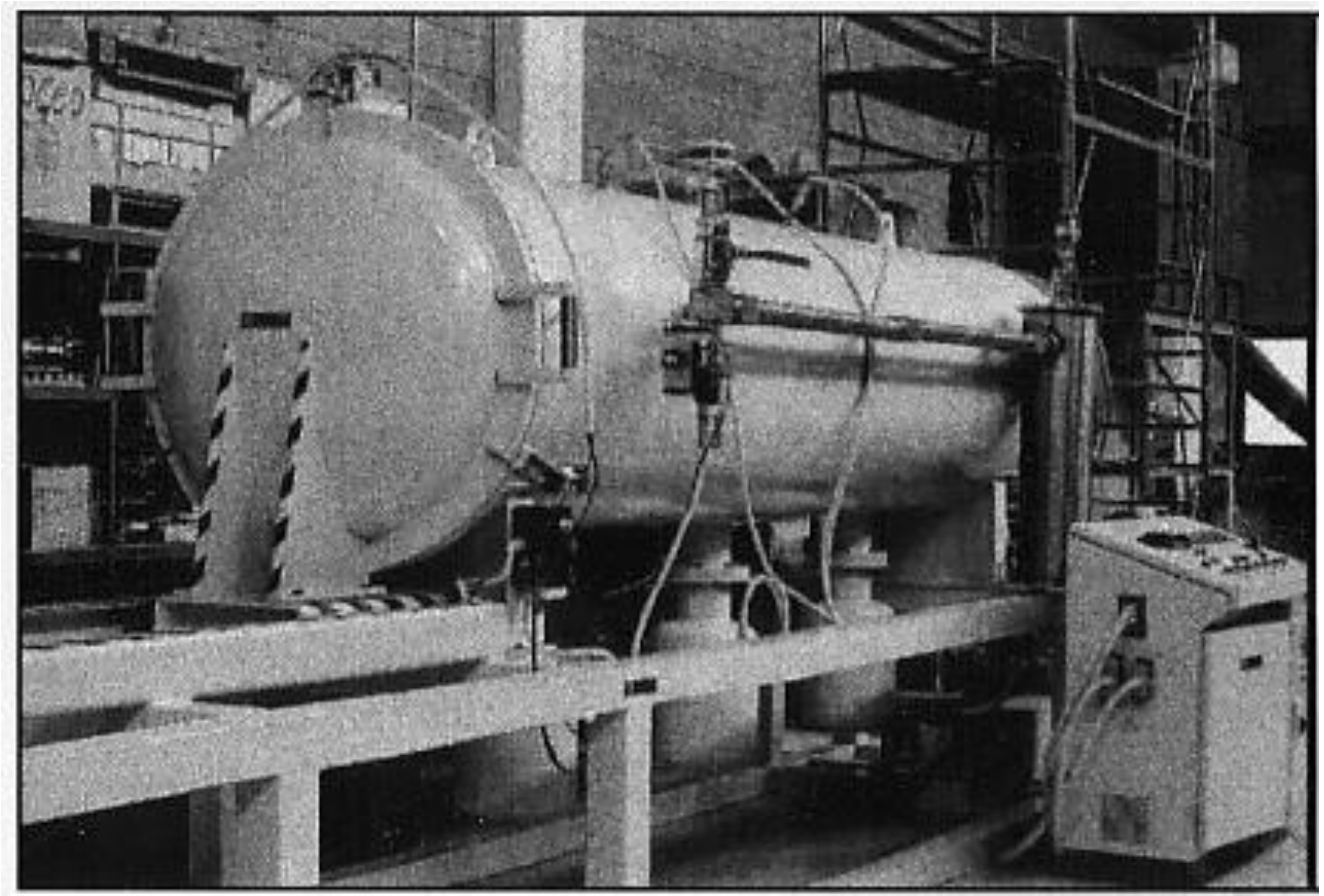


Boeing 787: fuselage structure



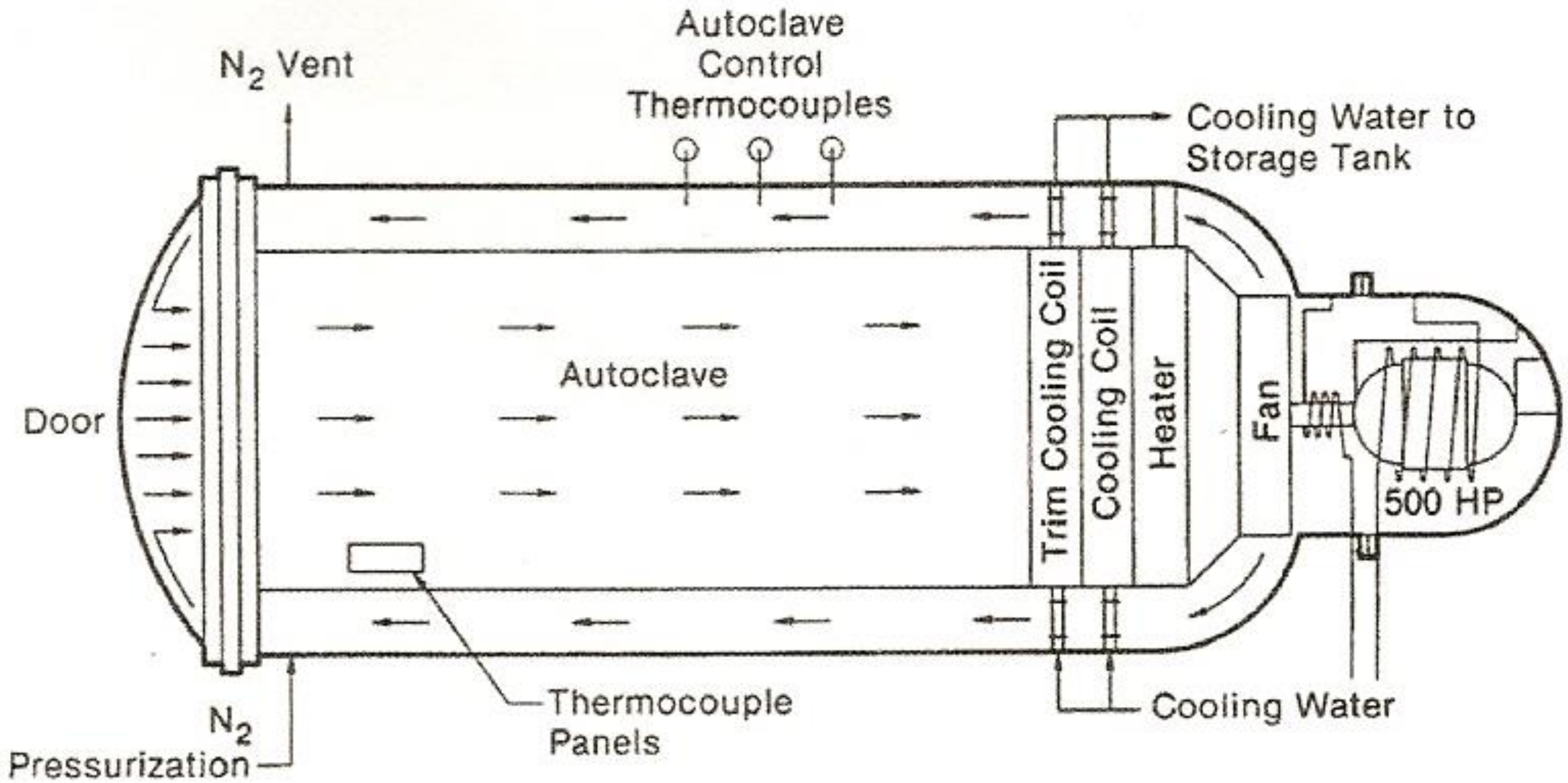
Autoclave lamination

- Autoclave= an oven where temperature and pressure (max 8 bar) are controlled
- The cure cycle is a defined program of temperature and pressure
- Prepregs are always used



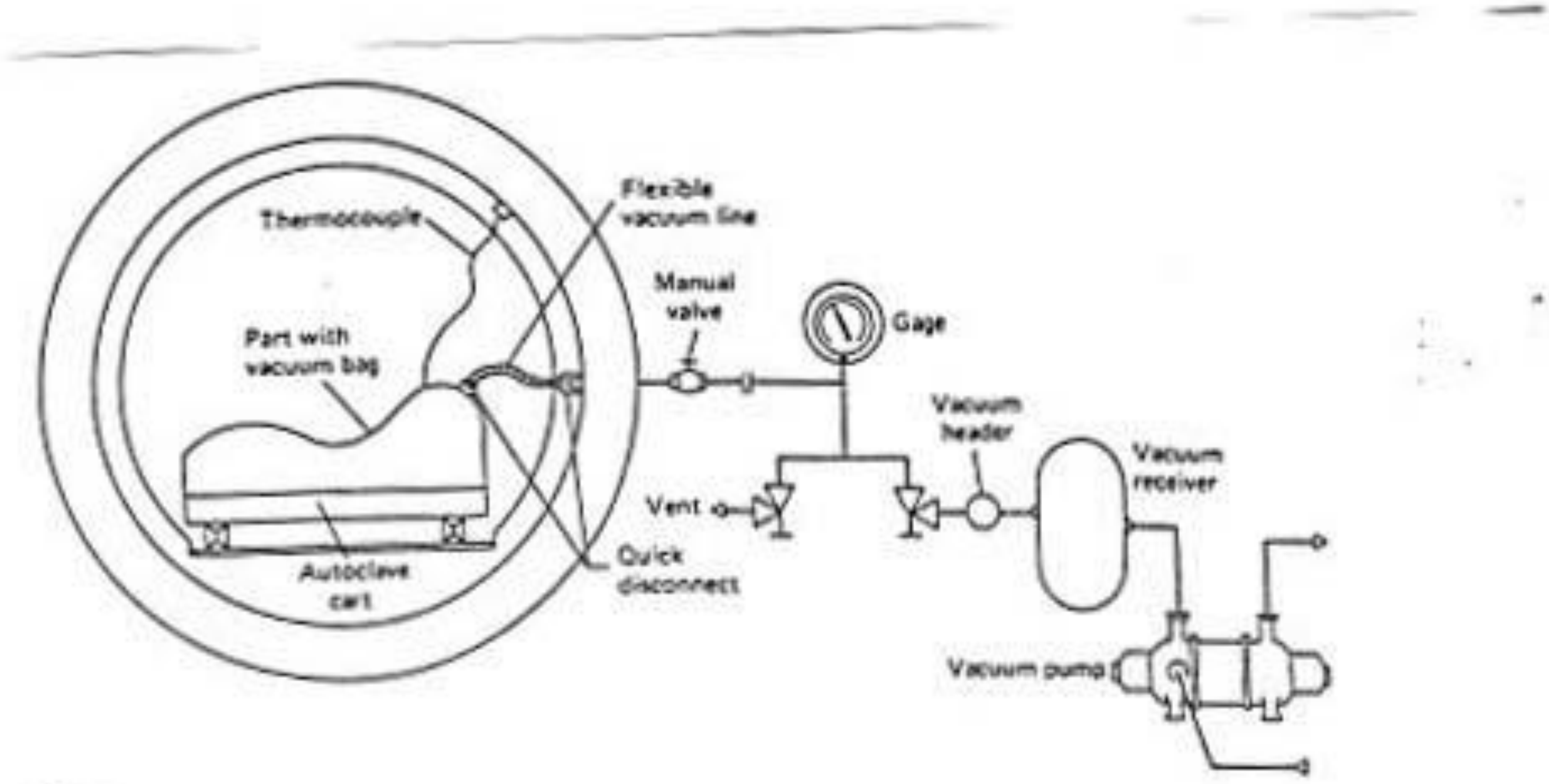
Sketch of an autoclave

Typical Production Autoclave Schematic

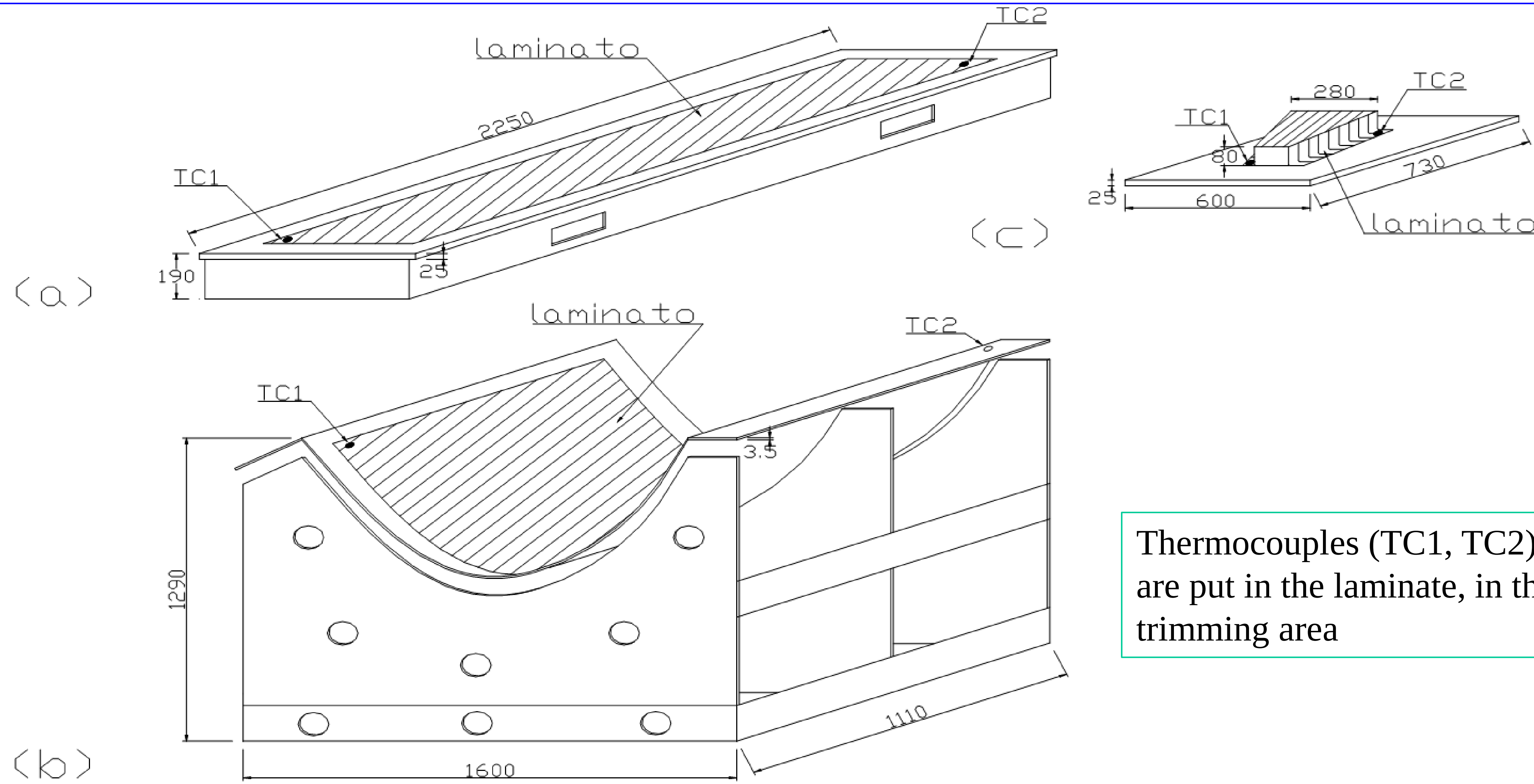


Working Space:	12 ft Dia × 40 ft Length	Heating:	Electrical – 3,120 kW
Max Temperature:	650°F	Air Movement:	60,000 ft^3/min at 600 RPM
Max Pressure:	150 psi	Part Monitoring:	48 Vacuum Supply Outlets 24 Vacuum/Pressure Monitoring Outlets 108 Thermocouple Jack Outlets

Sketch of an autoclave

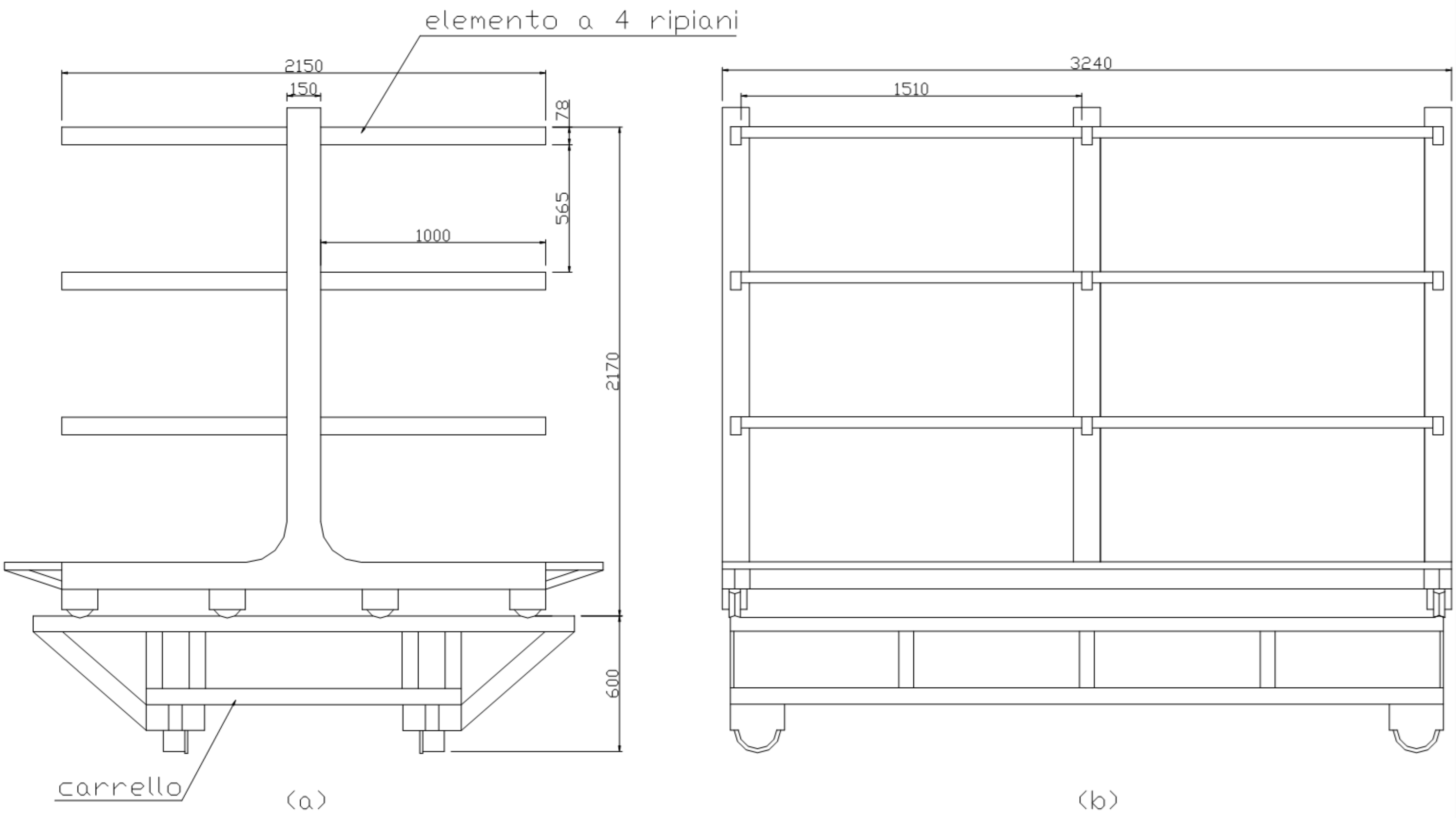


Some typical tools



Thermocouples (TC1, TC2) are put in the laminate, in the trimming area

The carts that bring the tools into the autoclave



Tool properties

- Thermal inertia
  - It has effect on the rate of heating and cooling in autoclave curing
- Themal expansion
  - Coefficients of thermal expansion ($^{\circ}F^{-1}\ 10^{-6}$) of composite and tool are often very different:

Alluminium 13

Composite 10^{-1}

The different shrinkage of the tool and of the composite in the cooling phase can induce residual stresses and deformations. This may be partly overcome with:

- Low Cooling rates
- Tools made in composite (Carbon reinforced)

