Spring Semester 2017

151-0548-00L Manufacturing of Polymer Composites

Autoclave Processing

29 March 2017

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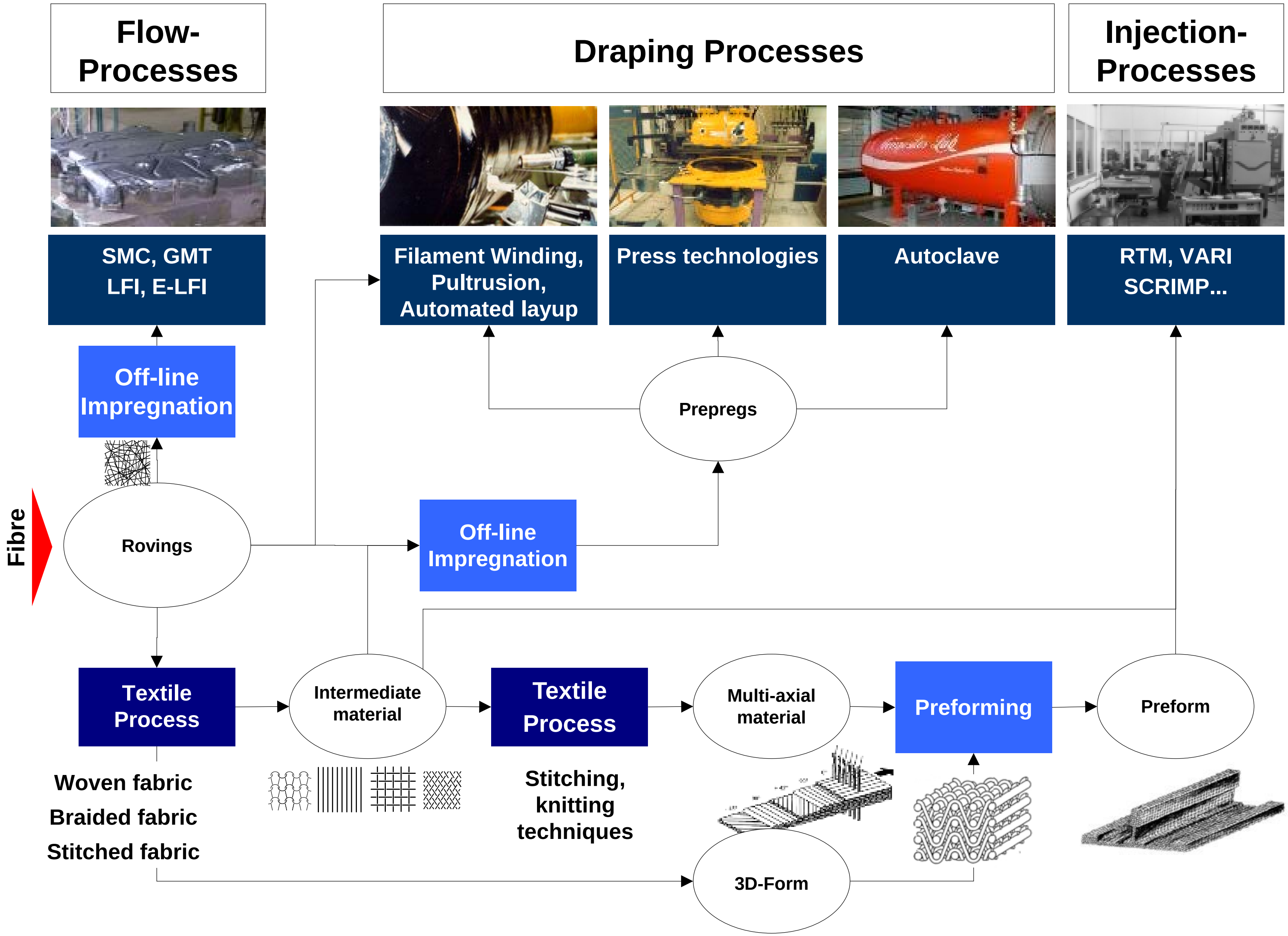

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Injection-Processes
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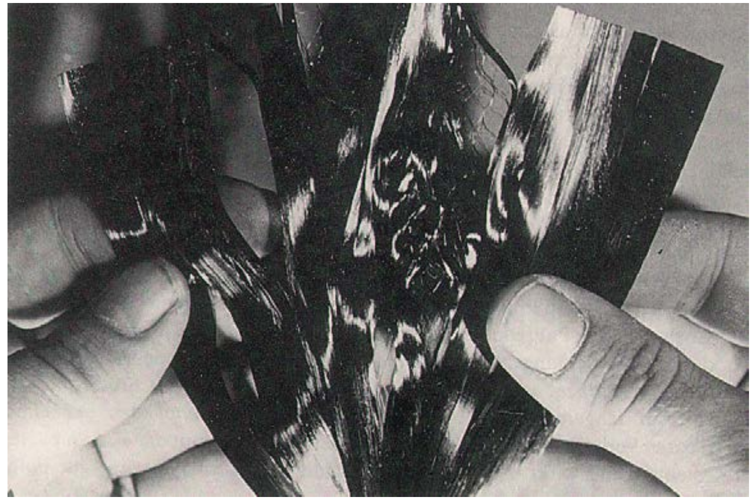
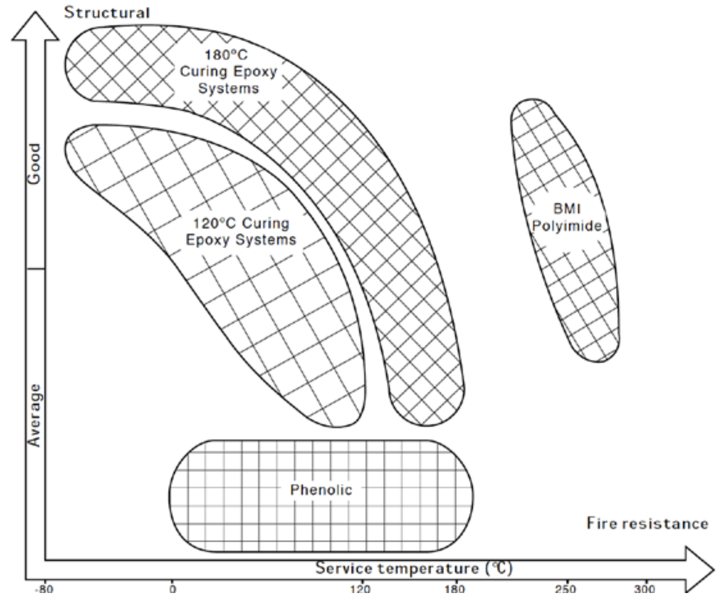
Prepreg materials

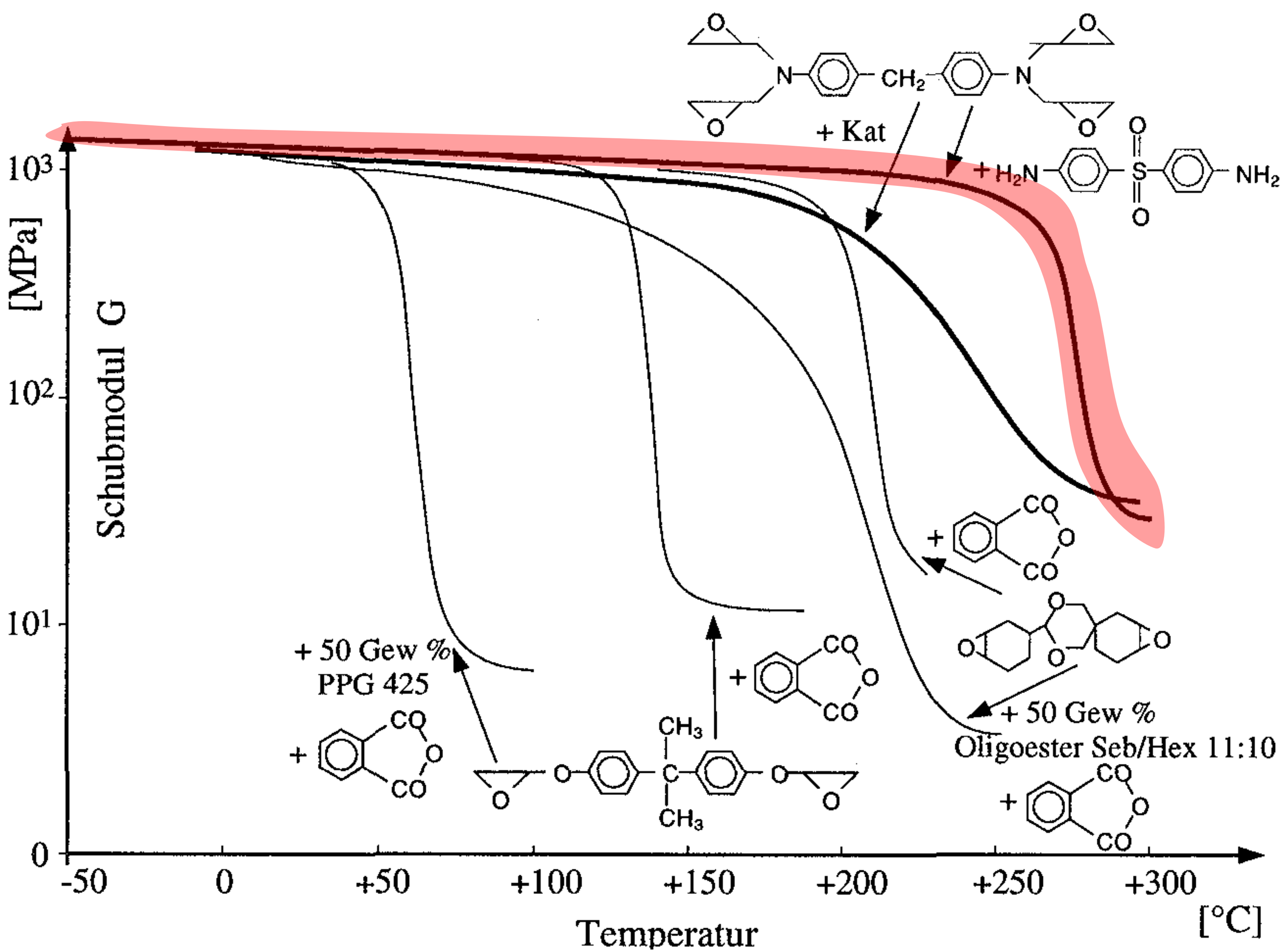
- Prepreg (PRE-imPREGnated sheets material) are material systems consisting of a matrix (resin) and a fibre reinforcement.
- Fibres are impregnated under well-controlled conditions:
  - Low void content
  - Well-controlled fibre volume content
  - Uniform fibre distribution
- Prepregs are available in different forms:
  - Unidirectional: sheet, tape
  - Fabric