- High stiffness
- Free of any porosity

Tool properties

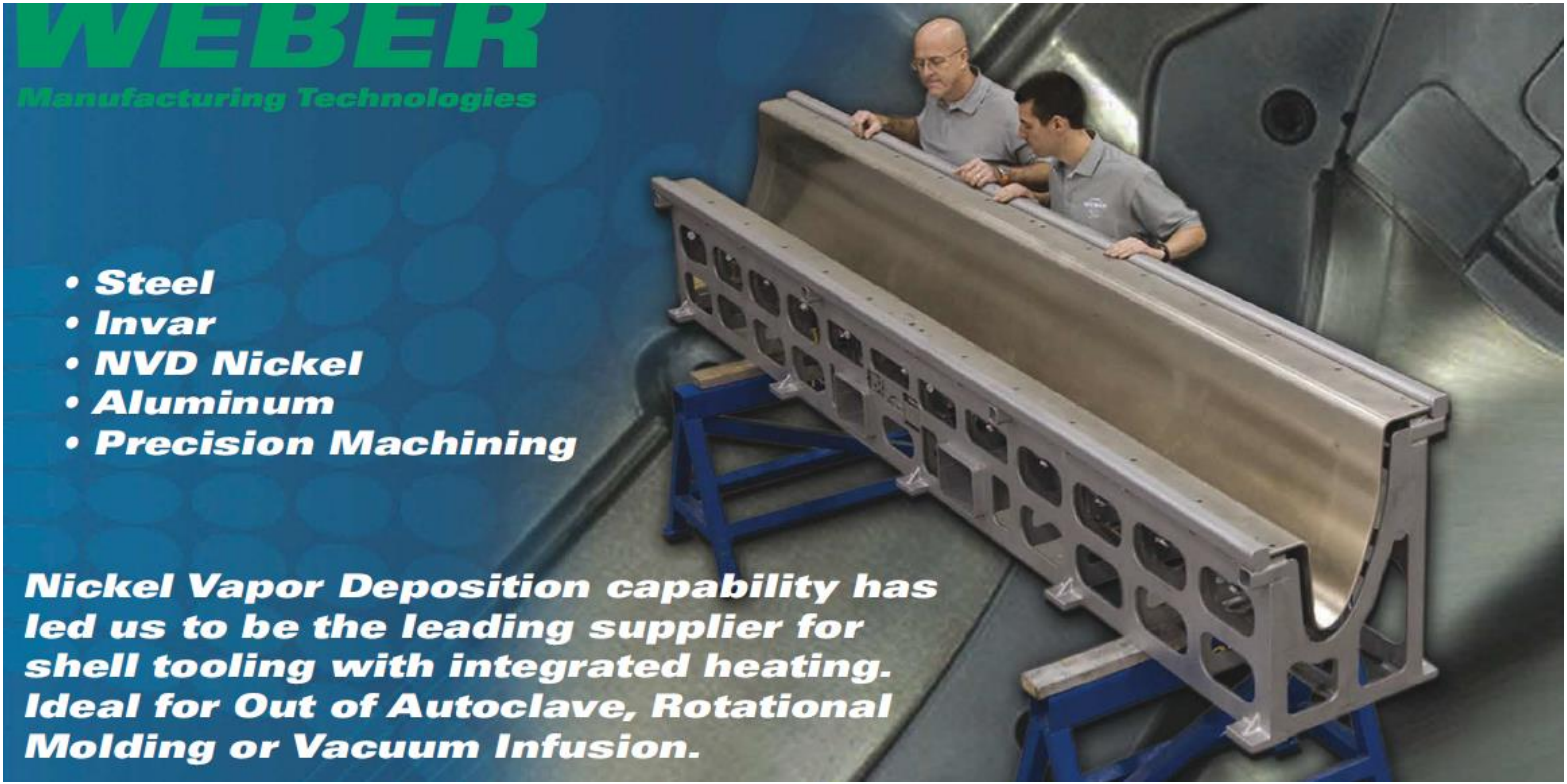
- Low weight
  - Low density materials
- Tolerances
  - The tolerances of the tool will be reflected on those of the composite laminated. Usually larger tolerances are obtained for the composite in comparison with those of the tool
- Repairability
- Capable to be used for several hundreds autoclave cycles

Tooling Material	Specific Gravity (g/cm^3)	Specific Heat (Btu/lb/° F)	Thermal Mass ($Btu/ft^3/°$ F)	Coefficient of Thermal Conductivity ($Btu/ft^2/hr/°$ F)	Coefficient of Thermal Expansion (CTE) (µin/in/° F)
METALS					
Cu-Be (C1751 O)	8.80	0.10	0.88	1680	10.0
Cast Aluminum	2.70	0.23	0.62	1395	12.9
Steel	7.86	0.11	0.86	360	6.7
304 Stainless Steel	8.02	0.12	0.96	113	9.6
Nickel	8.90	0.10	0.89	500	7.4
Zinc	7.14	0.09	0.64	746	19.0
Invar 36	8.11	0.12	0.97	73	0.8
Invar 42	8.13	0.12	0.98	106	2.9
CERAMICS					
MgO	2.90-3.58	1.13-1.50	3.28-5.37	79	6.1
Al_20_3	2-90-3.98	0.86-1.03	2.49-4.10	22	3.3
State Change (2-phase technology inc.)	0.45	na	na	0.83	1.1-3.3
PLASTER					
Gvpsum Based	1.4-1.6	0.84-1.00	1.18-1.60	10	8.3

Tooling Material	Specific Gravity (g/cm^3)	Specific Heat (Btu/lb/° F)	Thermal Mass (Btu/ft^3/° F)	Coefficient of Thermal Conductivity (Btu/ft^2/hr/° F/in)	Coefficient of Thermal Expansion (CTE) (μin/in/° F)
COMPOSITES (small numbers per year)					
Glass/Epoxy	1.8-2.0	0.3	0.54-0.60	21.8-30.0	8.0-9.0
Carbon/Epoxy	1.5-1.6	0.3	0.45-0.48	24.0-42.0	0.1-3.0
GRAPHITE					
Monolithic graphite foams	1.74-2.00	0.27-0.30	0.47-0.60	160-220	0.1-1.0
FOAM					
PU Foam Board (Models and prototypes)	0.24-0.80	na	na	na	27
Carbon Fiber Foam	0.1-1.6	na	na	1.7-173	2.7-3.2
WATER SOLUBLE MATERIALS: CORES IN PRESENCE OF UNDERCUTS					
Water Soluble (3D printed)	na	na	na	na	na

The thermal expansion of the composite depends on the stacking sequence.
In a UD lamina it is dominated by that of the fibers in direction 1 (that of fibers) and is dominated by the matrix in the directions 2 and 3

Tooling materials and shapes

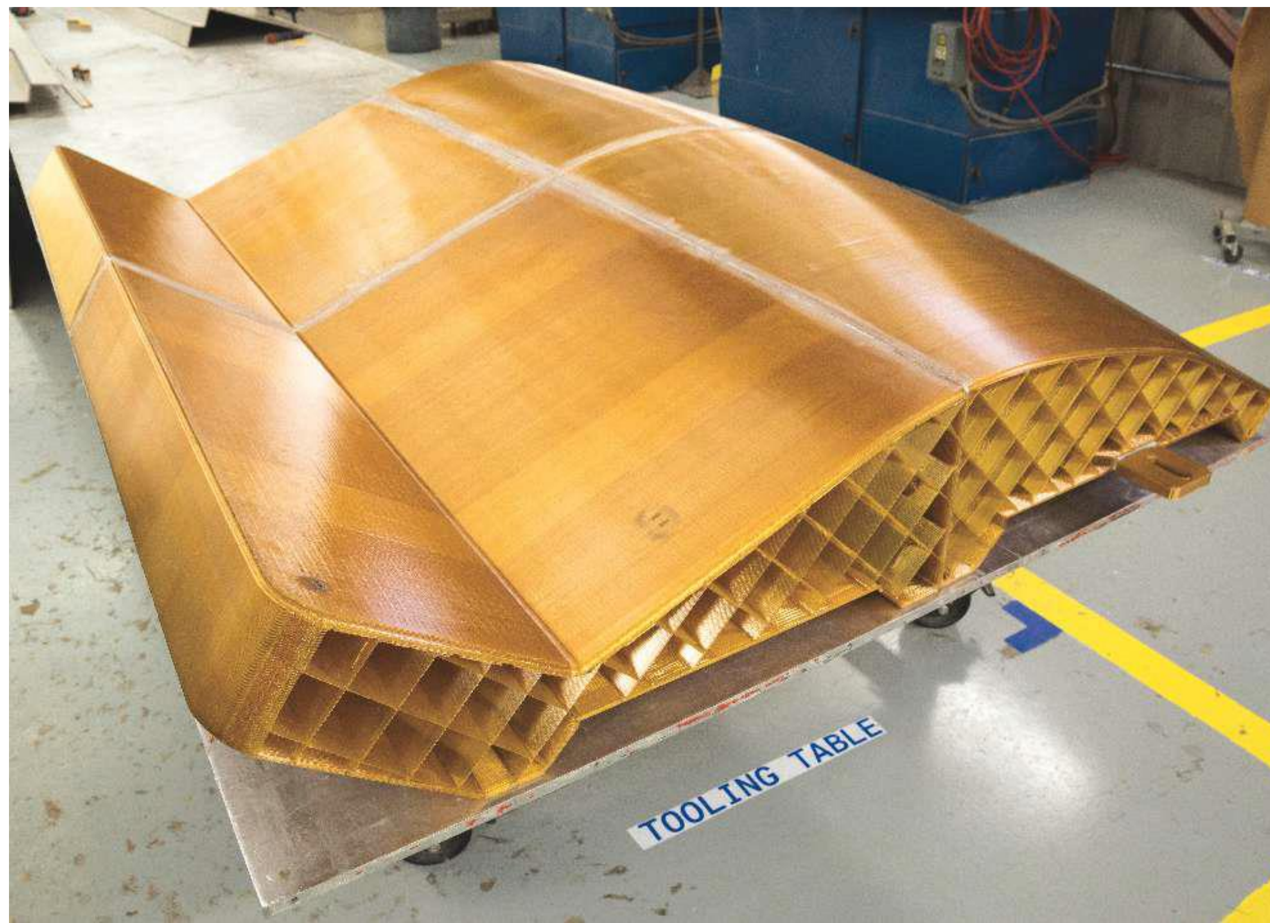


Tooling materials and processes:3D printing

- Polycarbonate, amorphous PET-G or ABS are also used, reinforced with short glass or carbon fibres
- The picture: ultem 1010 polyetherimide (PEI), with a Tg of 216° C
- Parts are vacuum-bagged and oven-cured at 121° C
- Surface smoothing needed
- Soluble resins available when

undercuts are present

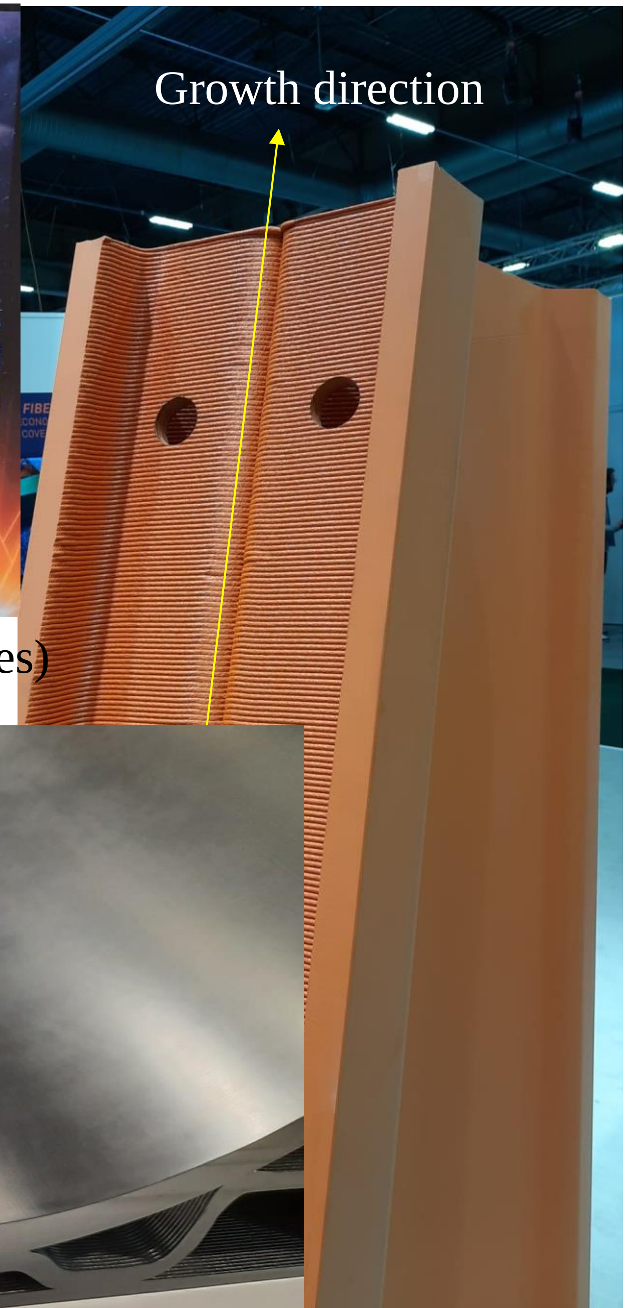
- Main advantage:
  - Dramatically reduced the time for tool fabrication
- 3D printing is candicate to substitute PU and epoxy foam boards



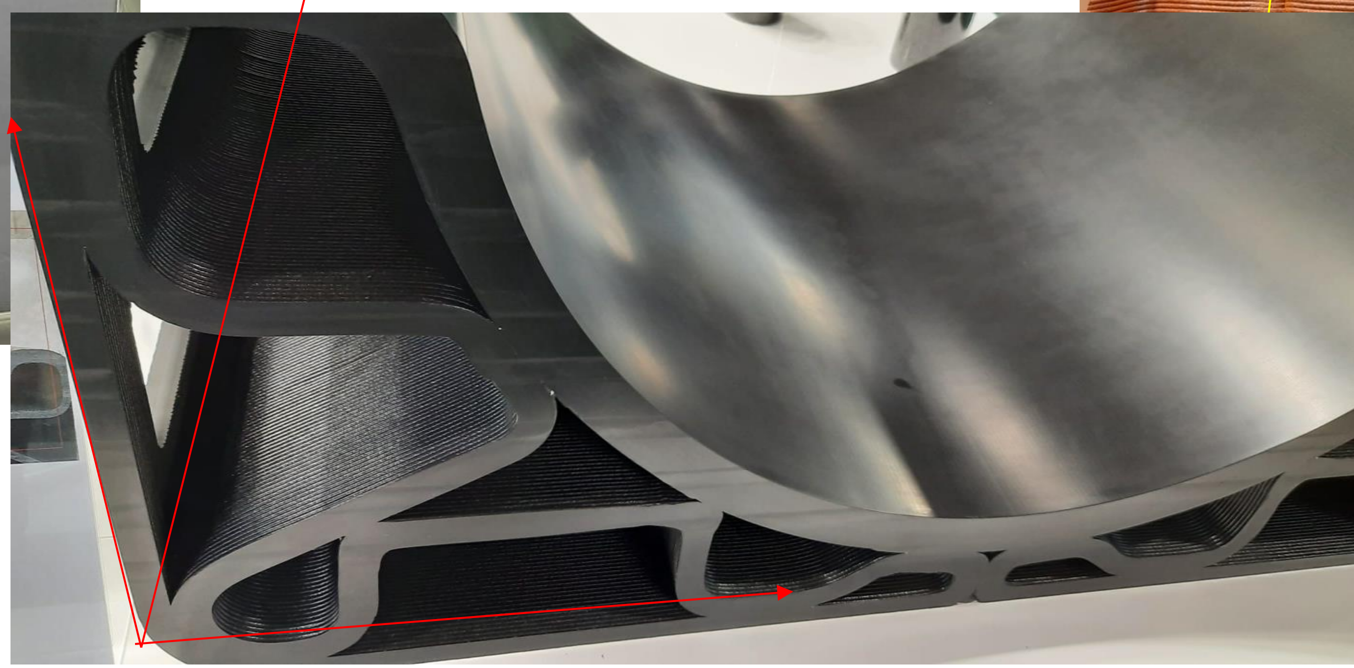
Tooling materials and processes:3D printing

Anisotropic strength and stiffness is obtained due to the layer-by-layer fabrication (see the rough surfaces not machined)

- Material: PC+CF
- Equipment: machine for additive and subtractive manufacturing



Growth direction (lower mechanical properties)



https://www.youtube.com/watch?v=g3mNEeUUFZQ&ab_channel=CEADGroup

Tooling materials and processes:3D printing

«Massivit» process (https://youtu.be/KCgnueUyPhU):

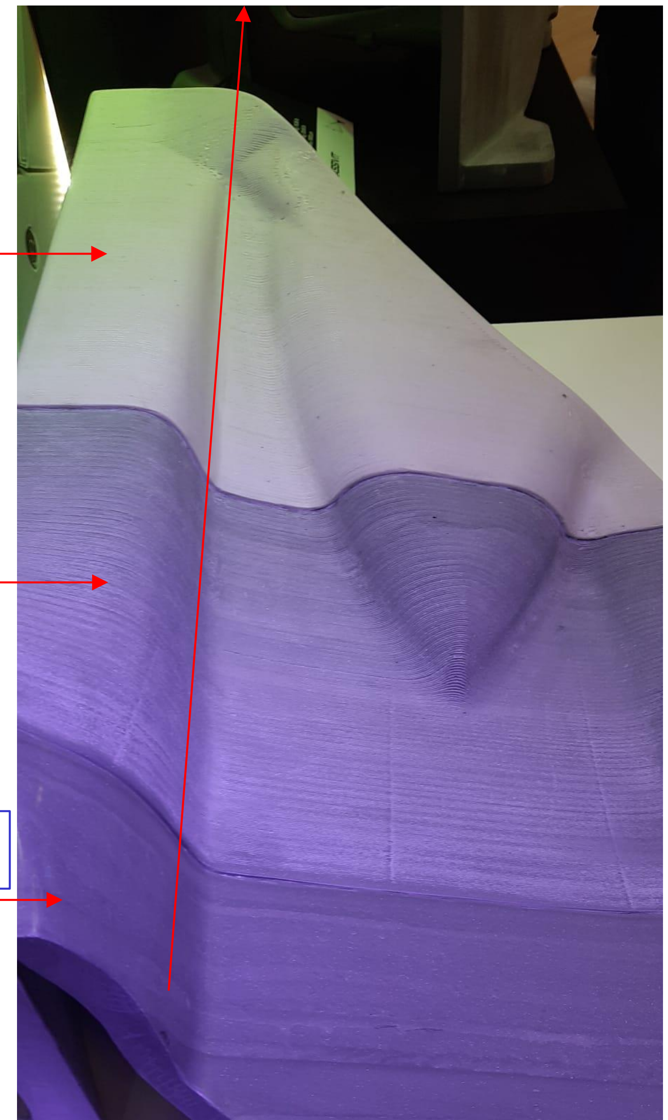
- Anisotropic strength and stiffness resulting from the layer-by-layer fabrication can be by-passed making first an external «mould» by 3D printing and casting into it an epoxy resin more stiff and strong.

Growth direction

1- An external sacrificial shell is 3D-printed by UV polymerization of an acrylic thermosetting resin. This resin after casting is dissolved

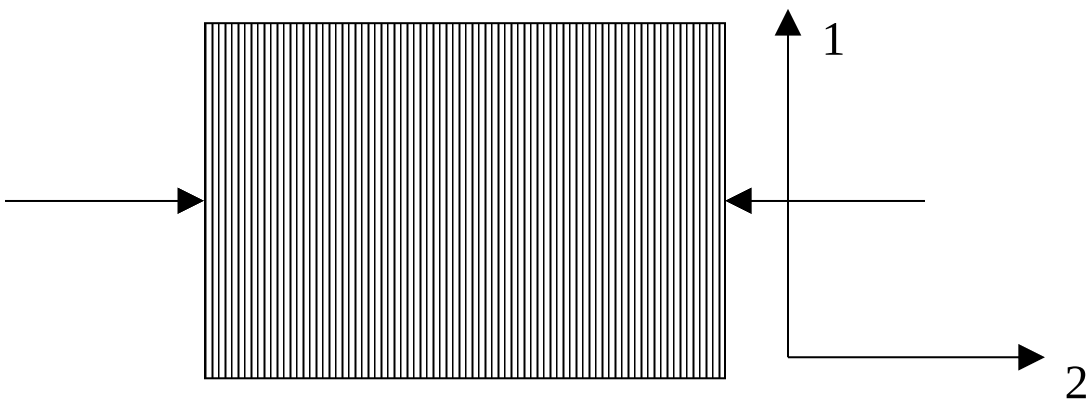
1- Cast epoxy resin still reproducing the rugosity resulting from 3D printing layer-by-layer deposition.

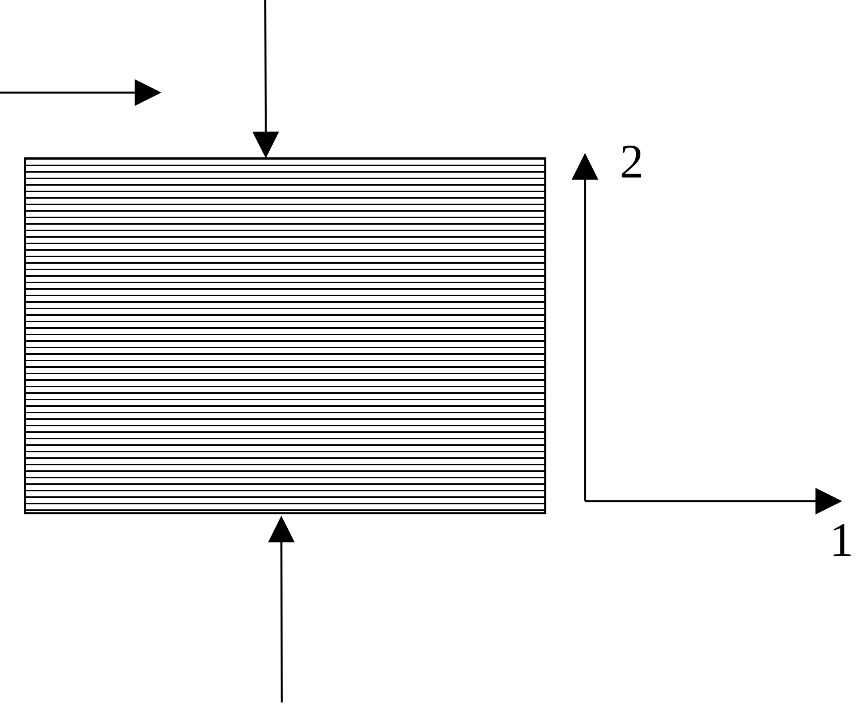
1- Epoxy resin after polishing



Effects of shrinkage

- The assembly of anisotropic laminae determines a state of residual stress that can never be eliminated. Relaxation mechanisms allow to reduce the values calculated for perfect elastic laminae considering an initial state of zero stress at the temperature of cure in the case of elastic behavior
- Direction of highest shrinkage= →





A laminate made of two superimposed plies with fibers oriented at 0° and 90° (as in the figure) will deform to a different extent in 1 and 2 directions being characterized by different stiffnesses in these directions→ After cooling from cure temperature a bend laminate will be obtained

Void content

Air, water and VOC (volatile organic compunds)

↓

Microvoids (porosity)

↓

Mechanical properties reduction
(in particular the interlaminar shear strength, ILSS)

Up to 4% void content, ILSS is reduced of 7% for every 1% of void.

In aeronautic primary structures the void content should be below 1%

Void content and interlaminar shear stress

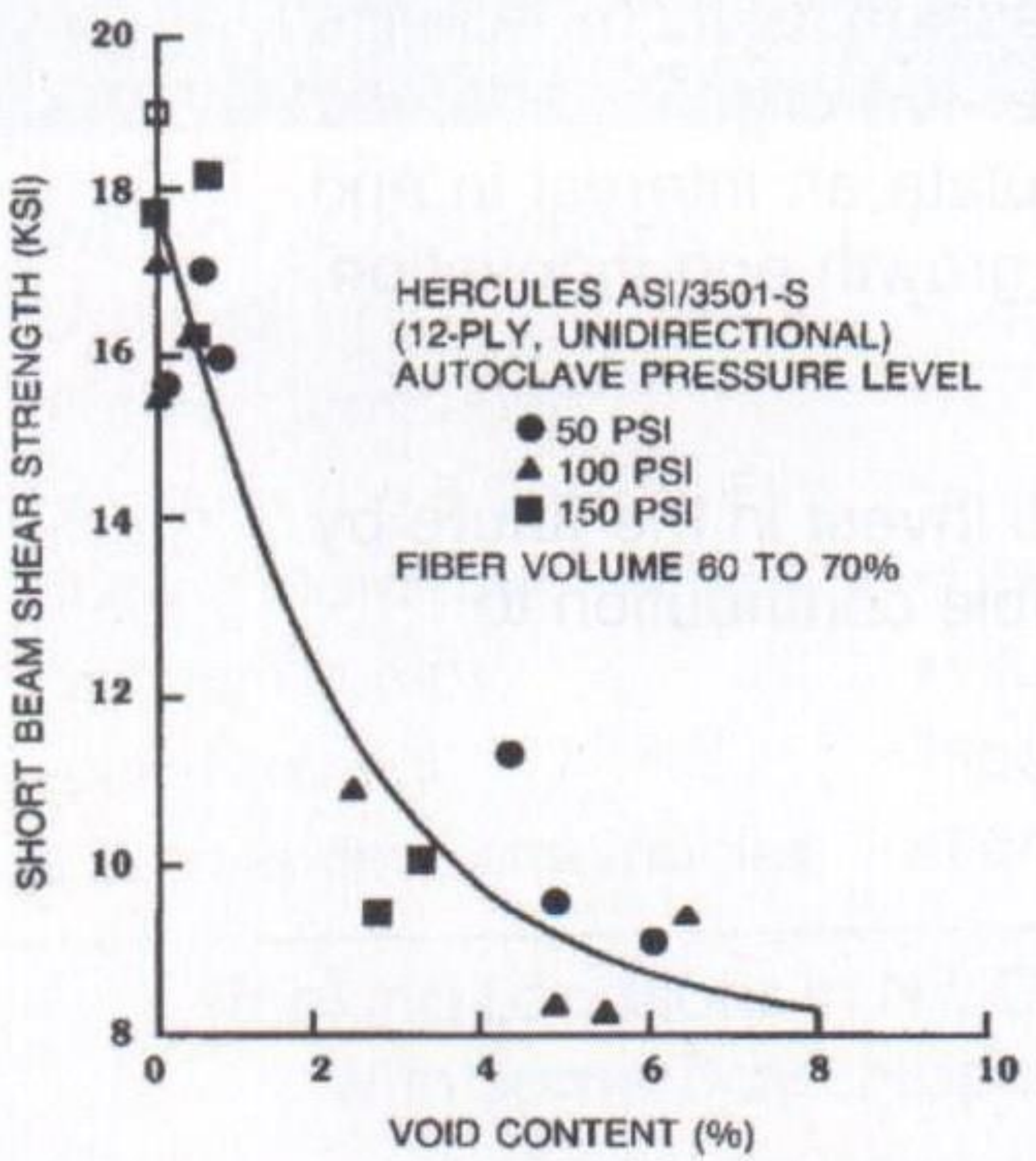
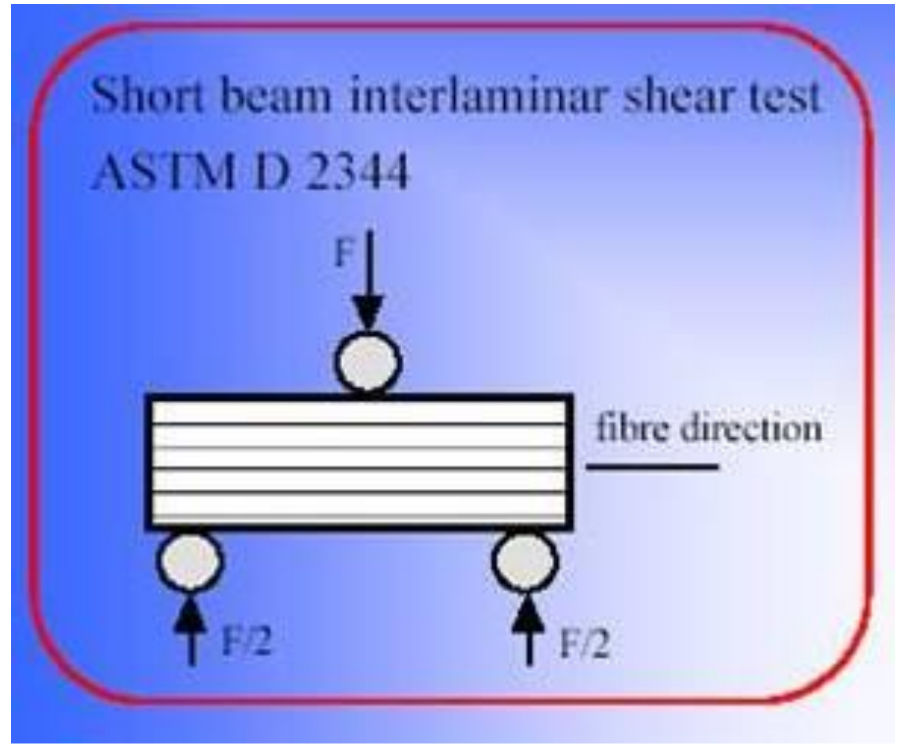
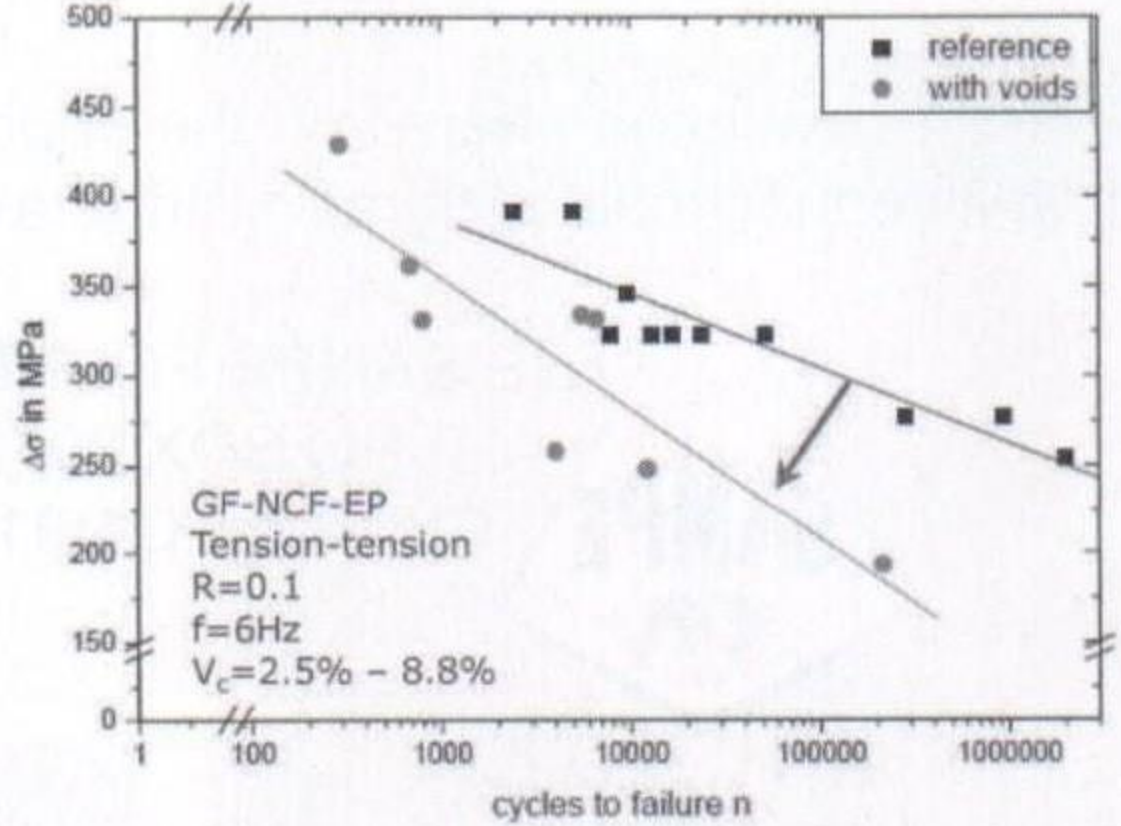


Figure 1. Effect of Void Content Upon Short Beam Shear Strength (Carbon/Epoxy)



In this test the failure occurs under shear loads

Void content and fatigue



Reduction in fatigue properties due to presence of micro-voidage

Figure 2. Effect of voids upon fatigue strength in carbon/epoxy composite.

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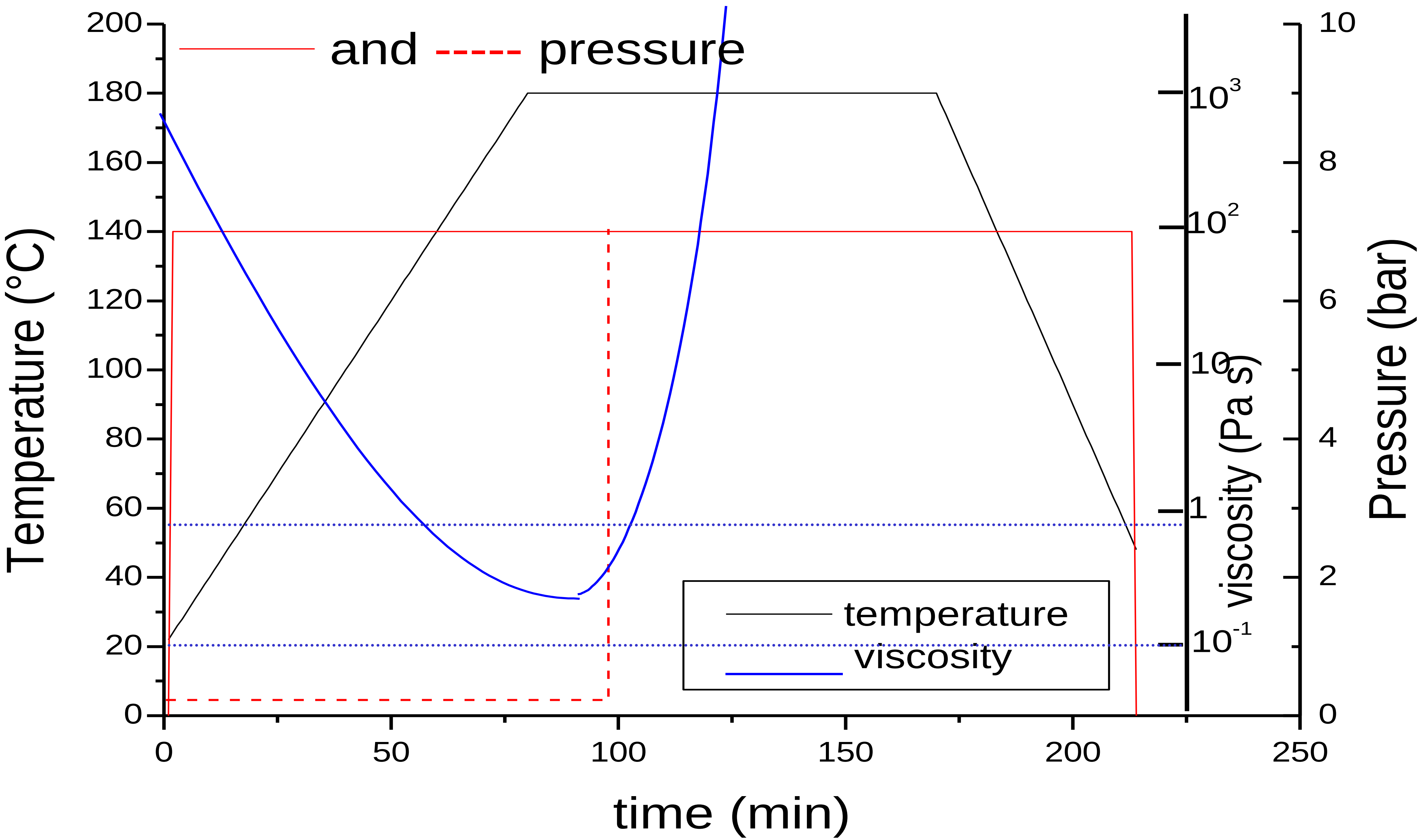
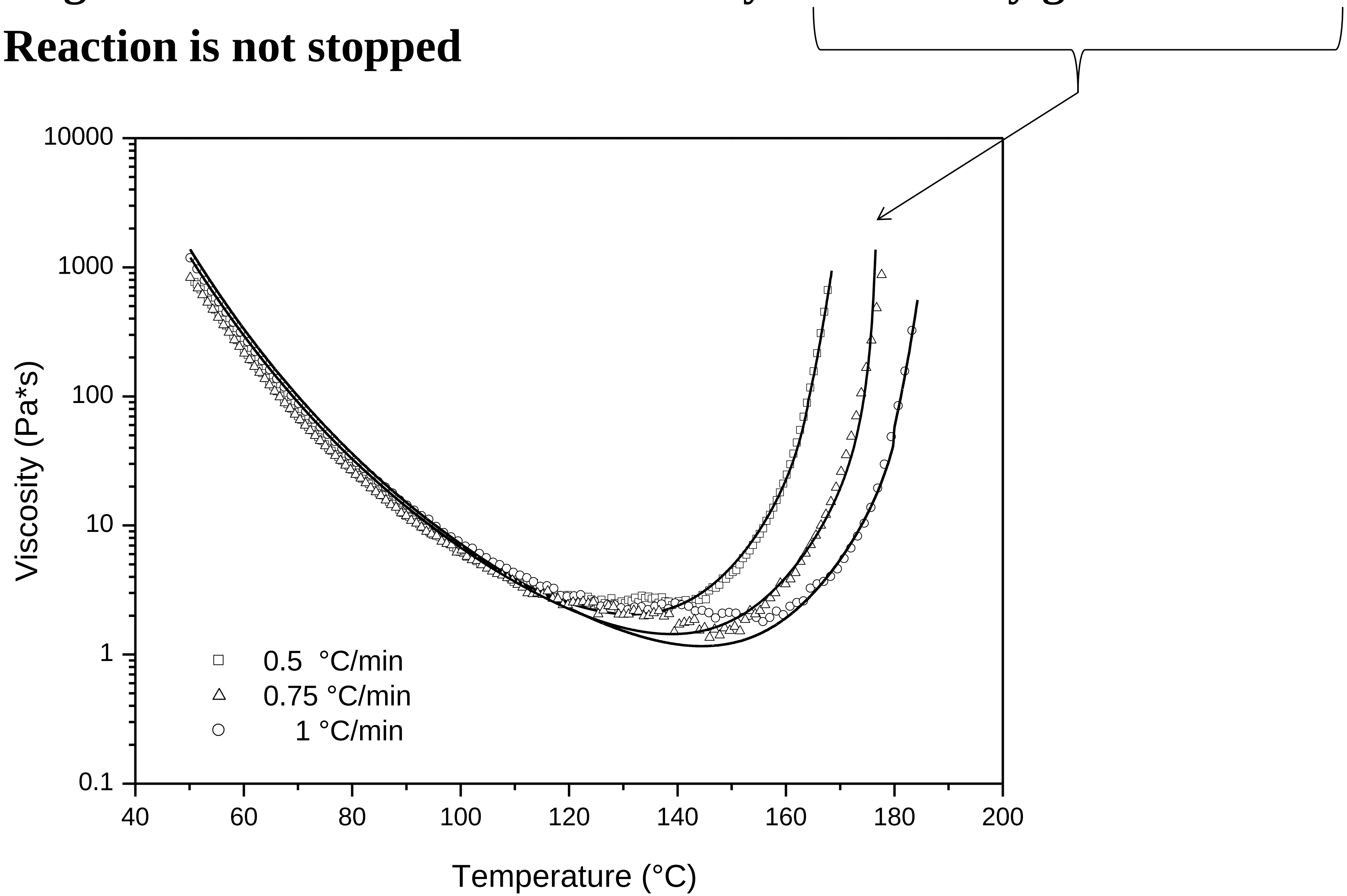
The most used cure cycle

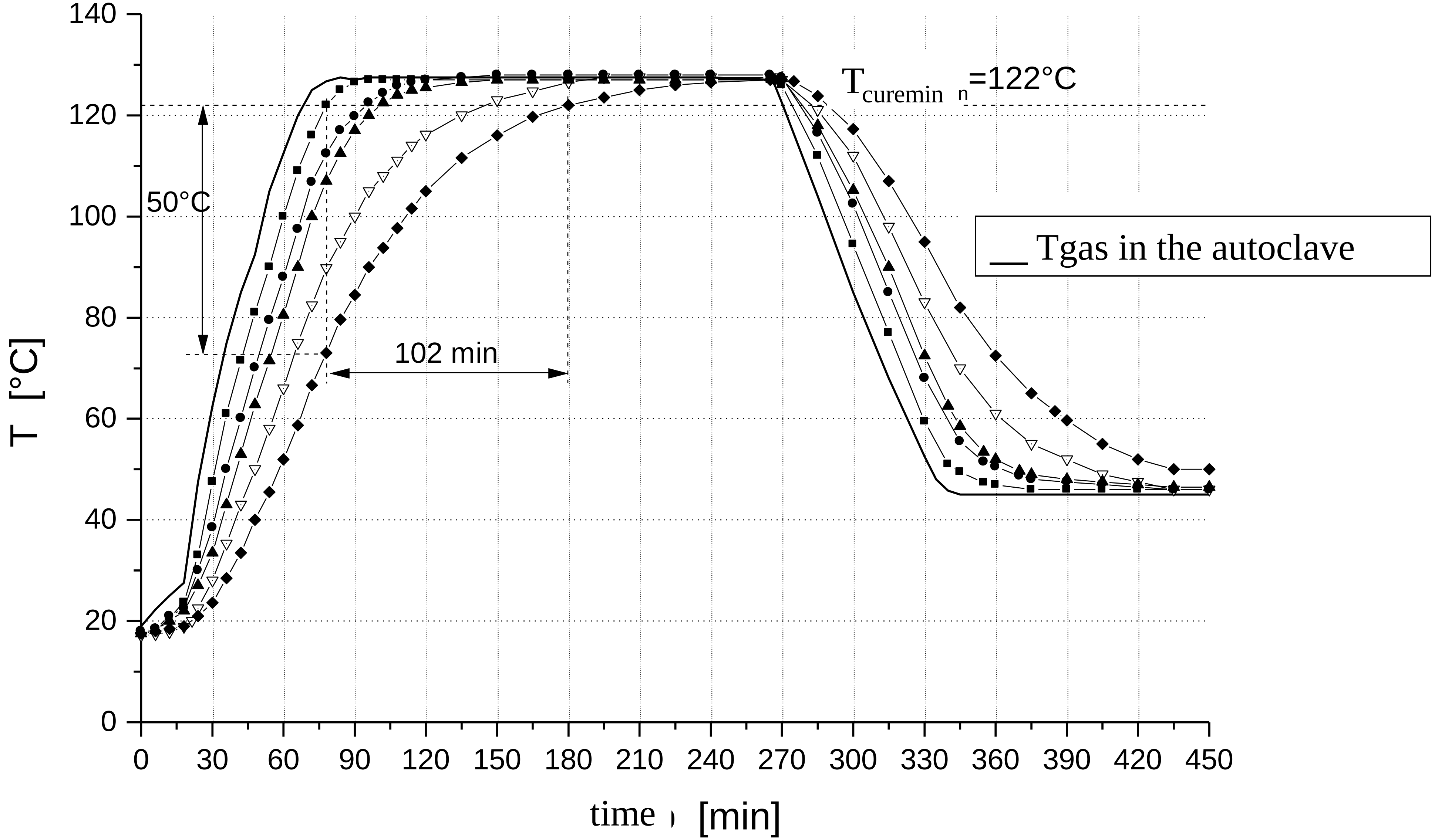


Viscosity changes during cure: a real case

- **At gelatiom the resin becomes rubbery and viscosity goes to infinite**
- **Reaction is not stopped**