Source: Hexcel, Prepreg Technology, www.hexcel.com/.../Prepreg_Technology.pdf

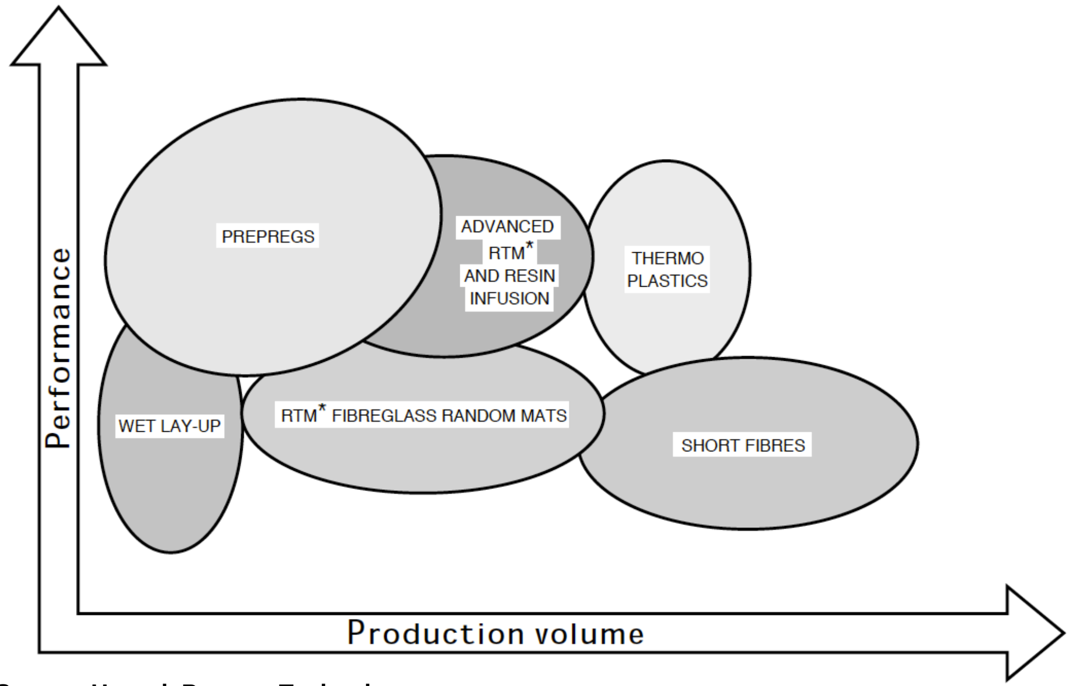
EP-resin: Structure-properties relationship



Quelle: Lohse, F.: Aufbau von Epoxidharzmatrices; 22. Internationale Chemiefasertagung, Dornbirn 1983

Rationale for the utilization of Prepregs?

- Final Part:
  - Weight/performance ratio
  - Outstanding mechanical properties
- Manufacturing aspects:
  - Quality and reproducibility
  - Control of fibre volume content
  - Reduced number of parts

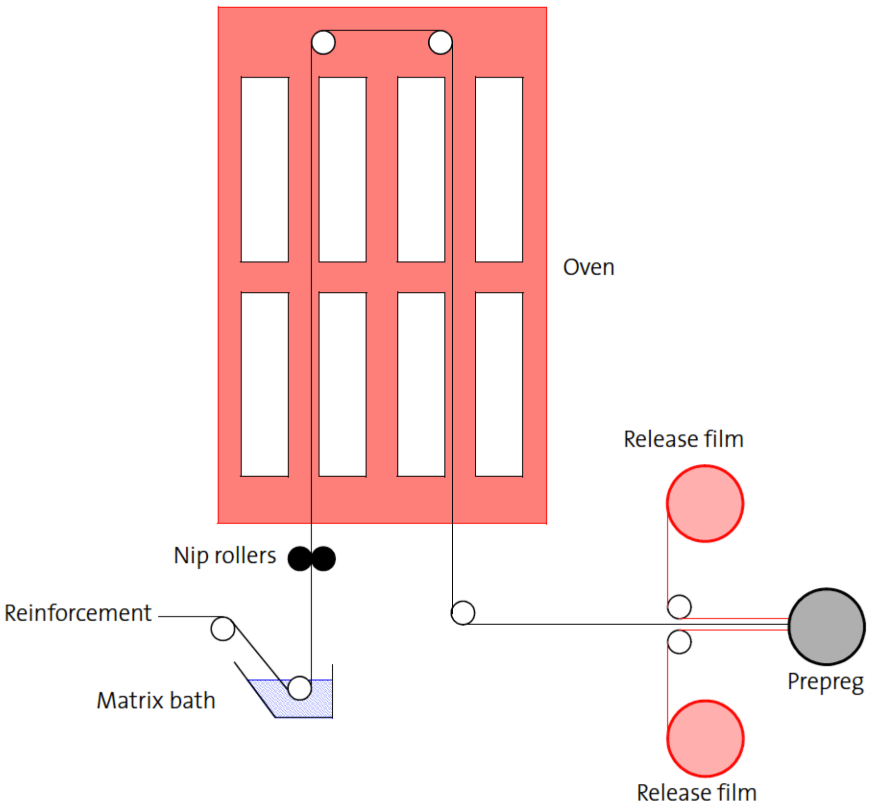


Source: Hexcel, Prepreg Technology

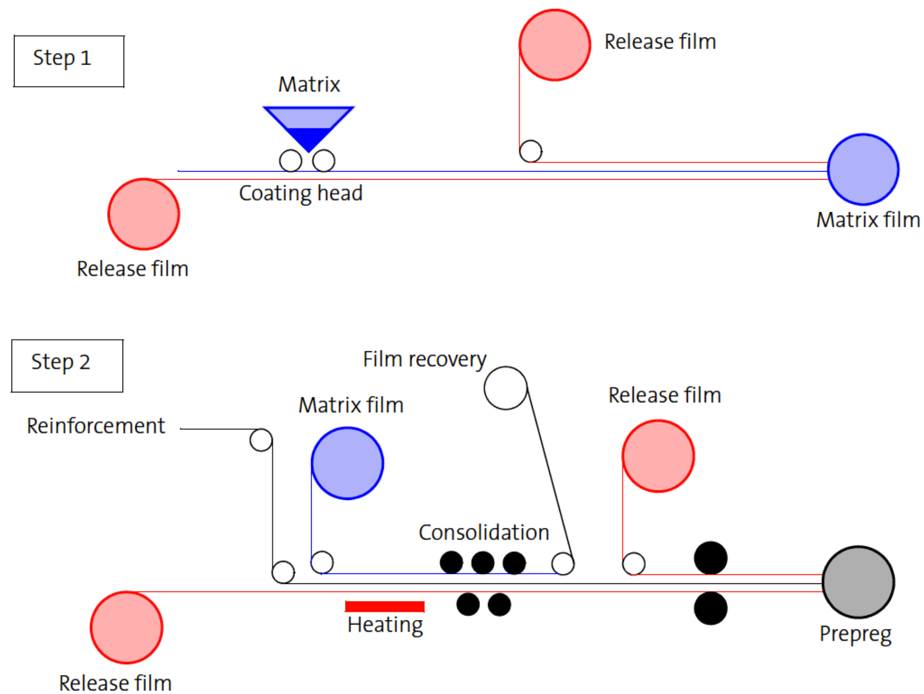
http://www.hexcel.com/user_area/content_media/raw/Prepreg_Technology.pdf?w=500