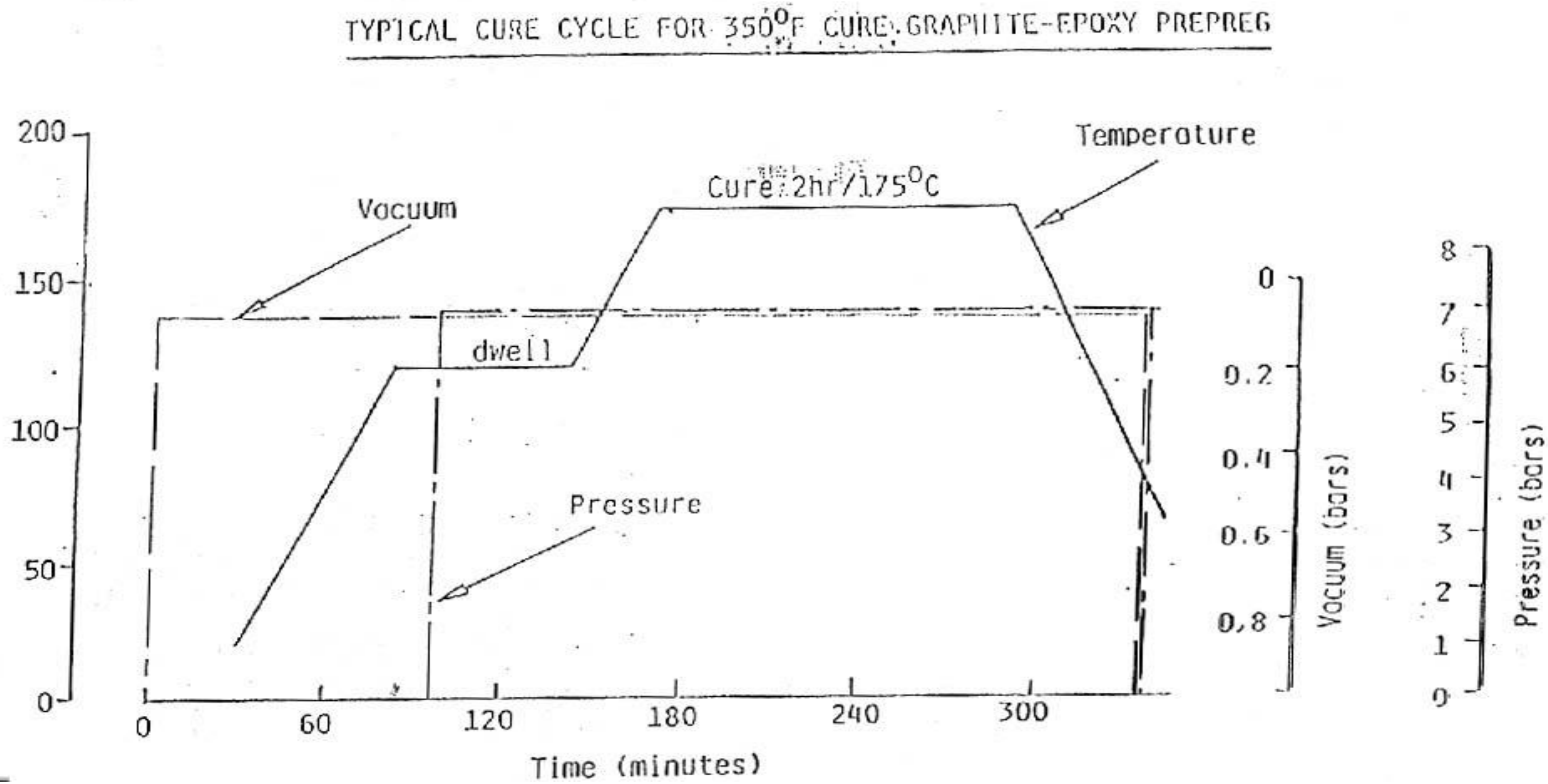


A real cure cycle: temperature measured on composite parts



Cure cycle with a dwell

(used for thick parts in order to keep more uniform the temperature across the thickness)



Monitored (imposed) parameters in a typical curing cycle to each composite part

- <u>Cure temperature $\pm$</u> a tolerance (e.g. 180$\pm$5 °C) measured by the thermocouples placed on the parts
- Minimum time at the curing temperature as measured by the thermocouples placed on the parts
- Heating and cooling rates $\pm$ a tolerance (typical heating rate 2 $\pm$1 °C/min, typical cooling 4$\pm$1.5 °C/min), as measured by the thermocouples placed on the parts
- Max temperature for autoclave door opening
- <u>Gas pressure</u> and pressure profile (with a tolerance)
- <u>Vacuum in the bag</u>: pressure below a given limit

Prepregs and Resin Systems

Primary and Secondary Structures

Thermoset Prepregs

Product/Features	Fibre	Product Form	Fibre Aerial Weight (gsm)[1]	Tg °F (°C)	Recommended Cure °F (°C)
CYCOM® 977-2: Toughened epoxy for primary and secondary structure applications	• Standard modulus • Intermediate modulus	• Uni-tape • Plain • 5 harness • 2x2 twill • Film	Tape: 134, 196, 268 Fabric: 193, 280, 370	414 (212) (dry) 313 (156) (wet)	3 hrs at 350 (177)
CYCOM® 5276-1: Highly-toughened epoxy for primary structure applications	• Standard modulus • Intermediate modulus	• Uni-tape • Plain	Tape: 145, 190 Fabric: 193	370 (188) (dry) 310 (154) (wet)	2 hrs at 350 (177)
CYCOM® 5320-1: Toughened epoxy for VBO processing of primary structures	• Standard modulus • Intermediate modulus	• Uni-tape • Plain • 5 & 8 harness	Tape: 145, 190 Fabric: 193, 370	451 (232) (dry) 356 (180) (wet)	3 hrs at 250 (121) plus free standing postcure of 2 hrs at 350 (177)
CYCOM® 5250-4: BMI system for use in primary structure applications	• Standard modulus • Intermediate modulus	• Uni-tape • Plain • 5 & 8 harness	Tape: 145 Fabric: 193, 280, 370	548 (287) (dry) 433 (223) (wet)	6 hrs at 350 (177) plus 6 hrs at 440 (227) postcure
MTM® 45-1: Toughened epoxy for primary and secondary structures	• Standard modulus • Intermediate modulus • E glass, S glass and quartz	• Uni-tape • Plain • 5 harness	Tape: 145, 228 Fabric: 193, 203, 370	356 (180) (dry) 320 (160) (wet)	4 hrs at 250 (121) 3 hrs postcure at 350 (177)
CYCOM® 977-3: Toughened epoxy resin with dry and wet service capability formulated for autoclave or press moulding	• Standard modulus • Intermediate modulus	• Uni-tape • Plain • 5 harness	Tape: 145, 228 Fabric: 193, 203, 370	400 (204) (dry) 334 (168) (wet)	6 hrs at 350 (177)
CYCOM® 970: Epoxy resin producing nonporous, void-free honeycomb sandwich structures and laminates	• Standard modulus	• Uni-tape • Plain • 8 harness	N/A	300 (149) (dry) 200 (93) (wet)	2 hrs at 350 (177)
AVIMID® S: Non-MDA addition type polyimide prepreg formulated for press or autoclave cure	• Standard modulus • Intermediate modulus • E glass, S glass and quartz	• Plain • 8 harness • Various	N/A	625 (330) (depending on cure cycle)	5 hrs at 200 (93) plus post cure of 4 hrs at 680 (360)
CYCOM® 5575-2: Modified cyanate ester formulated for high temperature mechanical properties and low dielectric and loss tangent properties	• E glass, S glass and quartz	• Various	N/A	500 (260)	4 hrs at 350 (177) plus post cure for 2 hrs at 440 (227)

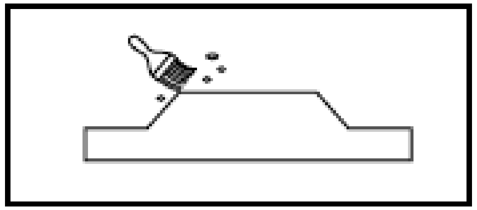
Prepregs for aeronautic applications

To be Noted:

- Recommended cure cycle
- T_g dry and wet
- Toughened epoxy
- VBO (Vacuum bag only)
- BMI (Bis-maleimide) and Cyanate ester resins (high Temp.)
- Type of reinforcement
- Prepregs for Honeycomb sandwich structures

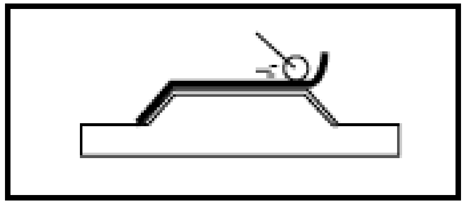
LAY-UP

1



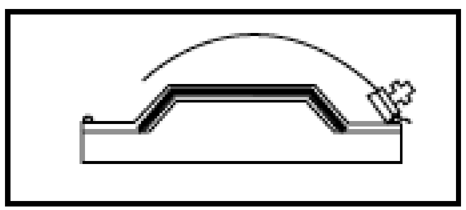
APPLY MOULD RELEASE

2



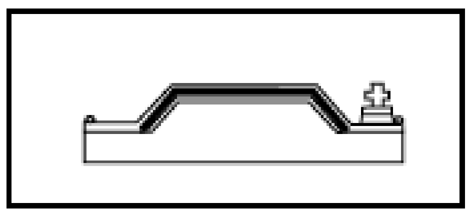
LAY-UP PREPREG

3



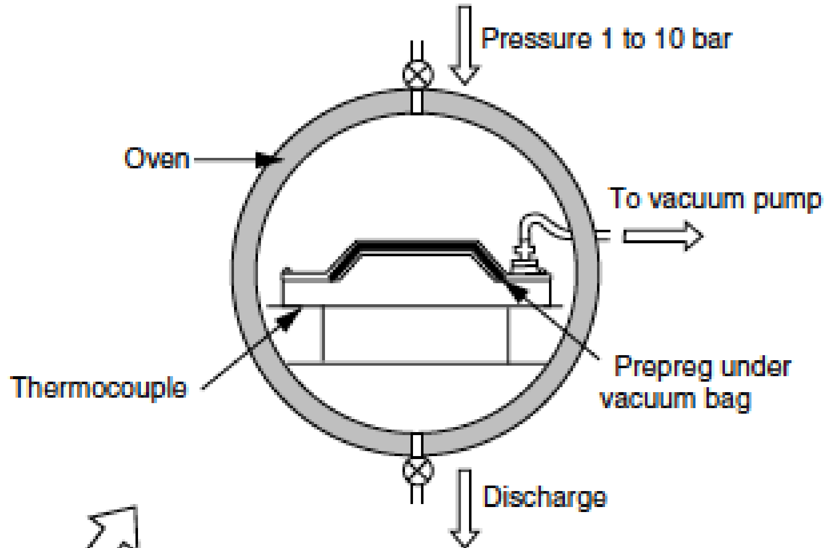
ASSEMBLE VACUUM BAG

4



CURING

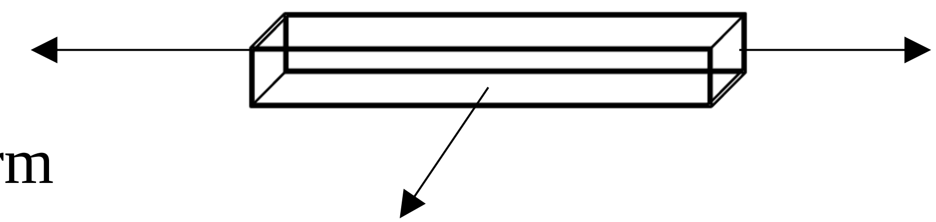
Autoclave process



Application of vacuum
+
heat

Resin flow

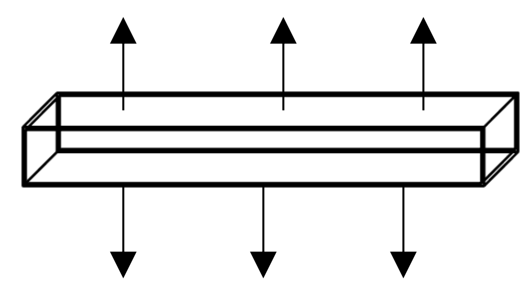
- Resin flow depends on the applied pressure (3 to 8 bar). It can occur:
  - At laminate edges (undesirable)



This must be avoided to limit non uniform

resin distribution and thickness gradients in the plane

  - At laminate surfaces (desirable)



Promote void removal

Uniformity of resin distribution

Void formation and growth

- Void growth can occur if the vapour pressure (T_v) of any potential volatile compound exceeds the actual pressure (P_r) in the resin (i.e. the hydrostatic pressure in the resin)

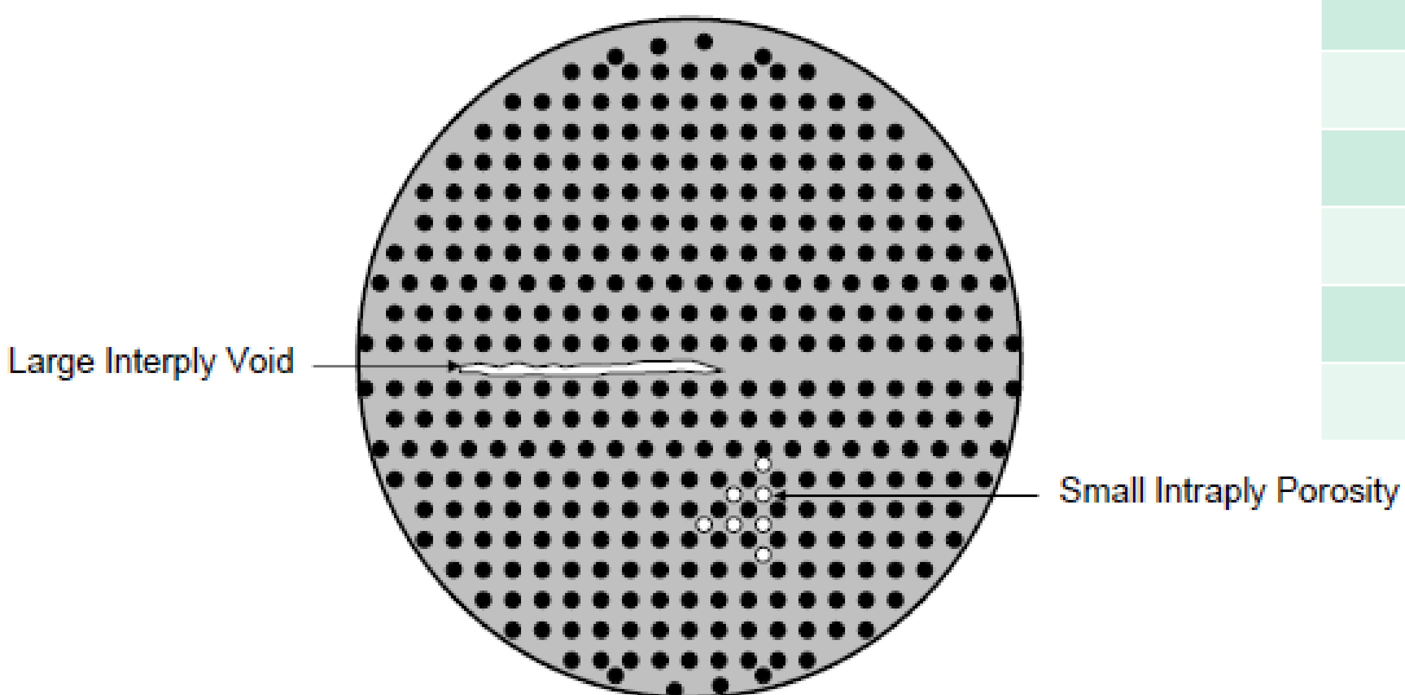
If $T_v > P_r$ voids can be generated and grow

Water vapour saturation pressure at 180 ^oC is 9.9 bar at 130 ^oC 2.7 bar

- At high viscosity and above gel point voids become entrapped in the matrix

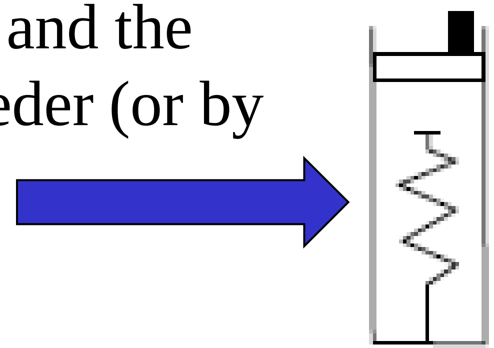
Interply and intraply voids

Temperature ° C	Vapour pressure, atm
100	1.001
110	1.42
120	1.96
130	2.67
140	3.57
150	**4.70**
160	**6.10**
180	**9.90**



Voids formation and growth

- Most of the void is due to water absorbed by the prepreg. Unreacted epoxy resins are strongly hydophillic.
- Other volatiles can originate from solvents used in the impregnation process.
- The hydrostatic resin pressure, capable to prevent the formation of voids, is only a fraction of the autoclave pressure: <u>also fiber beds have a load carrying capability</u>
- In the mechanical analogy, the spring represents the fiber bed and the liquid in the dashpot the liquid resin. Resin leakage in the bleeder (or by borders) is represented by the top valve.
- (also air entrapped during lay up may be the origin of voids)



Resin pressure:Vacuum bagging

At room temperature:

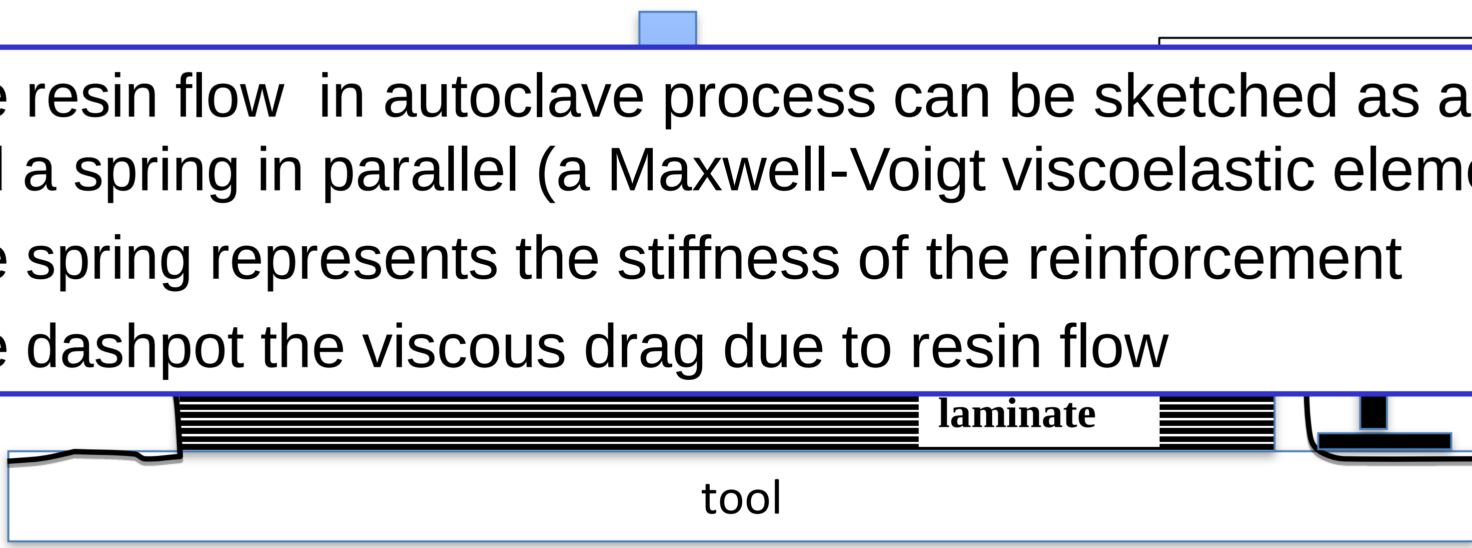
- there is no flow
- The top ply in the stack is kept under vacuum (between -700 and -980 mbar depending on the process)

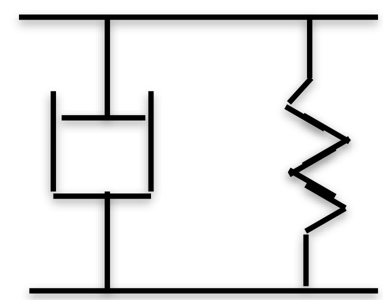
Autoclave pressure reduces the breather thickness. A single layer of breather under 8 bar pressure with a thickness of 0.5 mm was adopted

The resin flow in autoclave process can be sketched as a dashpot and a spring in parallel (a Maxwell-Voigt viscoelastic element).

The spring represents the stiffness of the reinforcement

The dashpot the viscous drag due to resin flow

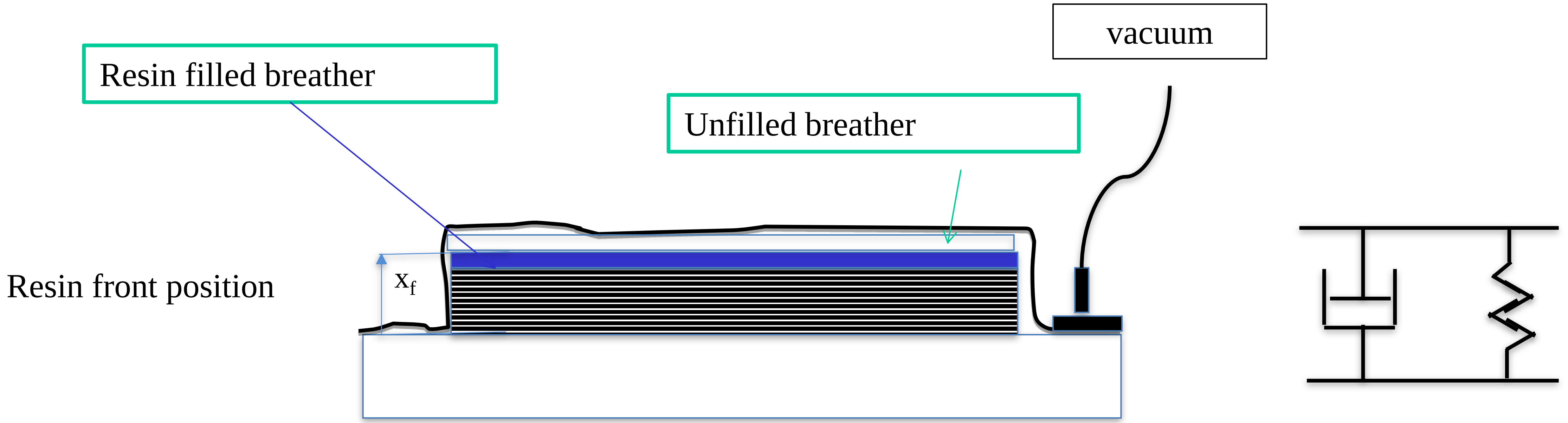




Resin Pressure: heating and resin flow

During heating:

- viscosity decreases
- A pressure gradient is developed across the lay up
- The resin flows through composite thickness filling the breather (in plane flow is neglected) under autoclave pressure
- The upper resin layer still under vacuum



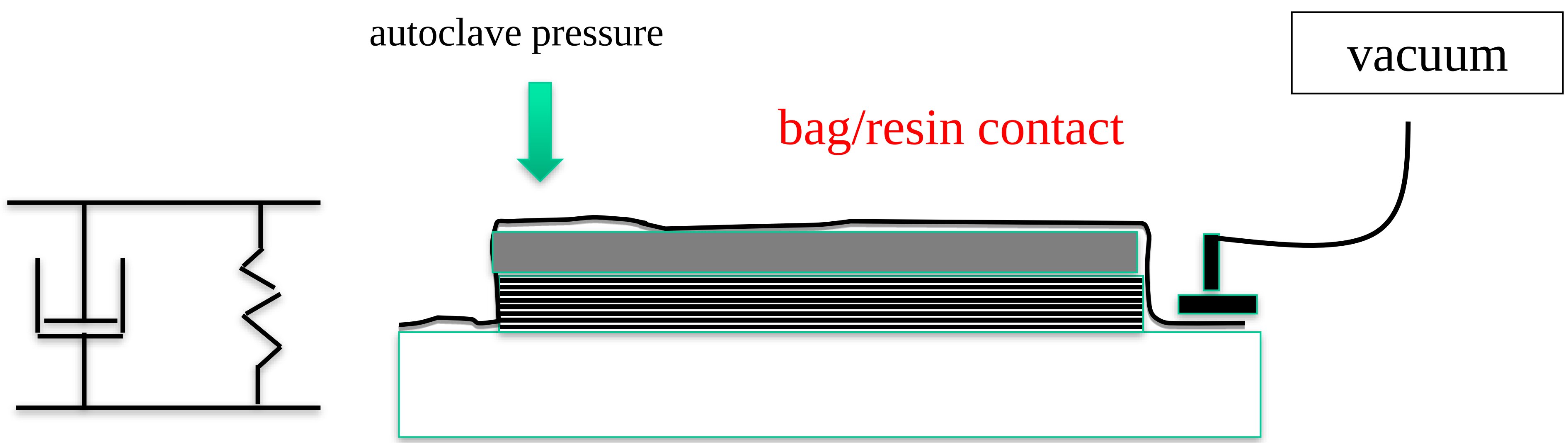
Resin Pressure: end of flow, pressure build up

When the resin touch the vacuum bag:

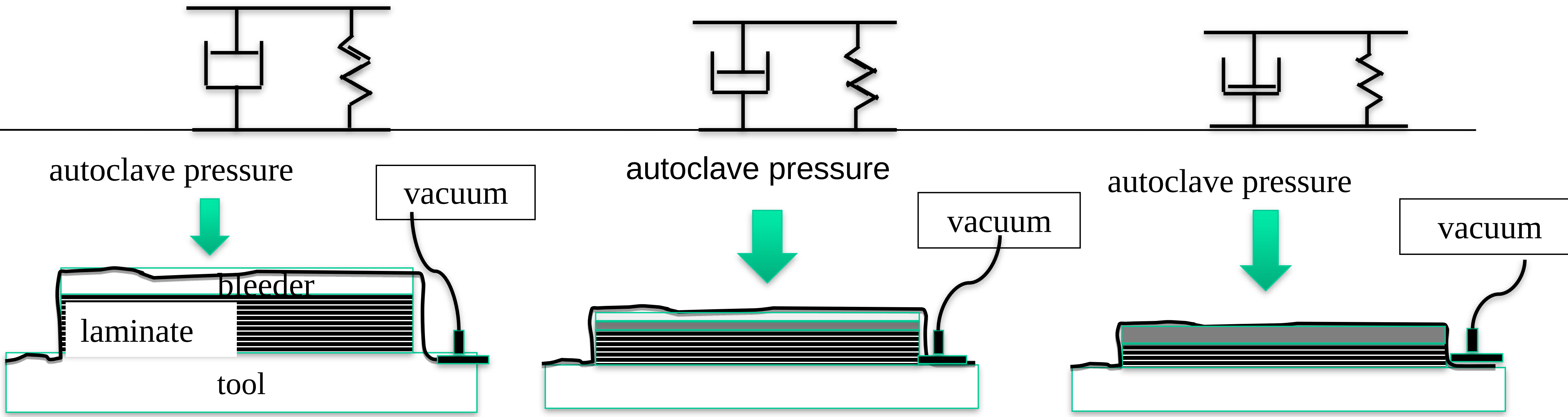
• The flow ends

• The pressure is distributed between that supported by the reinforcement, under compression strain, and the hydrostatic pressure in the resin.

•The resin pressure is always lower than autoclave pressure



A three stage process and the viscoelastic model



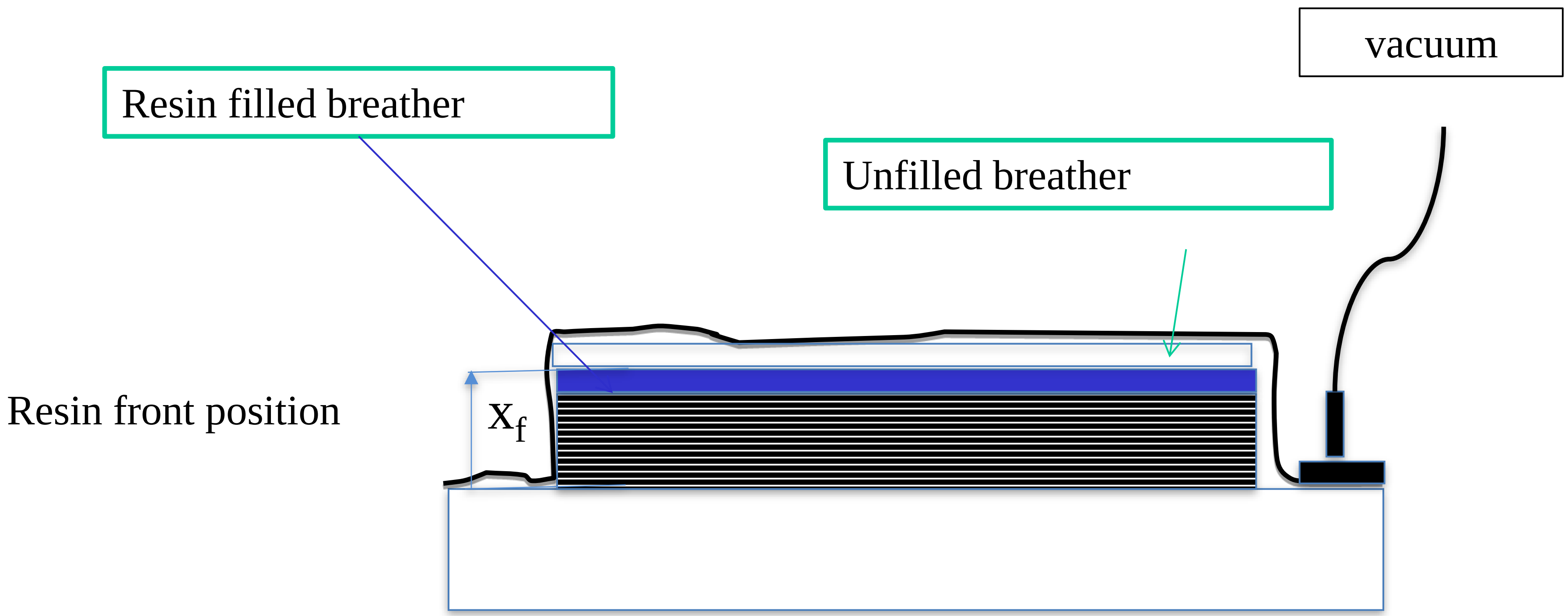
- Room temperature
- No flow.
- Eventual lost of volatiles by diffusion

- Heating: reinforcement compaction and flow.
- Still possible volatile extraction

- vacuum bag in contact to resin
- Flow end

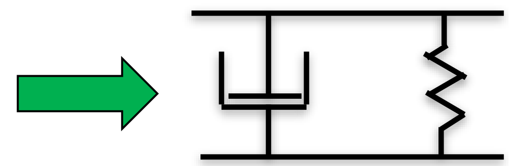
Pressure is distributed between the spring (elastic reaction of fiber stack) and the dashpot (hydrostatic pressure in the resin)

Other possible causes for flow end

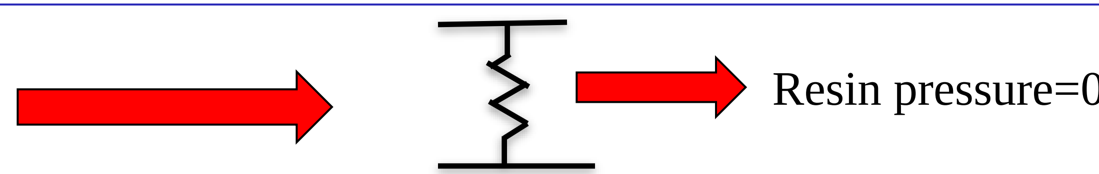


<u>The resin flow ends for three reasons:</u>

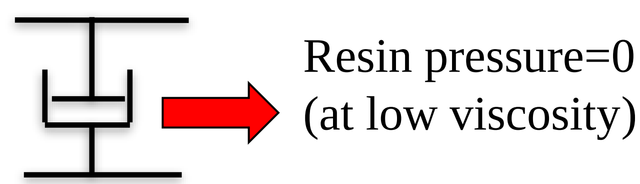
1. the bleeder is filled of resin(as formerly described): bag-resin contact occurs. <u>Pressure distributed between resin and fibers</u>



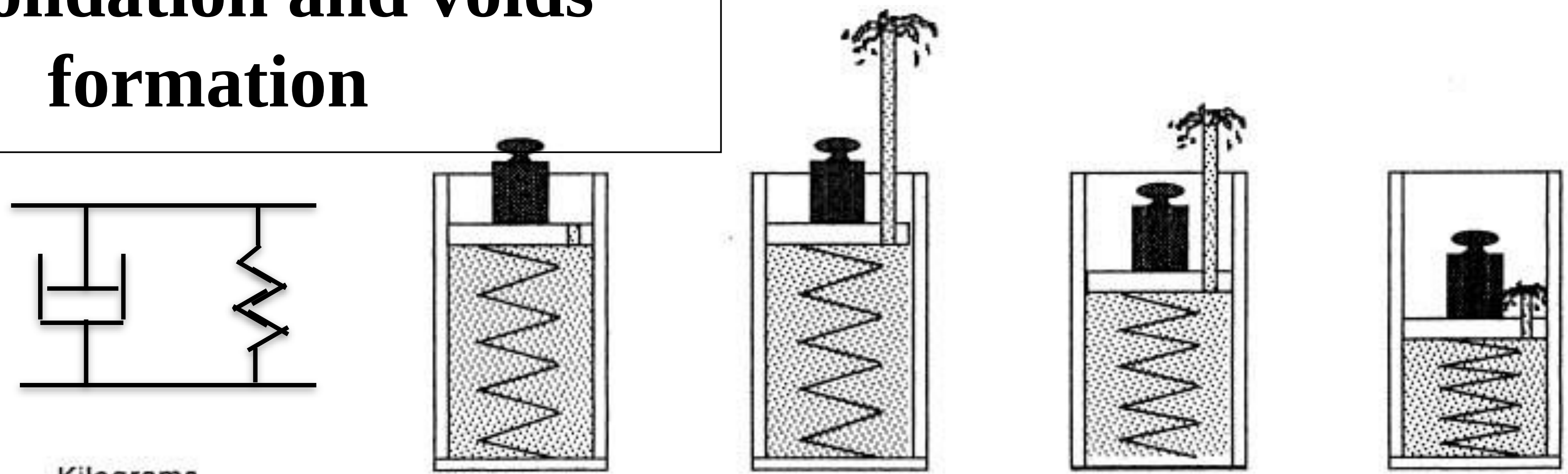
2. the spring takes all the load



3. resin viscosity is very high and the dashpot becomes not deformable and takes the load at high viscosity. <u>Low viscous resin is never in contact with bag</u>



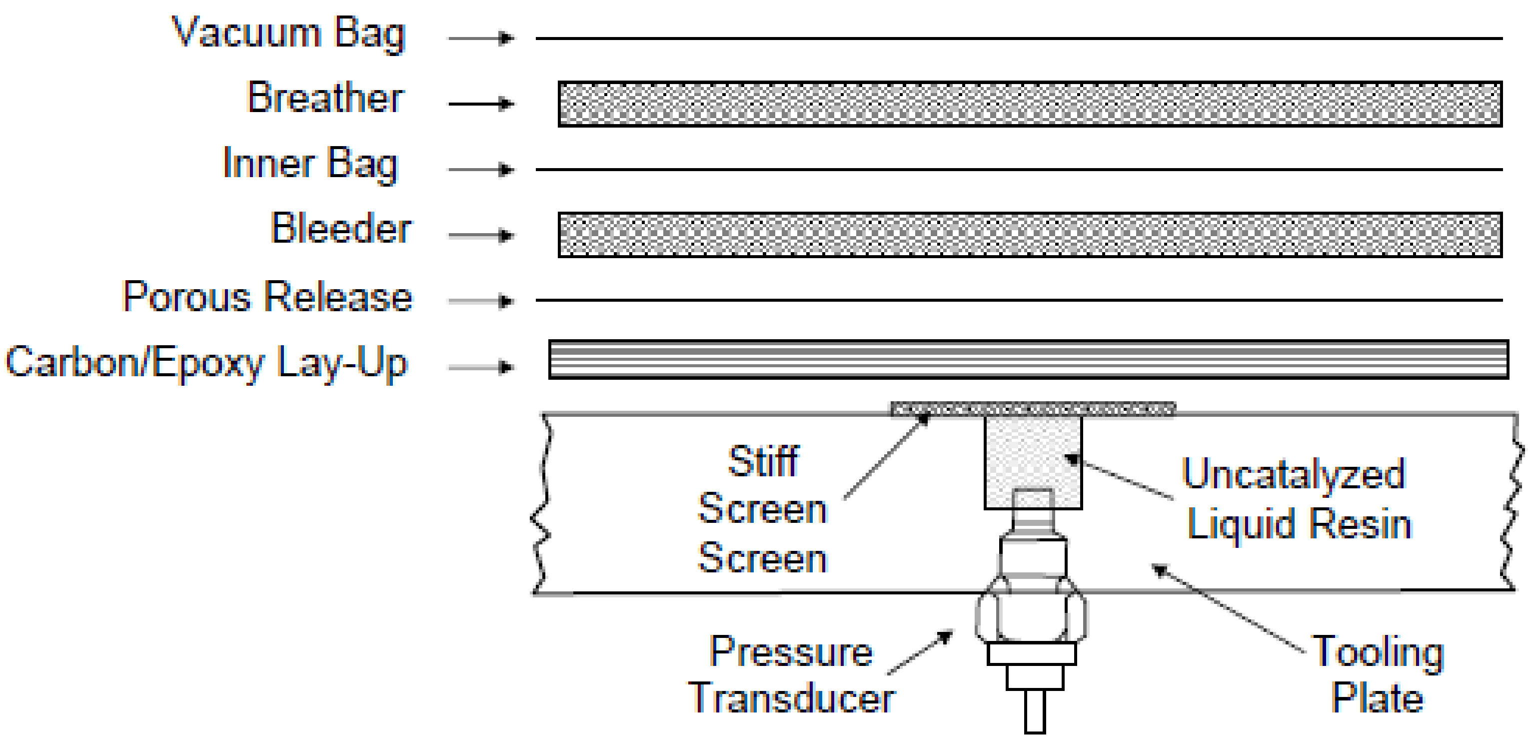
Consolidation and voids formation



Kilograms carried by liquid	10	10	5	0
Kilograms carried by spring	0	0	5	10
Percentage Consolidation	0	0	50	100

- **Step 1:** room temperature very high viscosity
- **Step 2**: Temp. increases, viscosity decreases and the liquid escapes from the damper. Fiber bed is compacted
- **Step 3**: the fiber bed start carrying load and its permeability reduces: the resin flow decreases
- **Step 4**: <u>if gelation is not occurred</u> all the load is carried by spring (compacted fiber bed)→ the hydrostatic pressure in the liquid drops and void formation is likely to occur

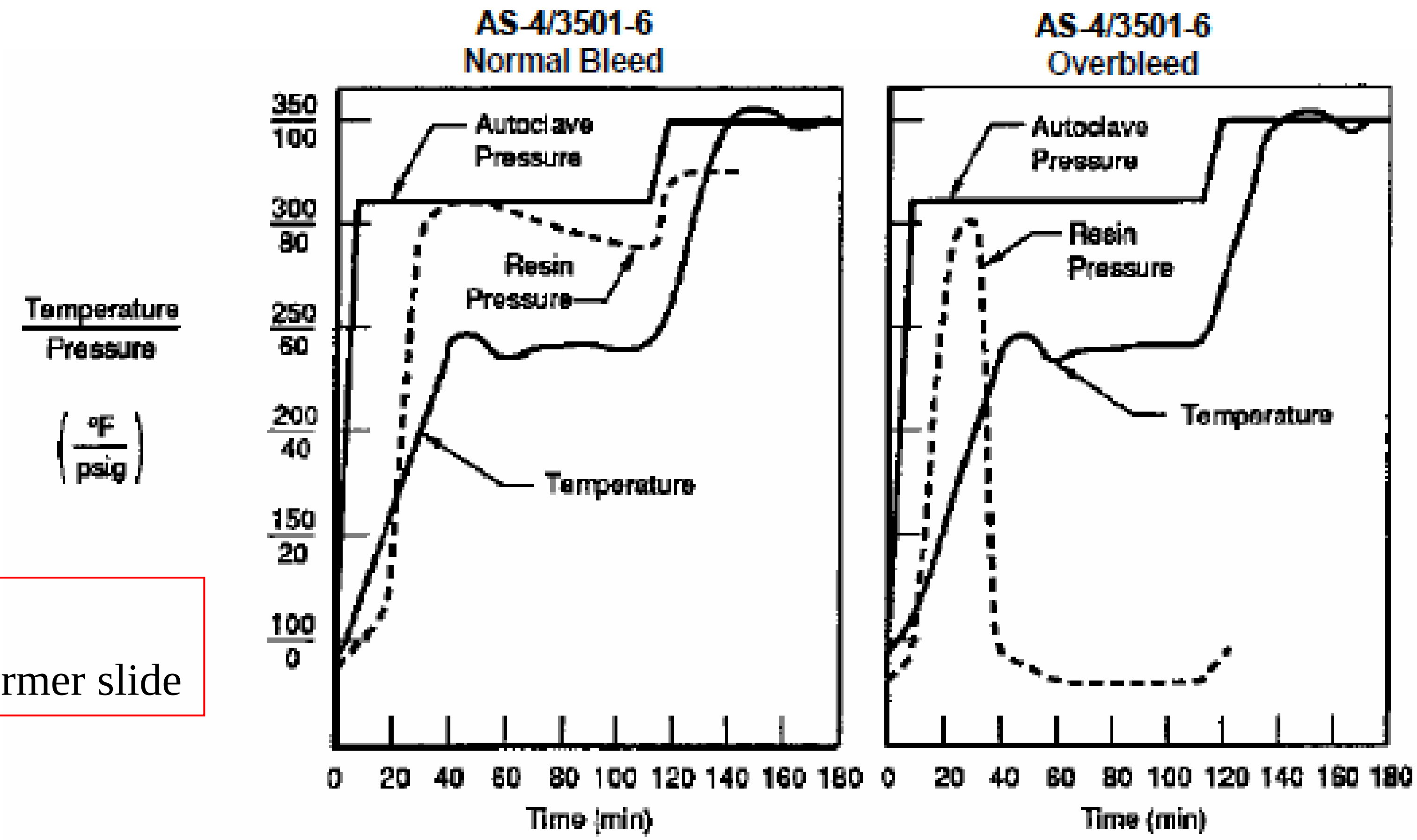
Hydrostatic resin pressure measurements



- The stiff screen prevents deflection into the hole in contatct with the pressure transducer
- Test with high and low flow resins in UD laminates
- 10 to 40 plies