Prepreg manufacturing

Solvent Dip Processing

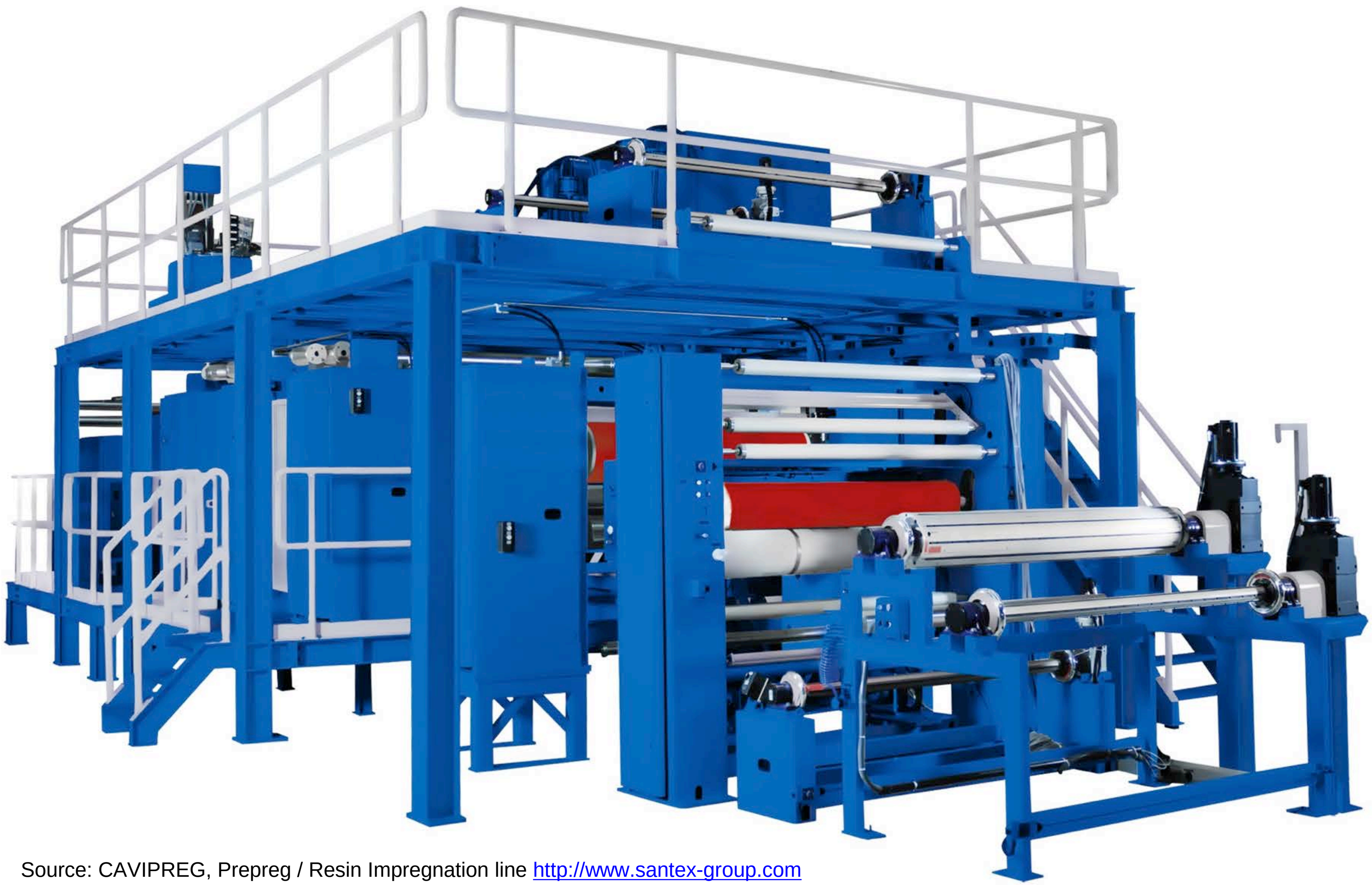


Hot Melt Processing



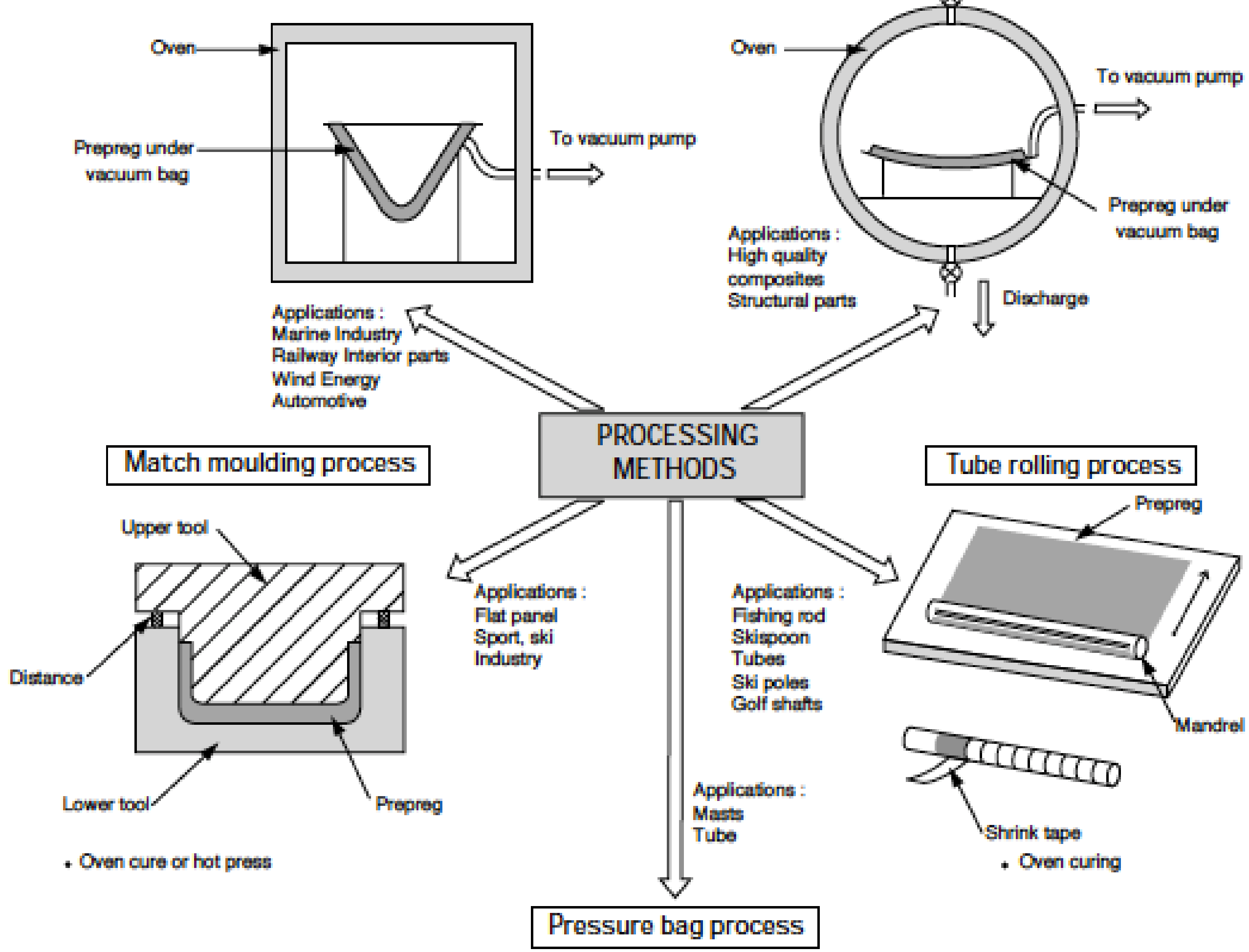
Source: Umeco - Introduction to Advanced Composites and Prepreg Technology