Campbell, J. Adv. Mat. 1995

Hydrostatic resin pressure measurements: results



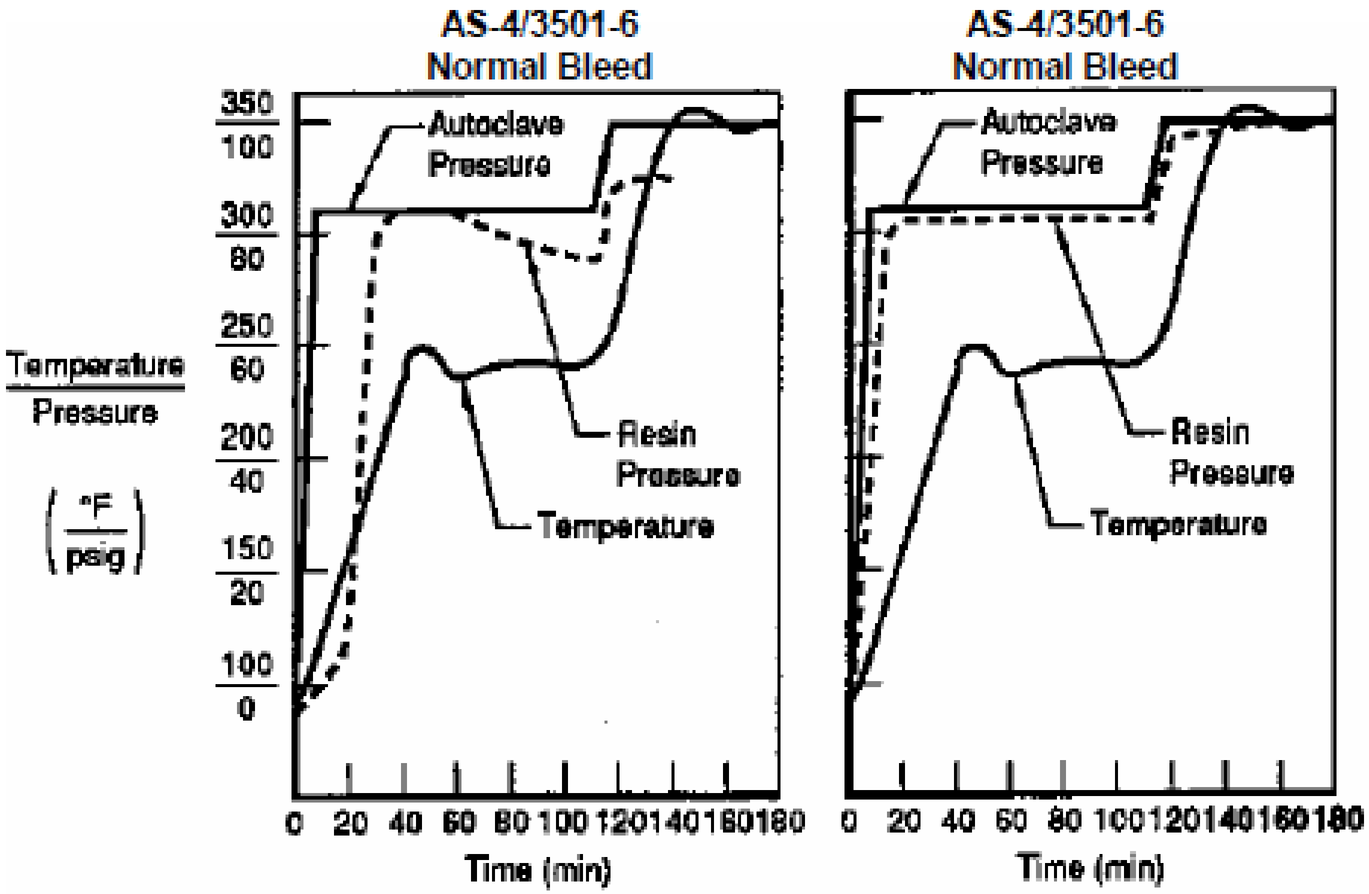
No porosity
Case 1 of former slide

Gross porosity
Case 2 of former slide

- **Normal Bleeder**
- **3X Normal Bleeder**

- Higher resin flow allowed with thick bleeder (overbleeding)
- Resin flow is associated to resin pressure decrease
- Resin flow is promoted by viscosity decrease and is associated to a decrease of the resin pressure

Hydrostatic resin pressure measurements: results



10-Ply Laminate   40-Ply Laminate

- In thicker laminates a higher resin pressure is obtained compared to thinner ones: the same amount of resin absorbed in the bleeder results in a lower fraction of resin loss

Cure process objectives

- Resin polymerization up to a degree of reaction of 0.9-0.95 in order to reach a T_g a bit lower than T_{gmax}
- Resin excess removal and consolidation
- VOC, water and air removal

prepregs →
•contain resin in excess
•entrapped, air, water and VOCs

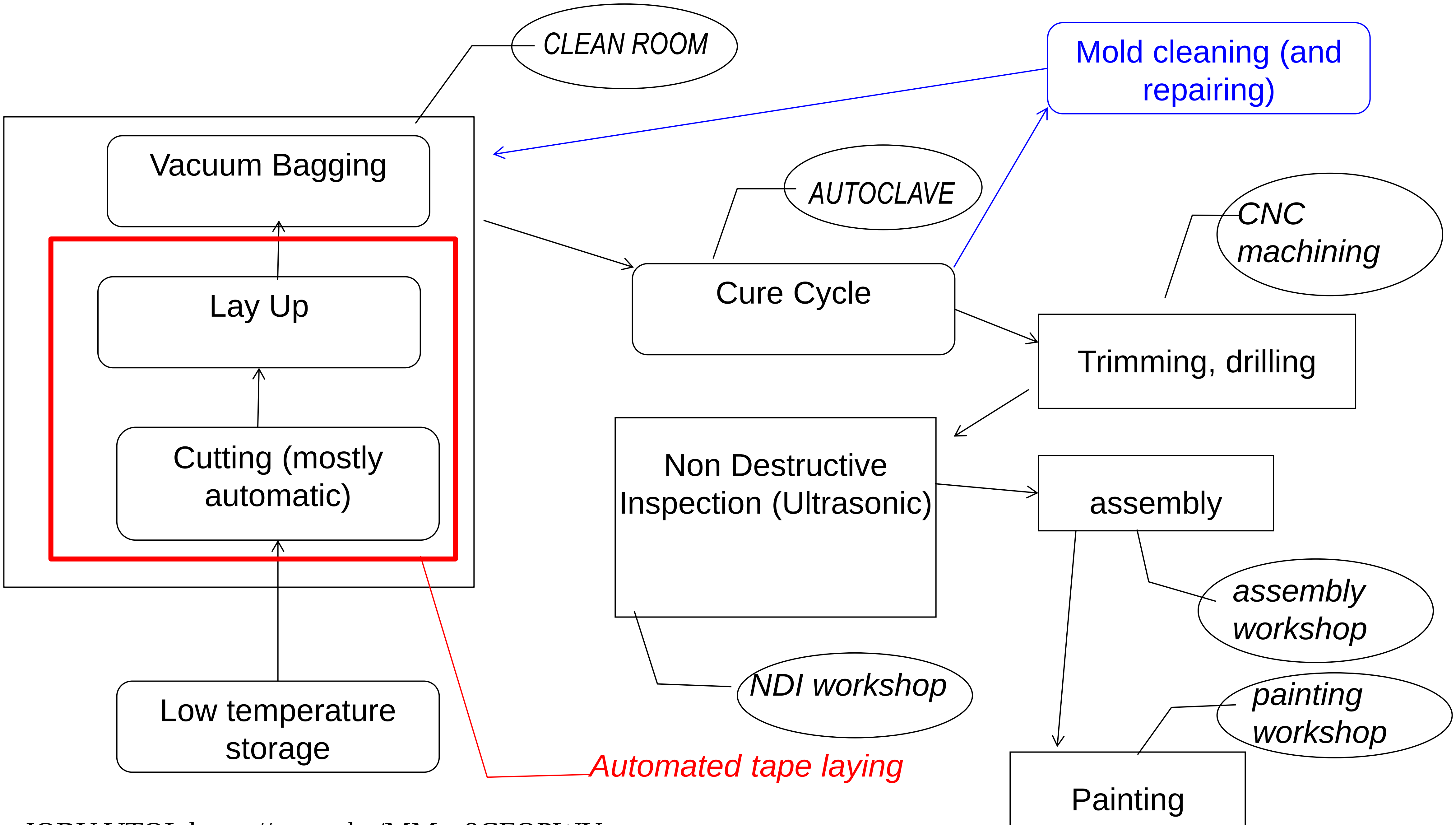
↓

Cure cycle →
•Removal of : resin in excess
entrapped, air, water and VOCs
•Polymerization
•Mechanical properties development (shear, etc.)

↓

Cured Laminate →
•The resin and fiber content must be constant and always the same
• Void content <1%

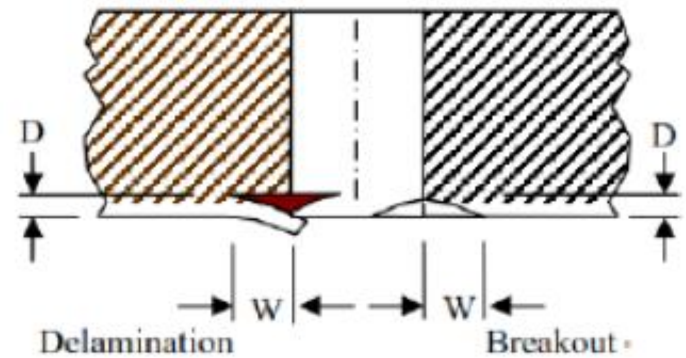
Steps of the fabrication process

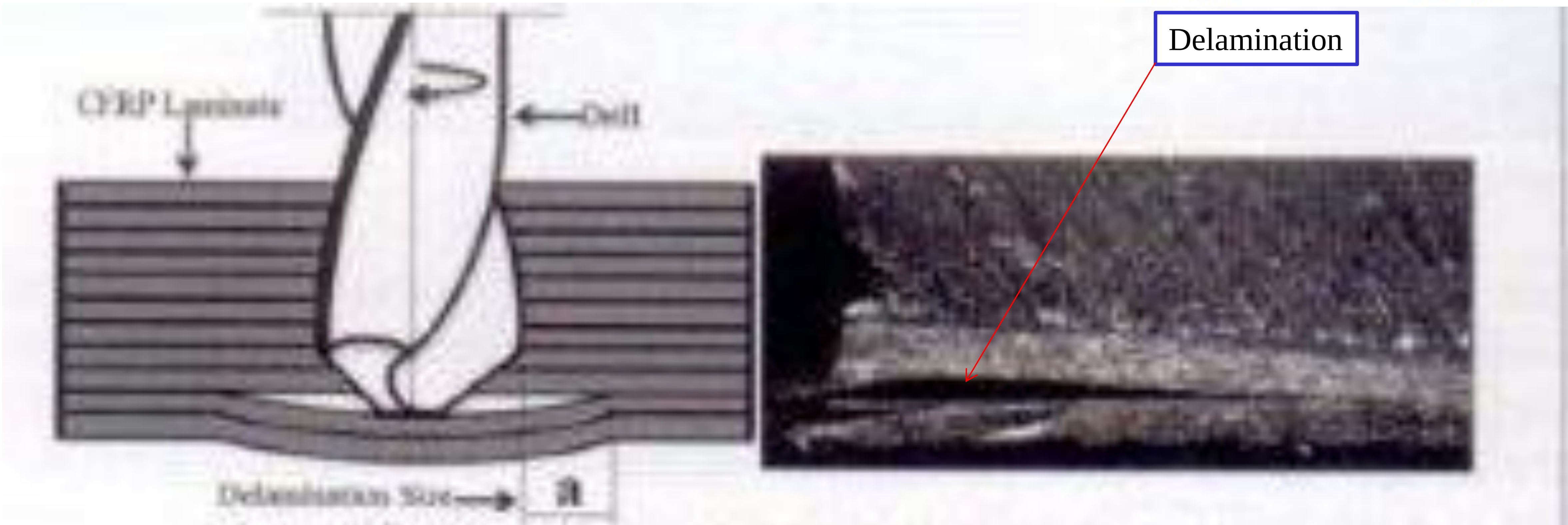


JOBY VTOL https://youtu.be/MMso8CFOPWY

Defects produced during drilling

- The last plies can be delaminated by the tool.
- This depends on the longitudinal force and velocity of longitudinal advancement
- Also the consumption of the tool plays a key role





Sketch of the process flow: car hood (two parts)

1 A day before they are scheduled to be used in production, plies of CFRP prepreg are cut and assembled into kits, then refrigerated. ■

2 As work begins on layup for a panel on the clamshell hood, the layup instructions for that part are loaded into the laser-guidance system. Also, retroreflective targets with cross-hairs are shot down at the lift table to calibrate the laser prior to start of layup. ■

3 A laser projection unit is suspended from the ceiling over each work area where the clamshell hood panels will be layed up. ■

4 The system sequentially projects a green laser outline in the exact shape of the next ply that should be laid down in its specific target location, providing a poka-yoke (mistake proofing) mechanism as well. ■

5 For reference, the work instruction/ply book is never far away. ■

6 Once layup is complete, the part is bagged and prepped for the autoclave cycle. ■

Sketch of the process flow: car hood

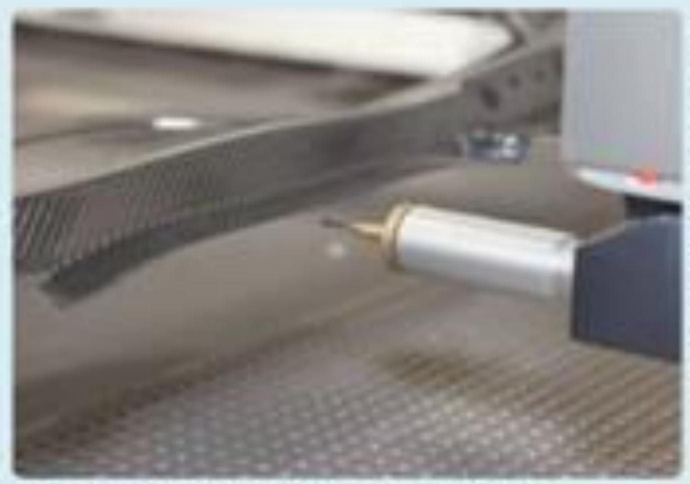
7 The NVD clamshell hood tools are so large that special racking had to be developed to move the bagged parts into and out of the autoclave. In fact, these tools barely fit in Plasan's 30 ft/9.1 m autoclave.

8 Once the autoclave cycle is complete and parts are cooled and demolded, both inner and outer panels are sent for routering.

9 Next, inner panels with visible carbon weave are buffed and polished to a high luster.

10 Once trimmed, inner and outer panels are brought together in a fixture and adhesively bonded and cured via hot-air impingement.

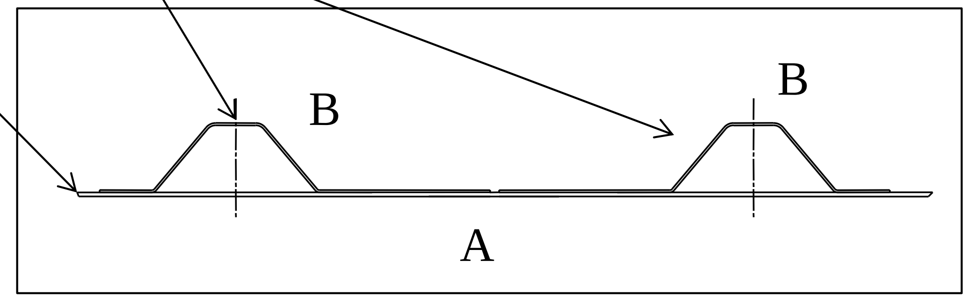
11 After that, the complete assembly is masked and then paint primer is applied to the outer panel.



12 The final step before the complete assemblies are shipped out to another supplier for paint is inspection/measurement to ensure dimensionality and surface quality.

Co-curing

- Two structural components such as a laminate (A) and stringers (B) are cured in a single fabrication cycle
- An adhesive could be added to the lay up
- See for example stringers and bottom skin of the wing panel of Eurofighter

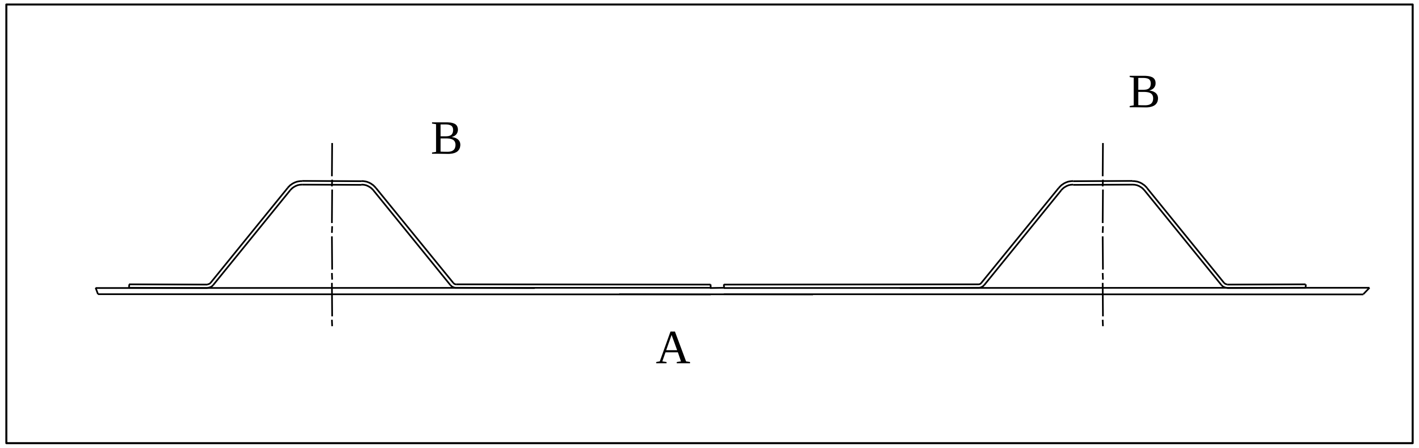


Secondary bonding

- Laminate and stringers are cured separately. Then a bonding autoclave cycle is performed using a thermosetting based adhesive (epoxy) between the two components
- See for example stringers and top skin of the wing panel of Eurofighter

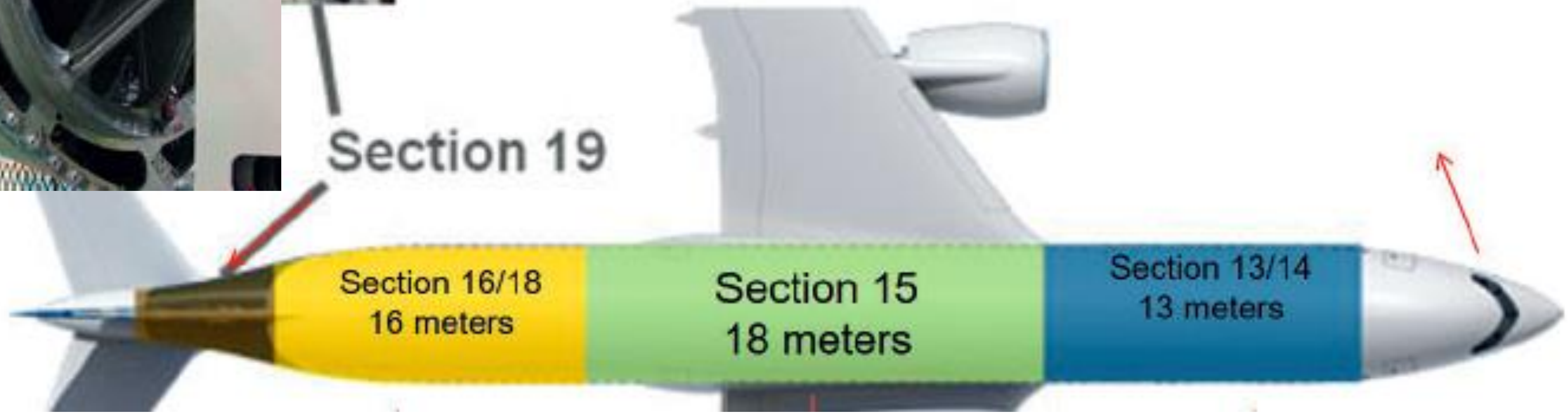
Co-bonding

- A laminate (A) is first cured. Then the stringers are assembled with the laminate starting from prepregs and adopting proper tooling
- The second cure cycle will be used to cure the stringers and simultanously bond them to the laminate
- An adhesive can be added to the lay up of the stringer



- For all the former three cases the use of laminate and stringers represents an example. Many other cases of co-curing and co-bonding are obviously possible

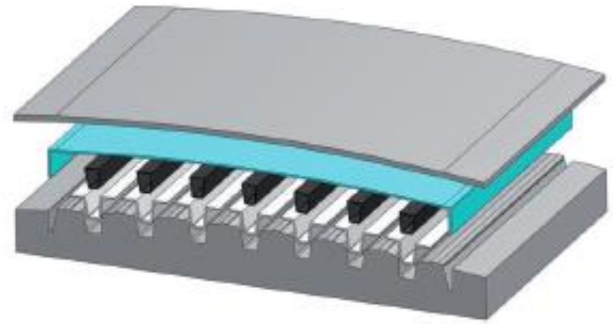
A350 Co-Bonding of Stringers of aft (13/14) and rear sections (16/18)



- Panels of section 15 is made using co-curing of omega stiffener as in B787
- Section 19, made in Spain, as one piece barrel following B787 approach
- Panels of sections 13/14 and 16/18 with Outer Mold Line (OML) Tooling: tool at the outer line of the fuselage

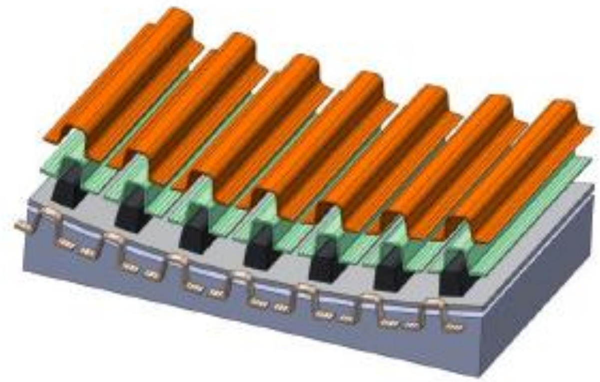
A350-Co-Curing of Stringers

Inner Mold Line (IML) Tooling: tool at the inner line of the fuselage (convex tool-B787)
Outer Mold Line (OML) Tooling: tool at the outer line of the fuselage (concave tool-A350)