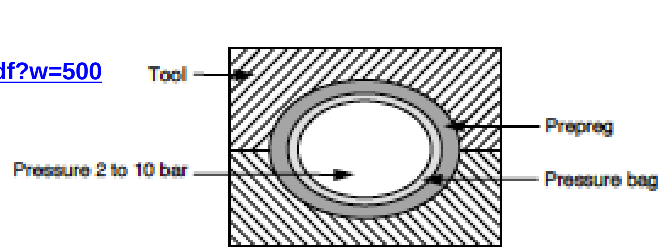
Prepreg/resin impregnation machine



Source: CAVIPREG, Prepreg / Resin Impregnation line http://www.santex-group.com

Prepreg Processing





Source: Hexcel, Prepreg Technology

http://www.hexcel.com/user_area/content_media/raw/Prepreg_Technology.pdf?w=500

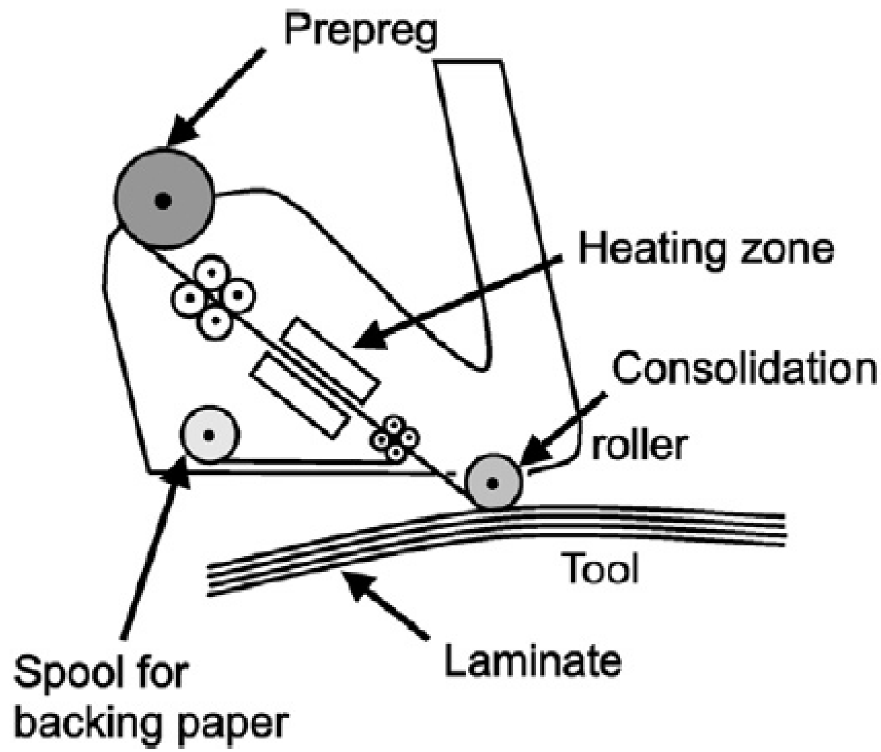
Autoclave Process: Processing steps

- Preparation
- Layup incuding cutting and debulking
- Curing including preparation
- De-molding

Autoclave used for production of the Boeing 787 at Triumph Aerostructures – Vought Aircraft Industries. North Charleston, South Carolina, USA.

Automated Prepreg layup technologies: Automated Tape Laying (ATL)

- Kind of additive manufacturing process
- ATL systems handles Prepregs with a typical width of: 75, 150, 300 mm
- Material is stored in the layup head
- Typical features:
  - gap between 2 contiguous layers: 0.5 – 1.0 mm
  - Layup speed: 0.83 – 1.0 m/s
  - Acceleration: 0.5 m/s^2
  - Compaction Force: 445 – 1000 N



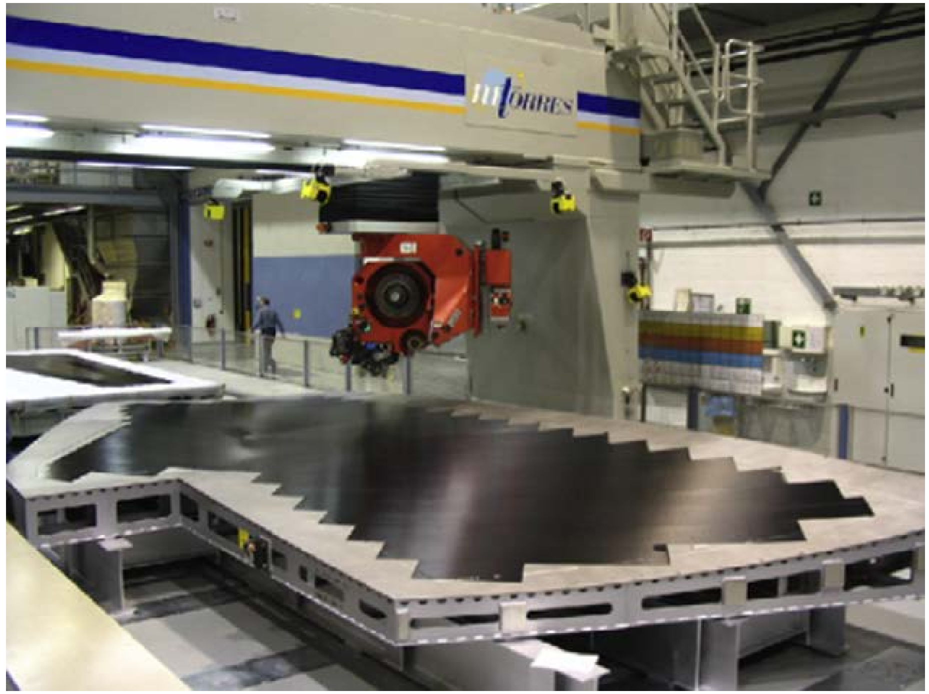
Aström. Manufacturing of polymer composites. London, UK: Chapman & Hall; 1997.

Lukaszewicz, D. H. J. A., et al. (2012). "The engineering aspects of automated prepreg layup: History, present and future." Composites Part B: Engineering 43(3): 997-1009.

Automated Prepreg layup technologies: Automated Tape Laying (ATL)

- TORRESLAYUP: 11 axes Gantry CNC automatic tape layer machine
  - https://youtu.be/P81EkSe53N8

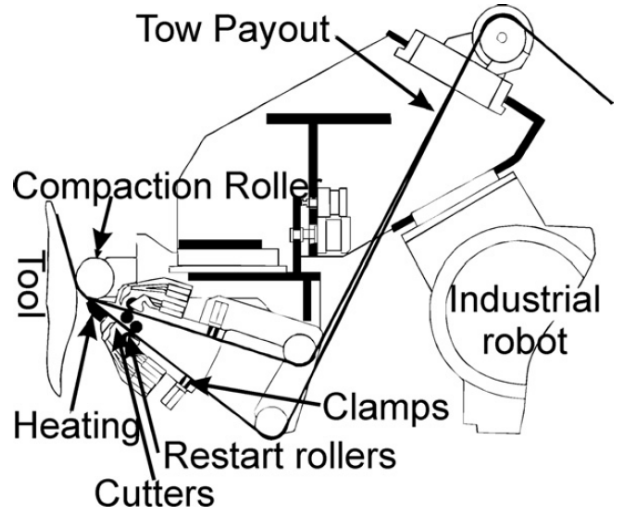
- Example of a gantry type ATL laying onto a female tool



MTorres Disenos Industriales S. Torres layup – Tape Layer Machine, vol. 2010; 2010. http://www.mtorres.es/pdf/torreslayup.pdf

Automated Prepreg layup technologies: Automated Fibre Placement (AFP)

- AFP systems handles Prepregs with a typical width of: 3.2, 6.4, 12.7 mm
- AFP can deliver up to 32 tows. Tows can be delivered at individual speeds, enabling (more) complex geometries and some tow steering
- Amount of gap between tows much larger compared to ATL, thus affecting mechanical properties
- Typical features:
  - Layup speed: up to 1.0 m/s
  - Acceleration: 2 m/s^2