IML Controlled Tooling

Variability floats to OML –
Aerodynamic surface

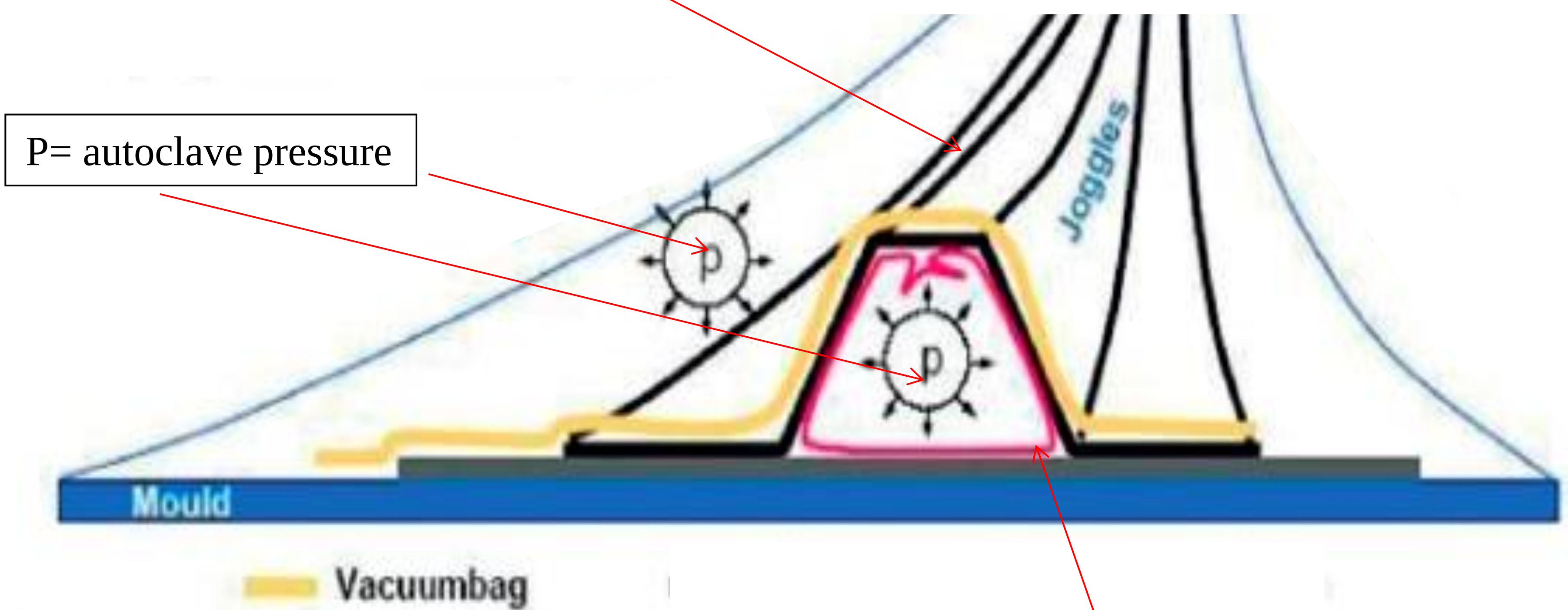


OML Controlled Tooling

Variability floats to IML –
Assembly interface

co-cured stringers

P= autoclave pressure



Silicone bag inflated by autoclave pressure

A. Hiken, Intertech open 2018

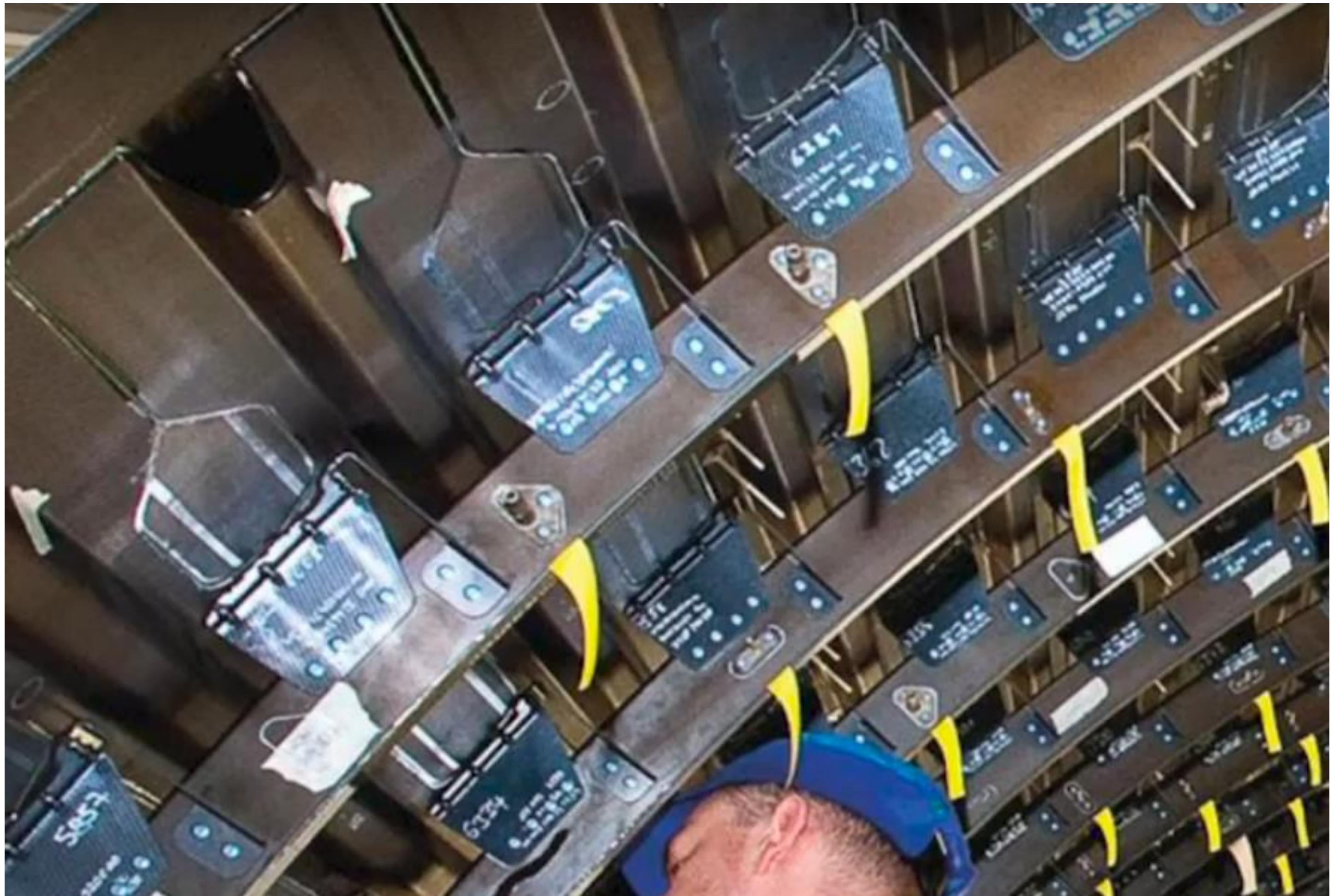
A350 mechanical fastening of frames to the fuselage skin

Airbus did not attach the frames directly to the skins because the IML of the fuselage skin is not a controlled surface.

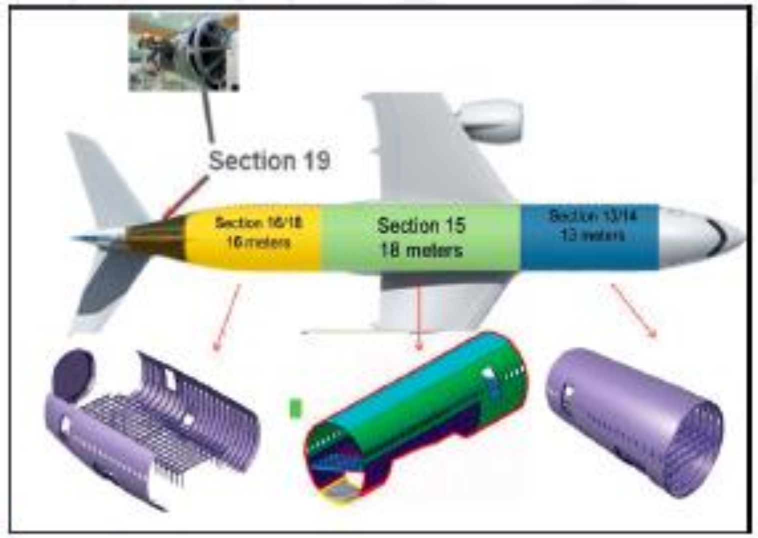
It is a bagged surface but the IML surface "floats" depending on factors such as bagging, resin bleed and initial prepreg resin content.

Just as the OML of each 787 fuselage "floats" and is different aircraft-to-aircraft depending on these same factors.

Airbus uses a standard carbon fiber reinforced clip, molded from thermoplastic material, to absorb the skin fabrication tolerance in the assembly process.



Composite fuselage: A350 vs. B787



- One Piece Barrel Construction
- IML tooling

Green: Leonardo (Italy)
Red: Japan
Light blue: Boeing

- One Piece Barrel Construction (section 19)
- Sector Panel Construction (Other sections)
- Cocuring (section 15 and 19)
- Cobonding (Other sections)
- IML tooling (section 15 and 19)
- OML tooling (Other sections)

Single lap joint configurations

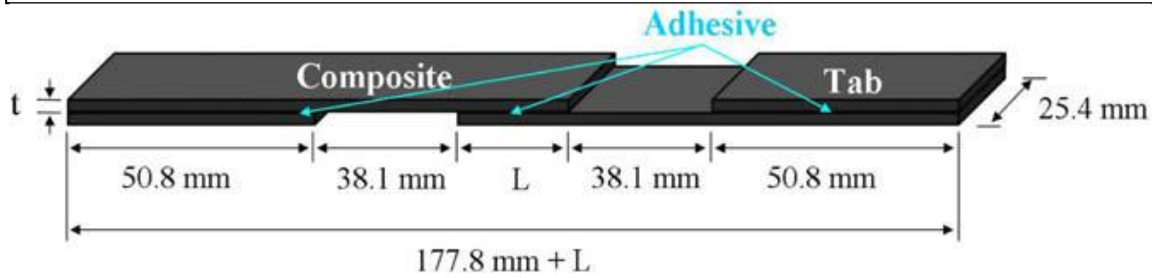
- CCN : Cocuring without adhesive
  - Prepreg + Prepreg

- CCA : Cocuring with adhesive
  - Prepreg + Adhesive + Prepreg

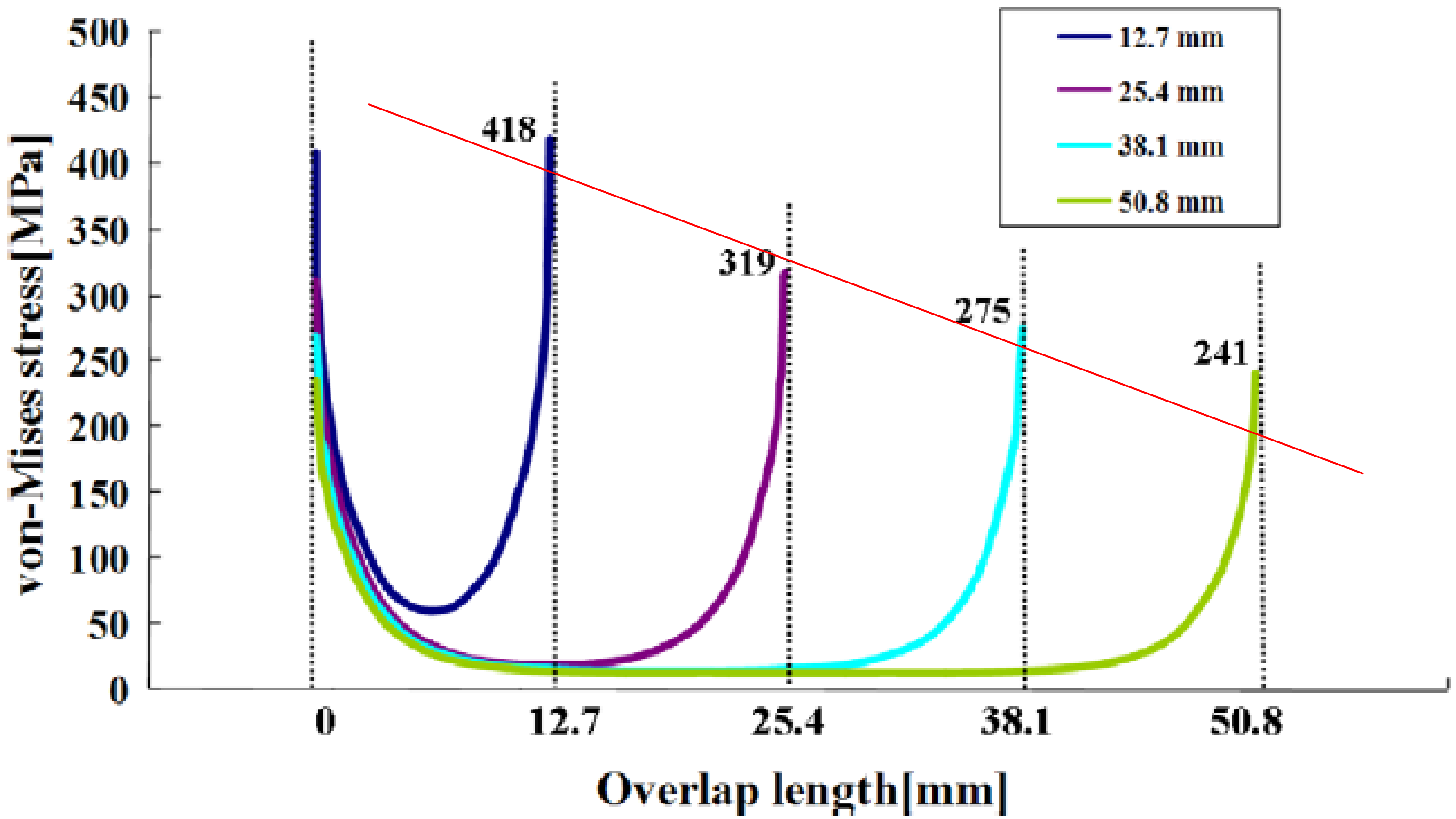
- SEB : Secondary bonding
  - Laminate + Adhesive + Laminate

- COB : Co-bonding
  - Prepreg + Adhesive + Laminate

Single lap joint, secondary bonding: stress distribution



12 kN were applied to the single lap joint changing the overlap length, L

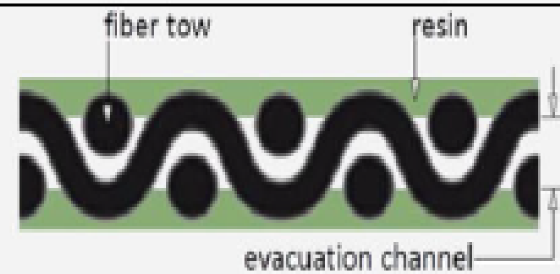


The von Mises stress is dominated by shear stress, which is not constant (see for comparison the load transfer between a fiber an the matrix in the micromechanic section). Peak stress decreases with overlap length

“Out of Autoclave (OOA)” processes

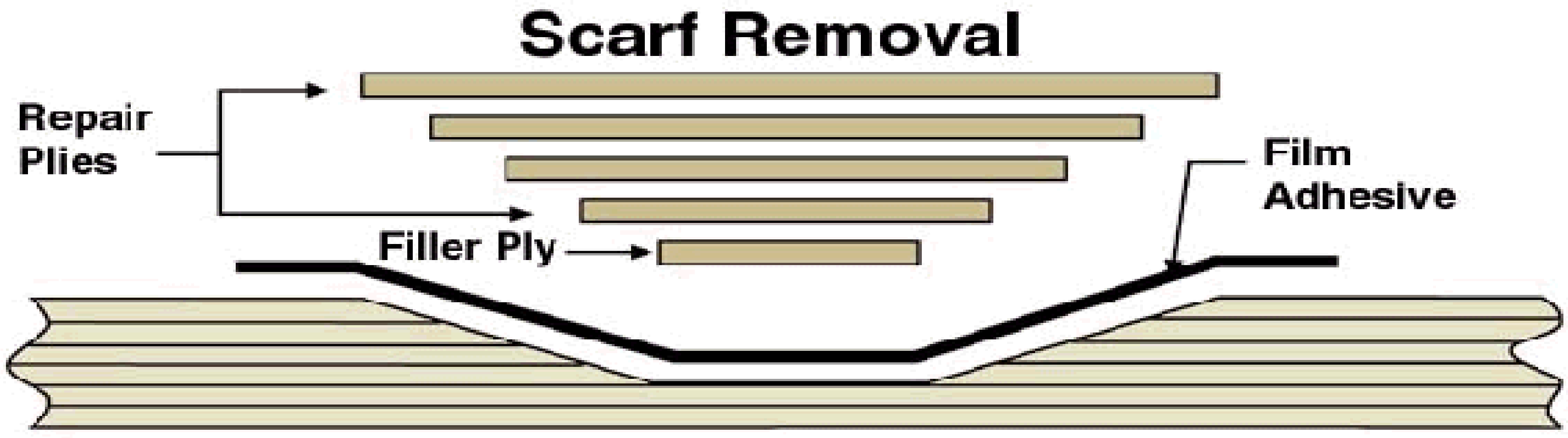
– Definition of OOA (also VBO Vacuum Bag Only): processes in which curing is performed under a vacuum bag <u>but in an oven</u> without applying any additional pressure beside those resulting fromn vacuum.
– The lay up is made using prepregs (OOA or VBO prepregs) with dedicated resin systems.
– Advantages:
  – Lower investment costs for autoclave purchase
  – Lower tooling cost
  – Larger volumes achieved with ovens
– Critical Issues
  – Keeping a low void content at a pressure < 1 bar
  – Reaching the same mechanical properties of autoclave cured prepregs
  – Keeping the same processability in hand lay-up and AFP (tack and drape for instance)

OOA (or VBO) prepreg

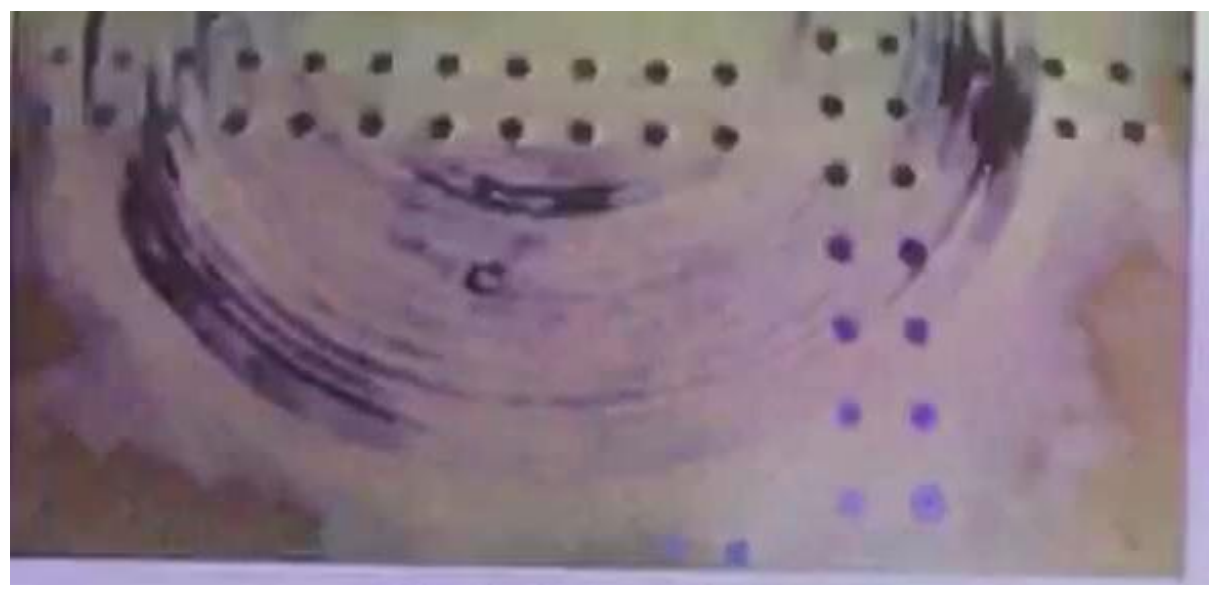
Properties	Conventional autoclave prepreg	New VBO prepreg
Sectional material forms	 Fully impregnated prepreg	 Partially impregnated prepreg
Key process parameters	Hydrostatic pressure	Air extraction, lower resin viscosity
Void content	Low (0-1%)	Moderate (0.5-3%)
Service temperature	Moderate to high (110-150°C)	Moderate to high (110-150°C)
Achievable fiber fraction	High (55-65%)	Moderate to high (50-60%)
Structural application	Primary structures	Primary and secondary structures

OOA processes in aeronautic: repairing

– Bonded repair, OOA:



- Vaccum bag and auxiliary materials+ Thermal blanket



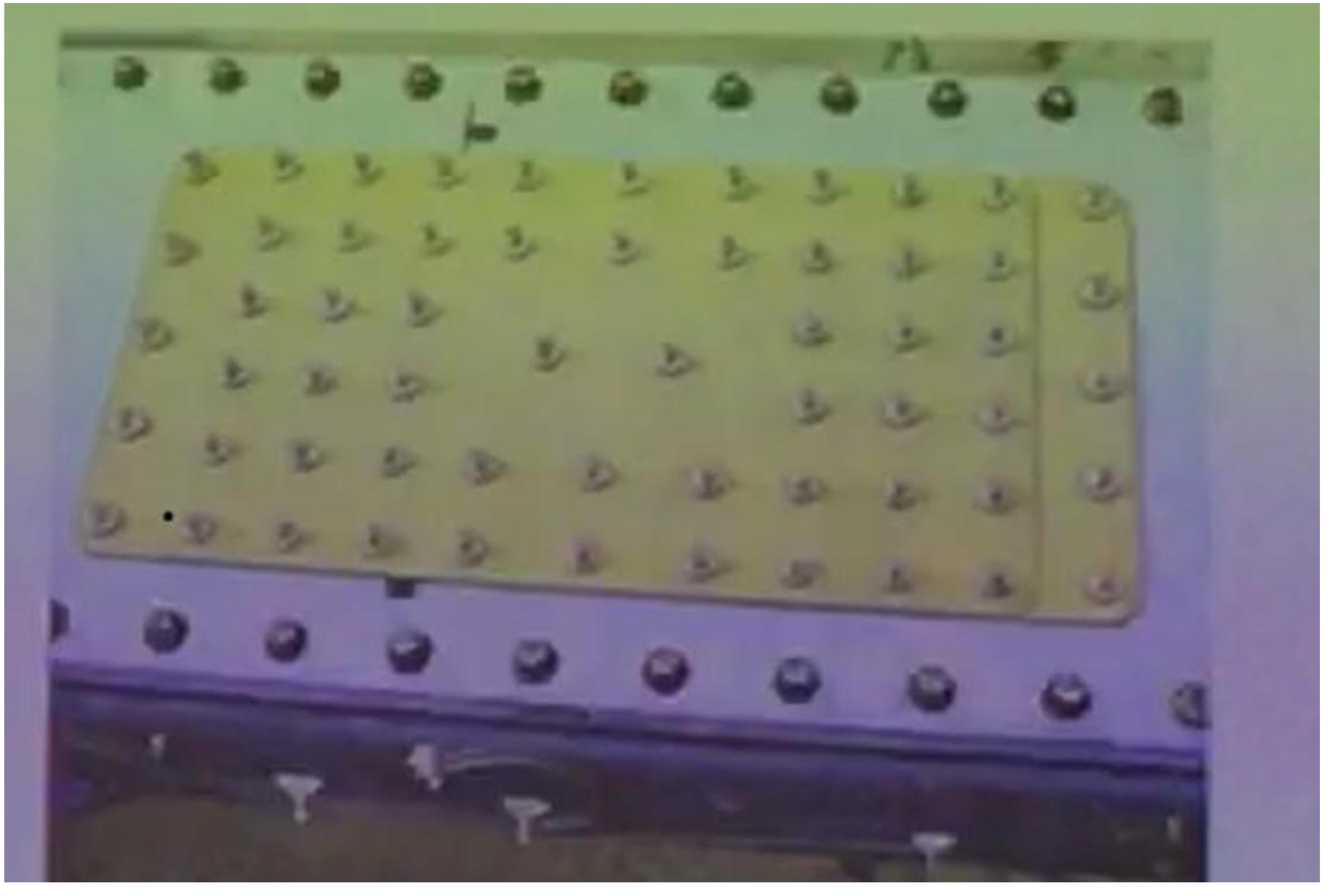
– Prepregs+adhesive film

Courtesy Airbus

Vacuum bagging and heating cycle for repair
(low pressure compared to autoclave conditions)

Repair

– Bolted repair on CFRP: CFRP or aluminum plate and fasteners

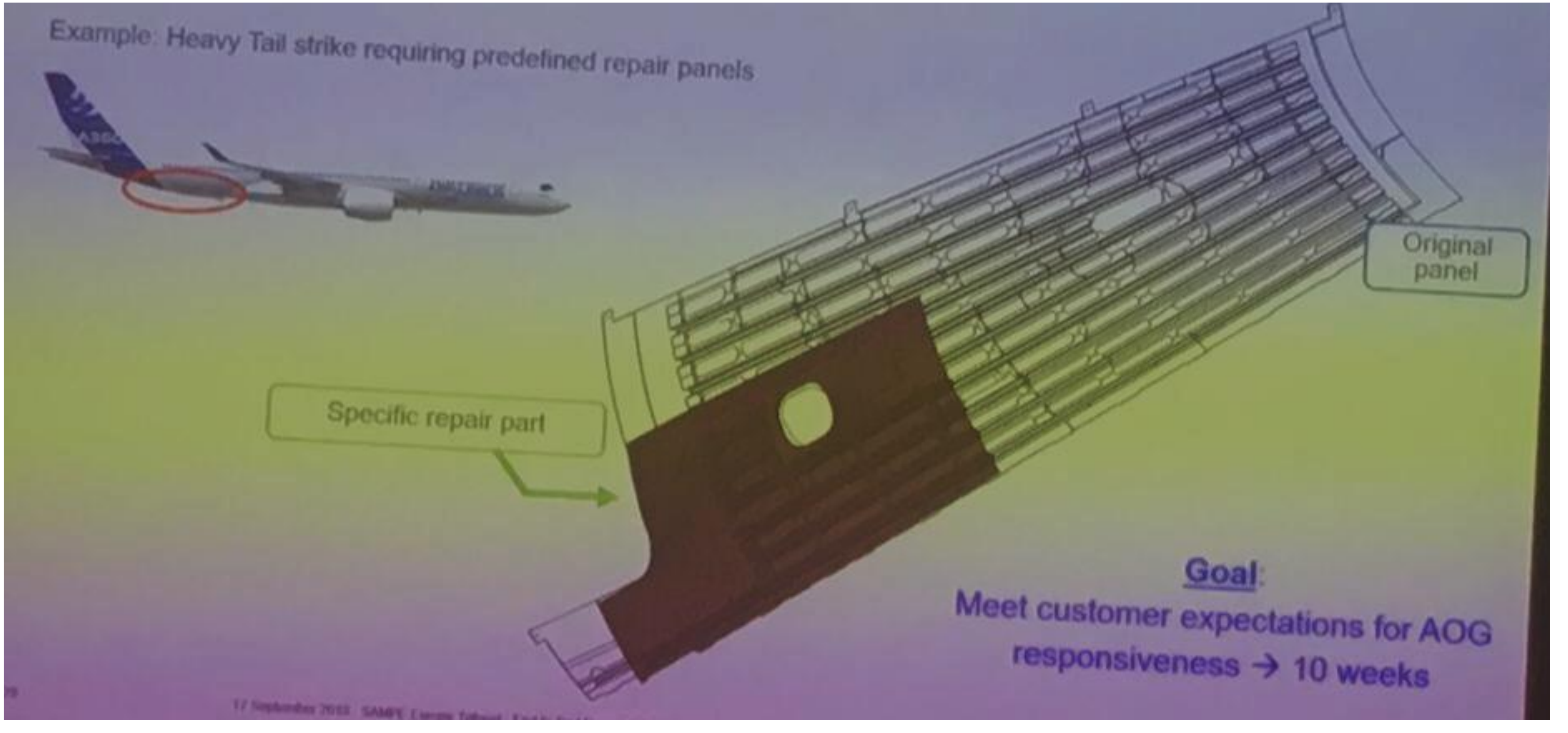


Courtesy Airbus

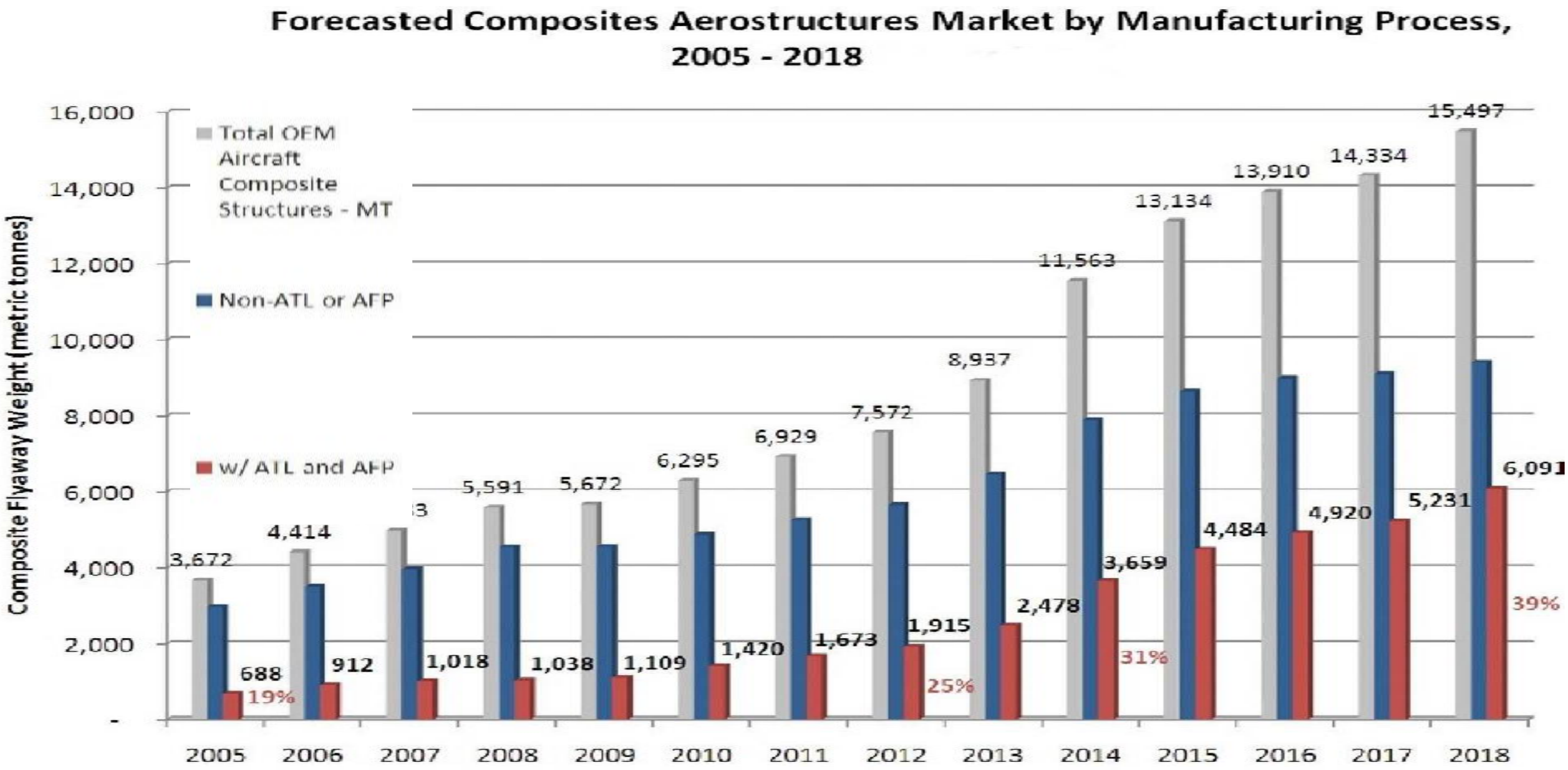
Composite repair

Fabrication of spare parts:

– Trial of Airbus with a rear sub-panel of A350



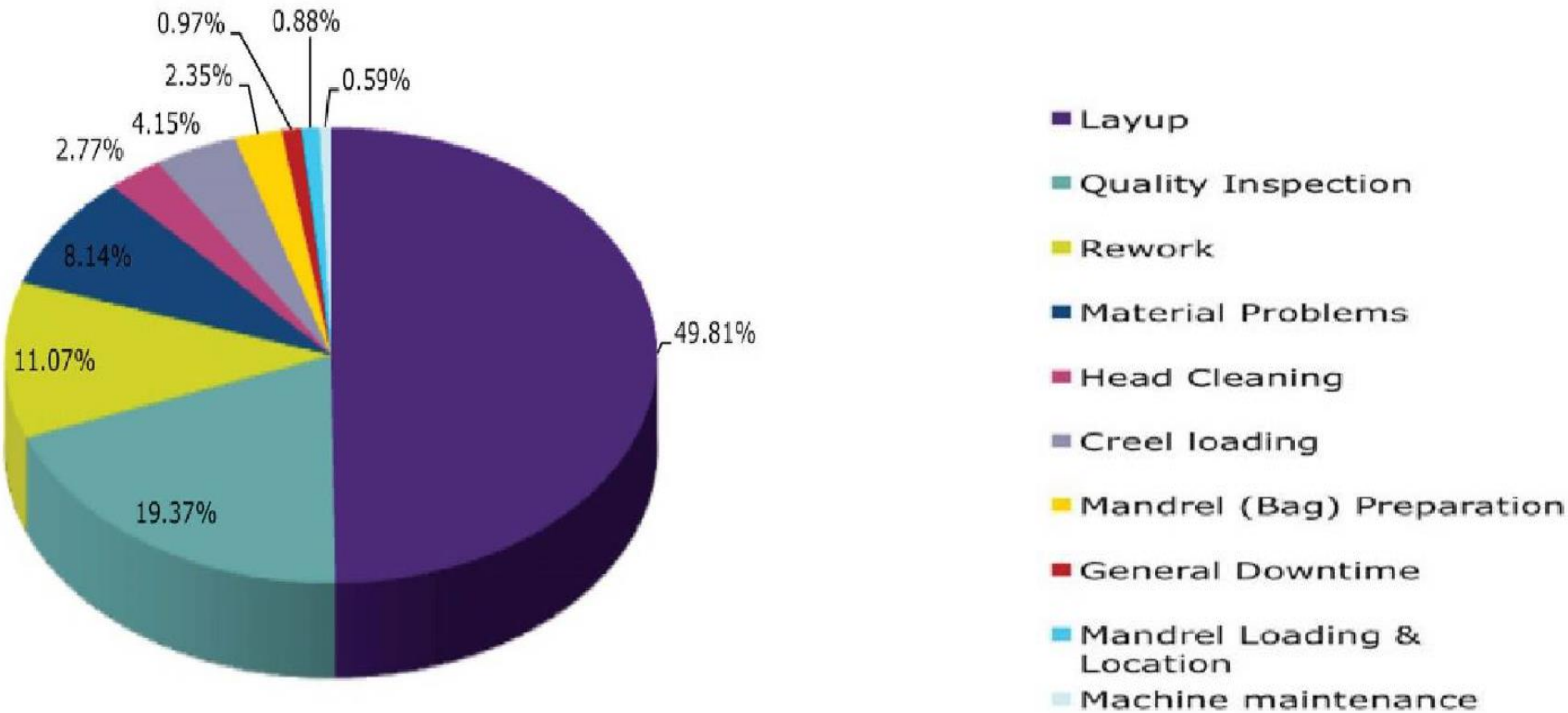
Courtesy Airbus



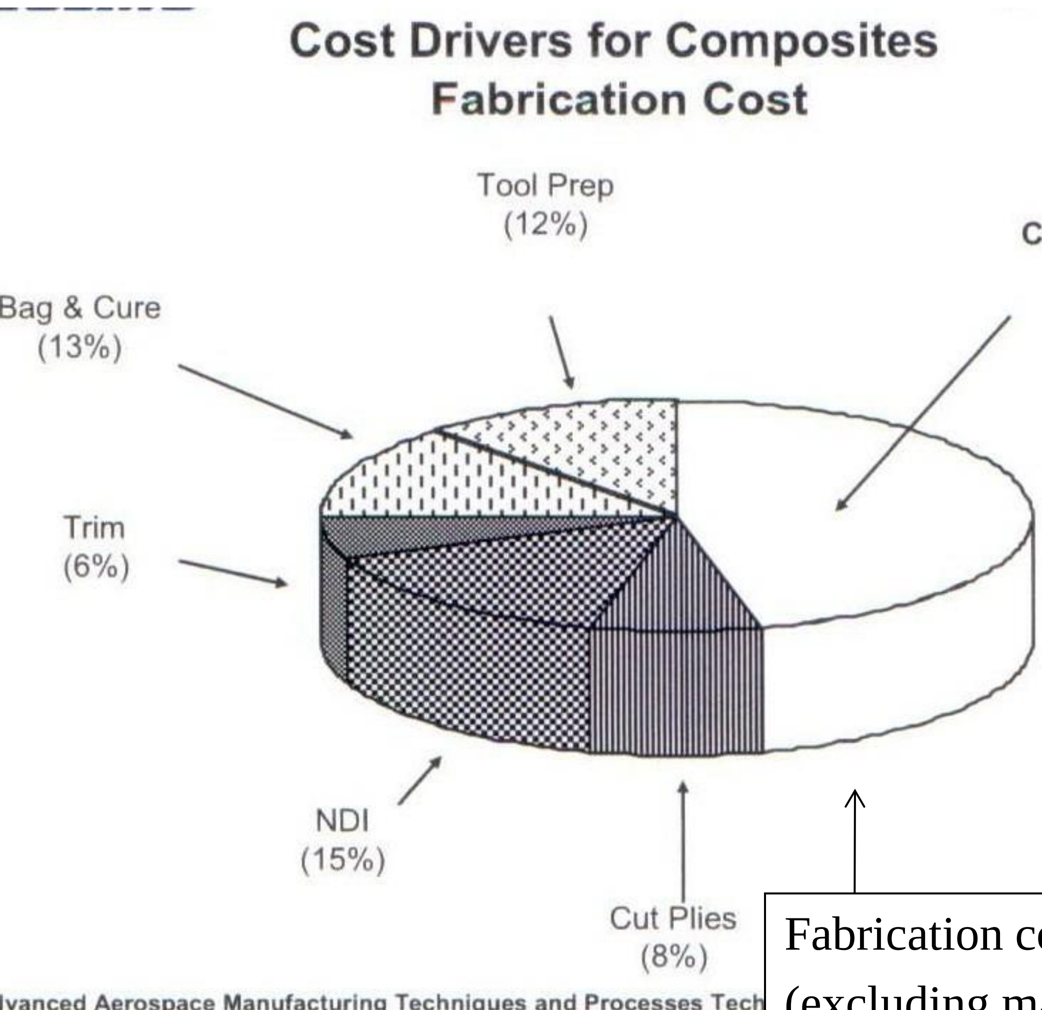
ATL = Automated Tape Laying (wide tapes of about 10 mm laminated in plane or on tools with very small curvatures)

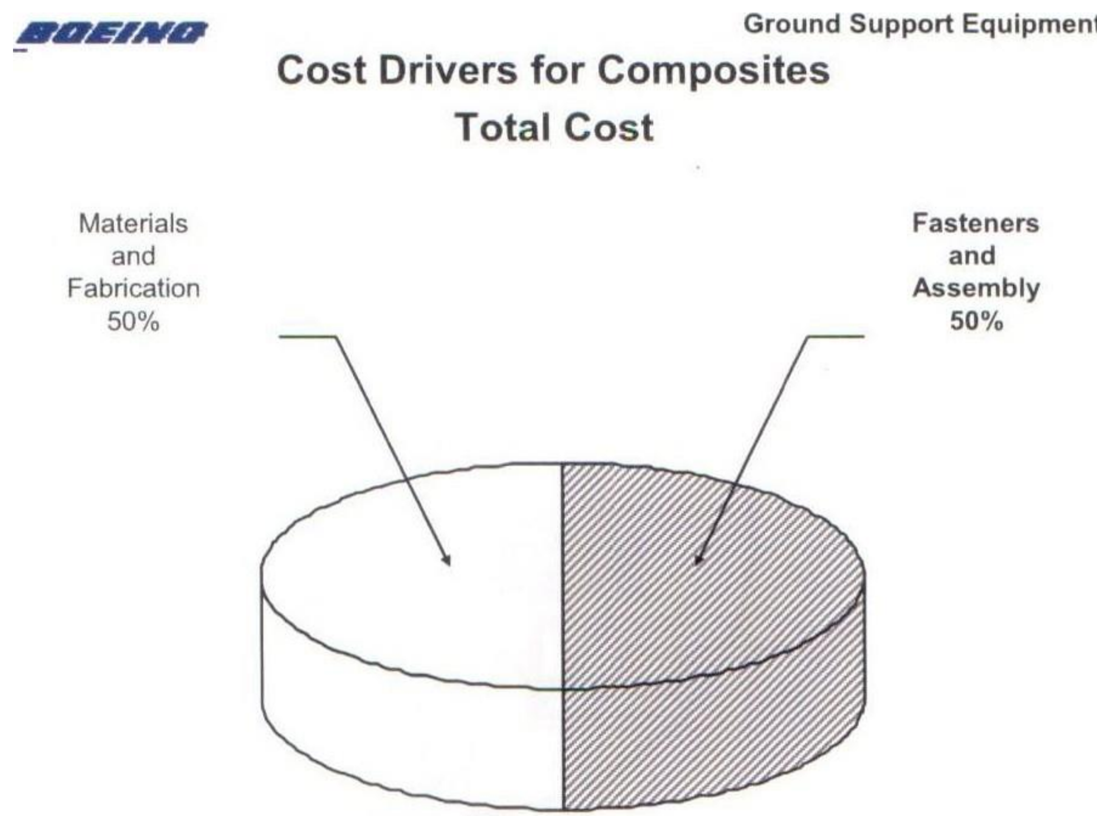
AFP= Automated Fiber Placement (UD tapes about 12.5-25 mm wide, laminated on surfaces of any complexity)

Production time with AFP (Ingersoll)



Key cost factor in the production of advanced thermosetting matrix composites





Fabrication costs
(excluding materials and including NDI and Trimming)

Commercial airplane are characterized by costs of composite parts between 450 e 550 $/kg including NDI (Non Destructive Inspection). Ratio of end-user cost and raw material cost, is nearly 6.5

These costs are:

100-150 $/kg materials 200 $/kg Quality controls, NDI, machining and trimming