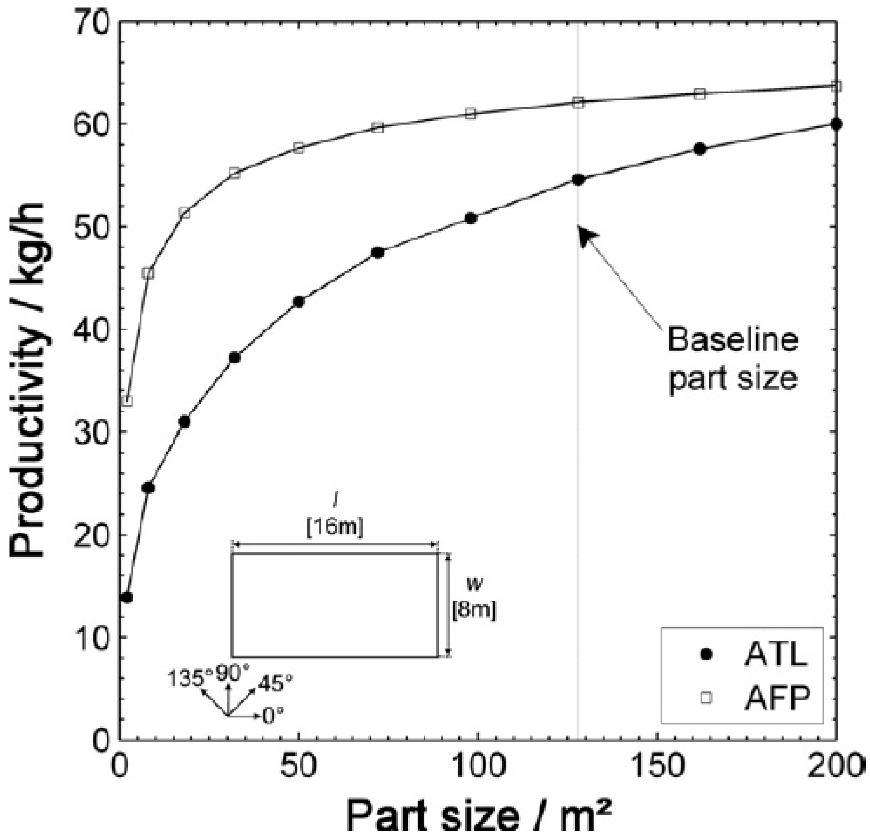


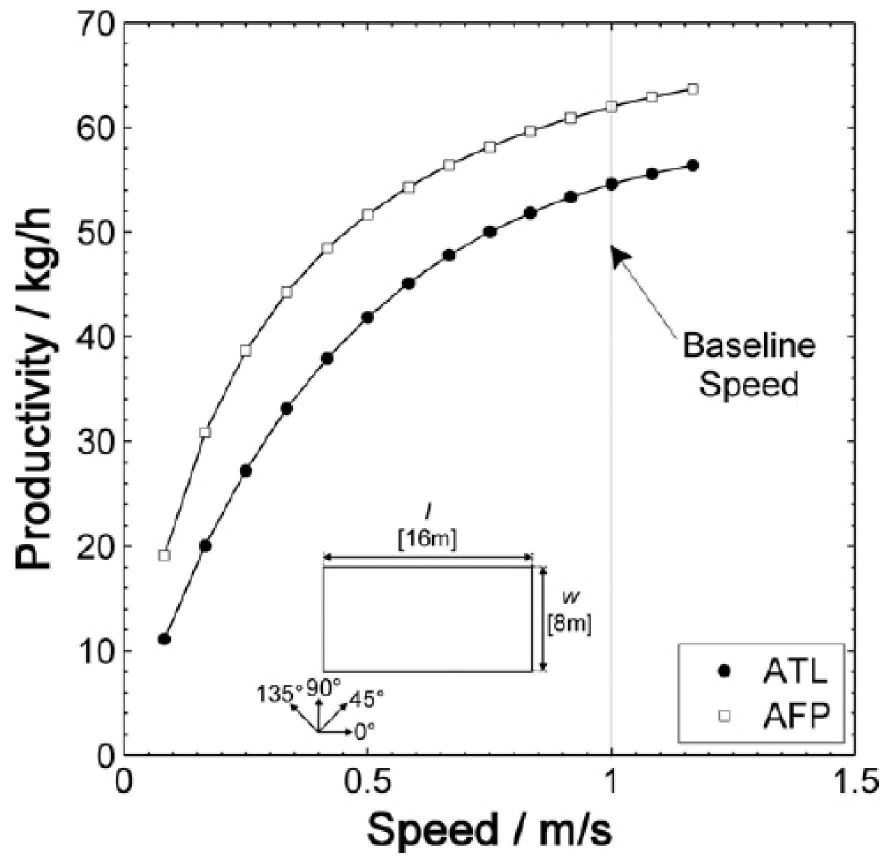
Evans DO. Fiber placement. Cincinnati: Cininnati Machine; 1997.

Blom AW, Lopes CS, Kromwijk PJ, Gurdal Z, Camanho PP. A theoretical model to study the influence of tow-drop areas on the stiffness and strength of variable-stiffness laminates. J Compos Mater 2009;43:403–25

Lukaszewicz, D. H. J. A., et al. (2012). "The engineering aspects of automated prepreg layup: History, present and future." Composites Part B: Engineering 43(3): 997-1009.

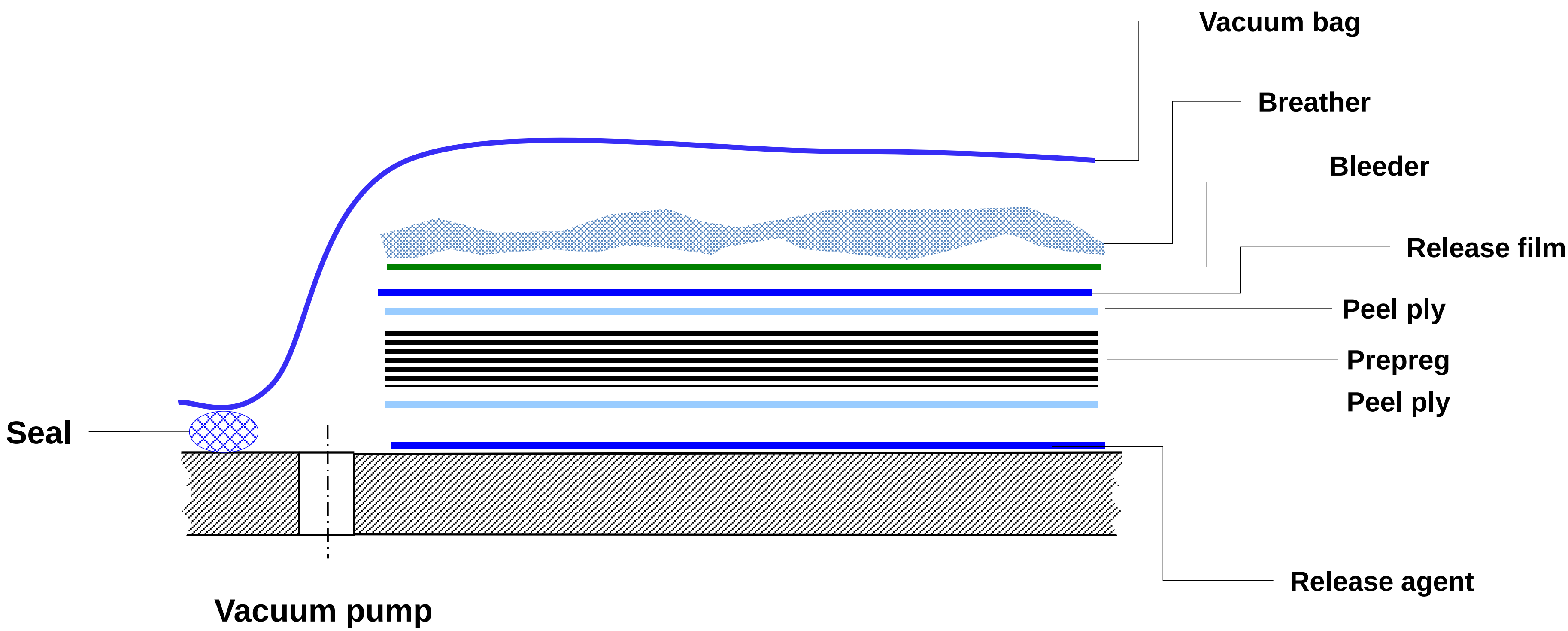
Theoretical productivity comparison for ATL and AFP



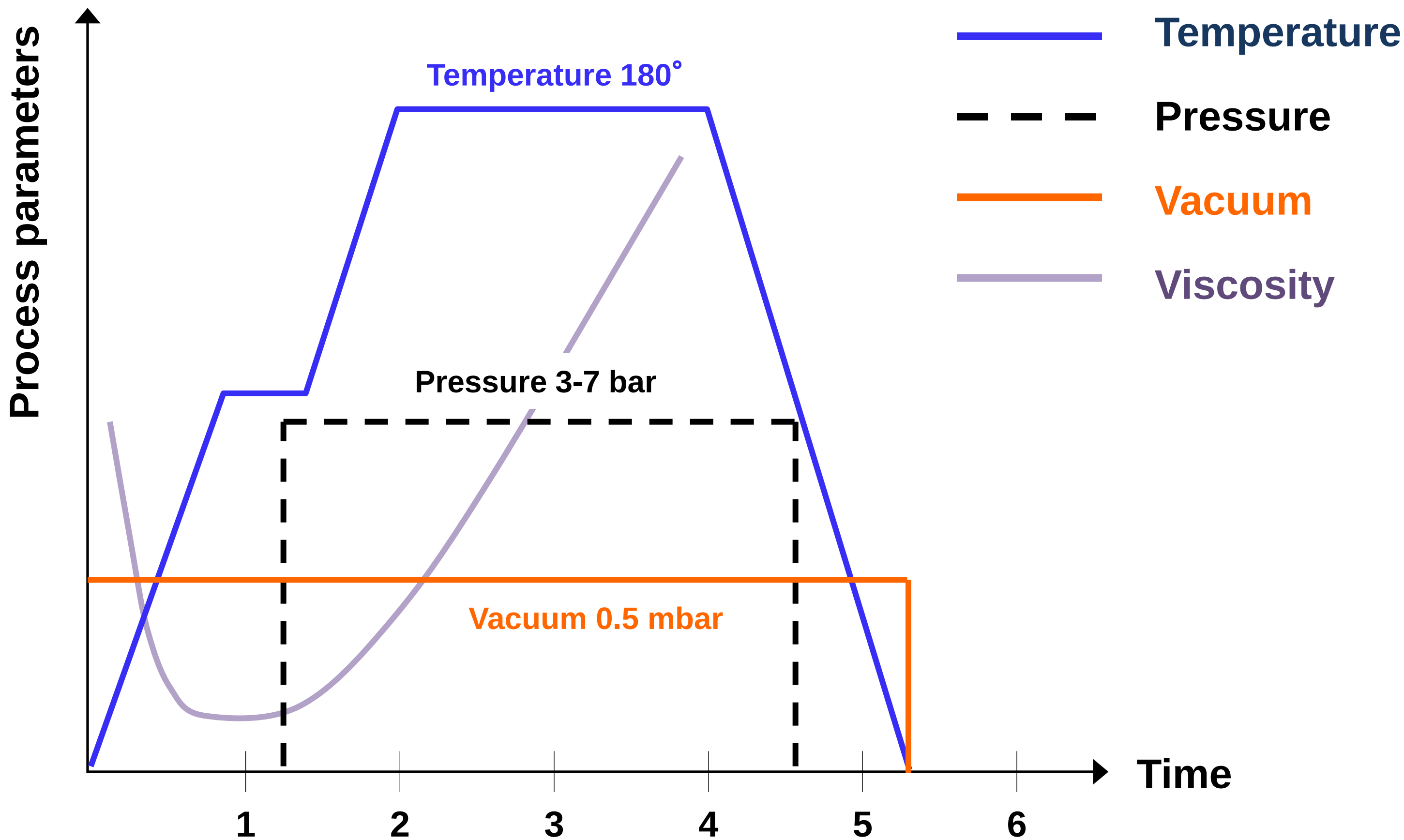


Lukaszewicz DH-JA. Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates. Ph.D. Thesis. Bristol: University of Bristol; 2011

Vacuum bag lay-up

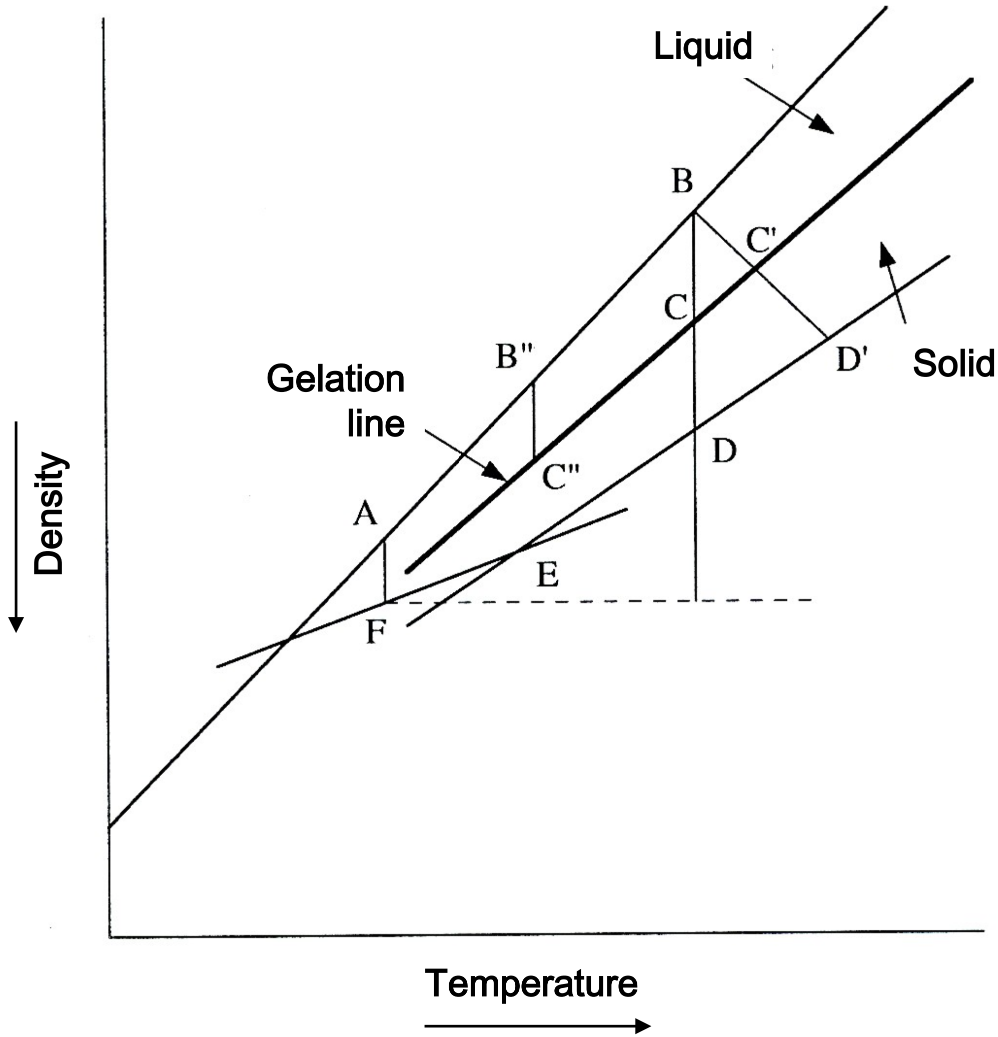


Curing cycle

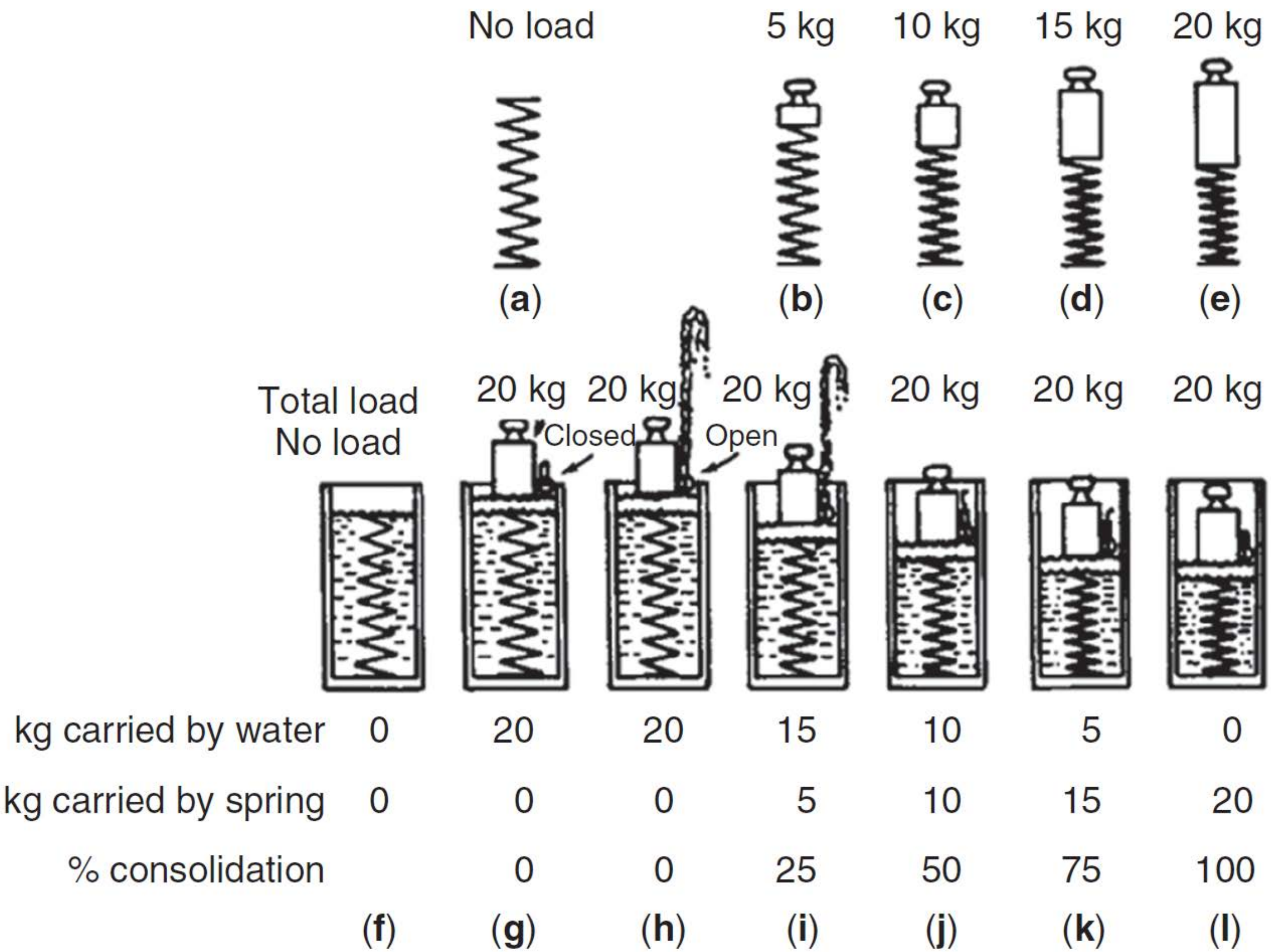


M. Flemming, G. Ziegmann, S. Roth, Faserverbundbauweisen – Halbzeuge und Bauweisen, Springer Verlag Berlin, Heidelberg, New York, 1996

Dichte/Temperturverlauf von Epoxidharzen



Piston-and-spring analogy to consolidation of resin-filled fiber composites



D. W. Taylor, Fundamentals of soil mechanics, Wiley, New York, 1969

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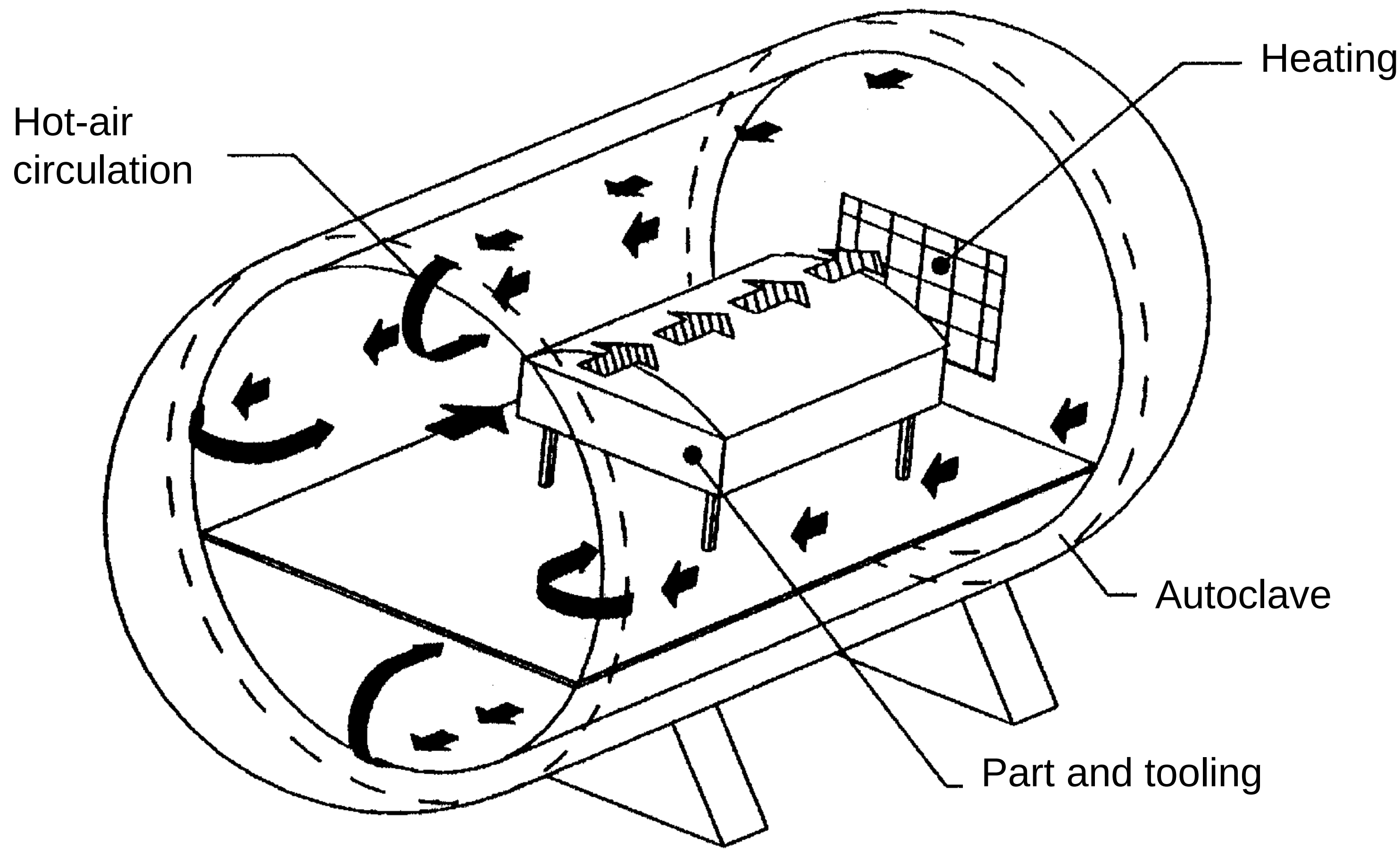
Air-circulation in the autoclave



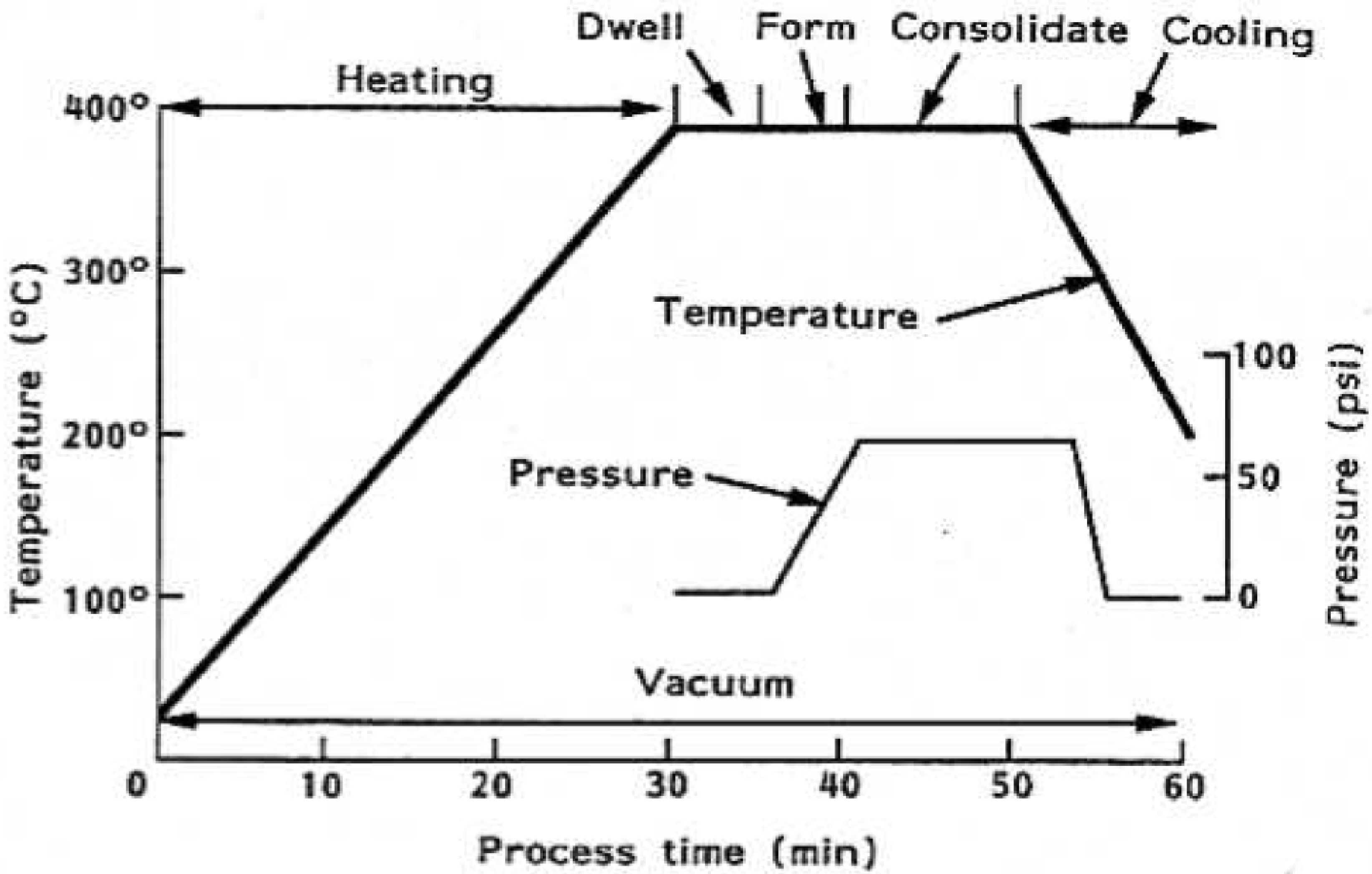
Heat transfer in an autoclave for processing thermoplastic composites

P.F. Monaghan, M.T. Brogan and P.H. Oosthuizen

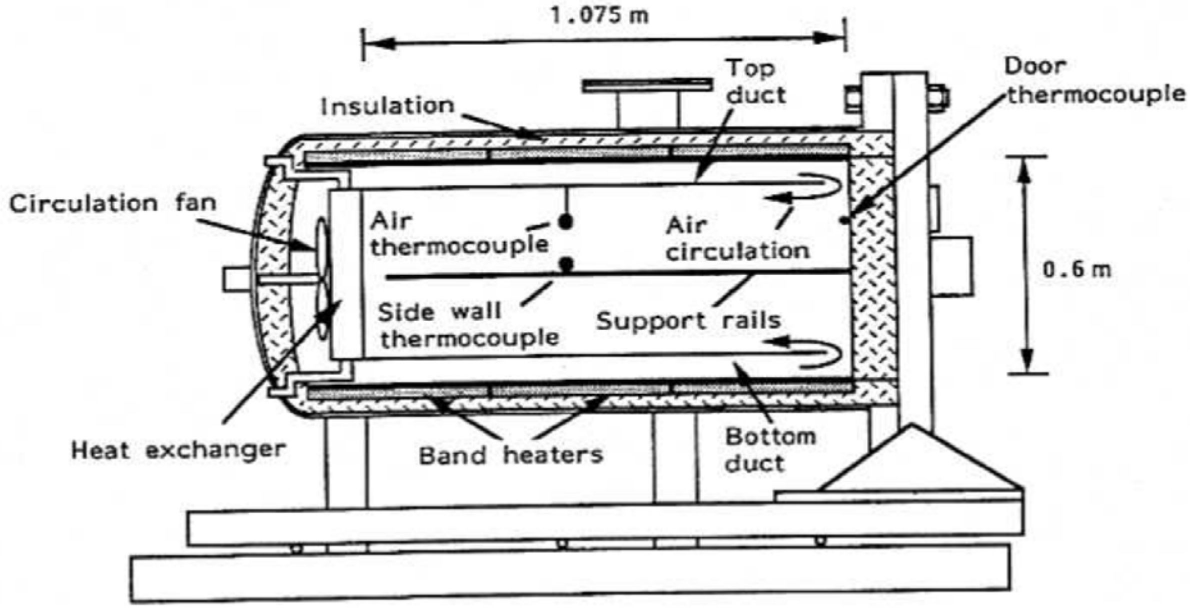
This paper deals with a preliminary analysis of the heat transfer within autoclaves as used in the diaphragm forming technique. Simple experiments are carried out to estimate the convection and radiation heat transfer and a simple mathematical model is developed. The results presented for the autoclave tested show that the convection coefficient does not vary significantly along the length of the autoclave and radiation may be as high as 60% of the total heat transfer. The temperature distribution through a mould and lay-up is measured and this shows that the thermal resistances inside and outside the mould and lay-up are both significant during the process.

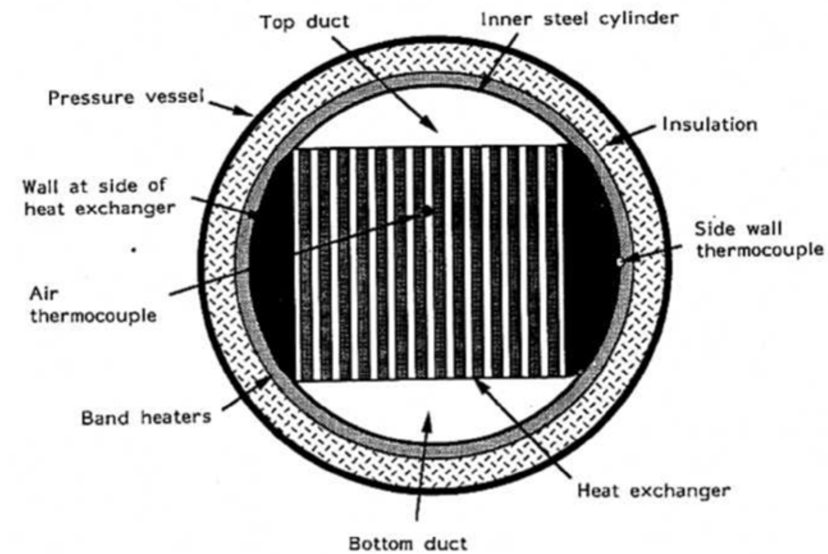
Keywords: autoclaves; heat transfer; thermoplastic composites; diaphragm forming; model; experiment

Source: PF Monaghan, MT Brogan, PH Oosthuizen, Heat transfer in an autoclave for processing thermoplastic composites, Composites Manufacturing Vol 2 No 3/4 1991



Source: PF Monaghan, MT Brogan, PH Oosthuizen, Heat transfer in an autoclave for processing thermoplastic composites, Composites Manufacturing Vol 2 No 3/4 1991





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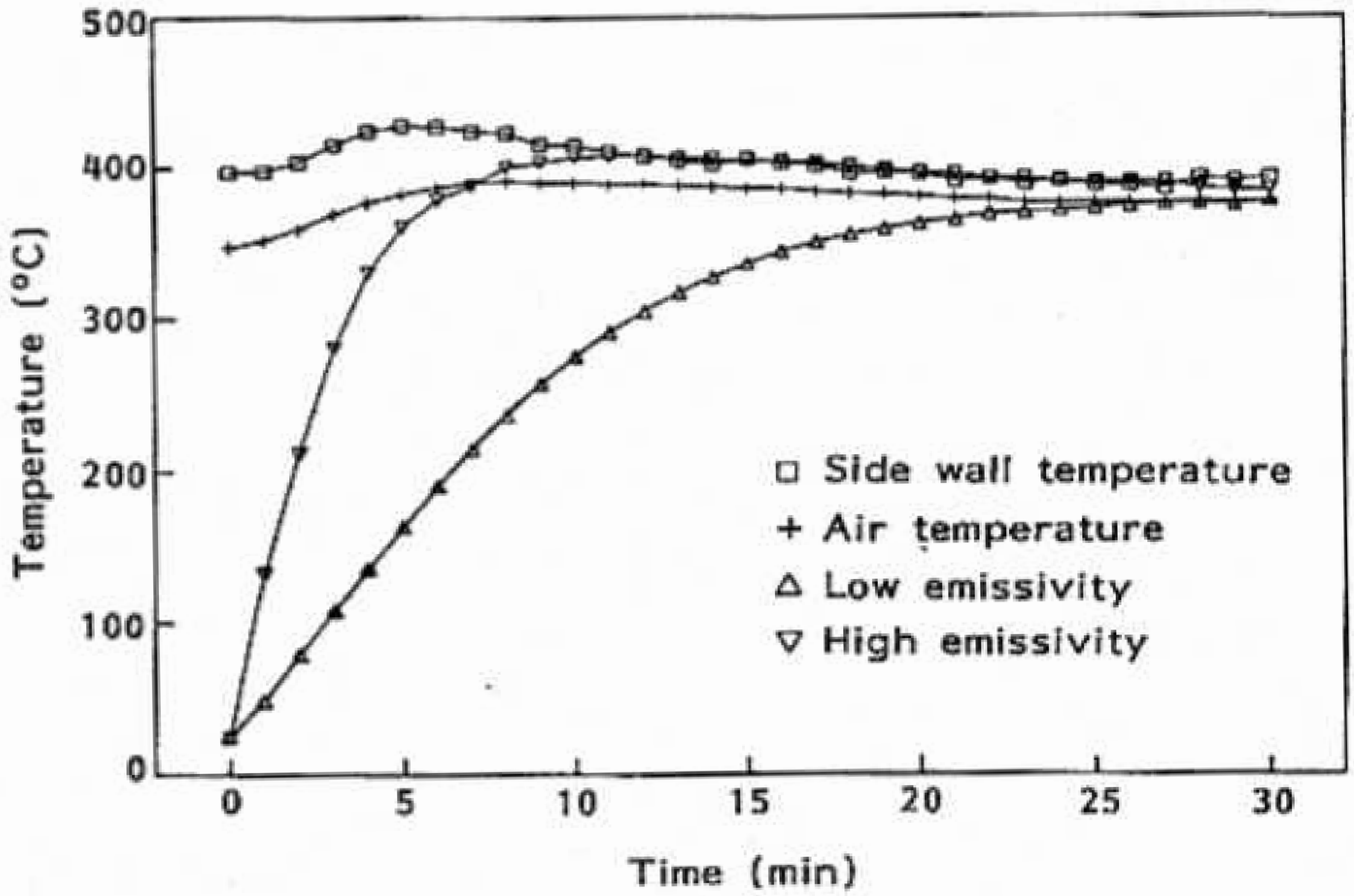


Figure 8 Temperature against time for the low and high emissivity plates heated in a preheated autoclave at 575 mm from door

Source: PF Monaghan, MT Brogan, PH Oosthuizen, Heat transfer in an autoclave for processing thermoplastic composites, Composites Manufacturing Vol 2 No 3/4 1991

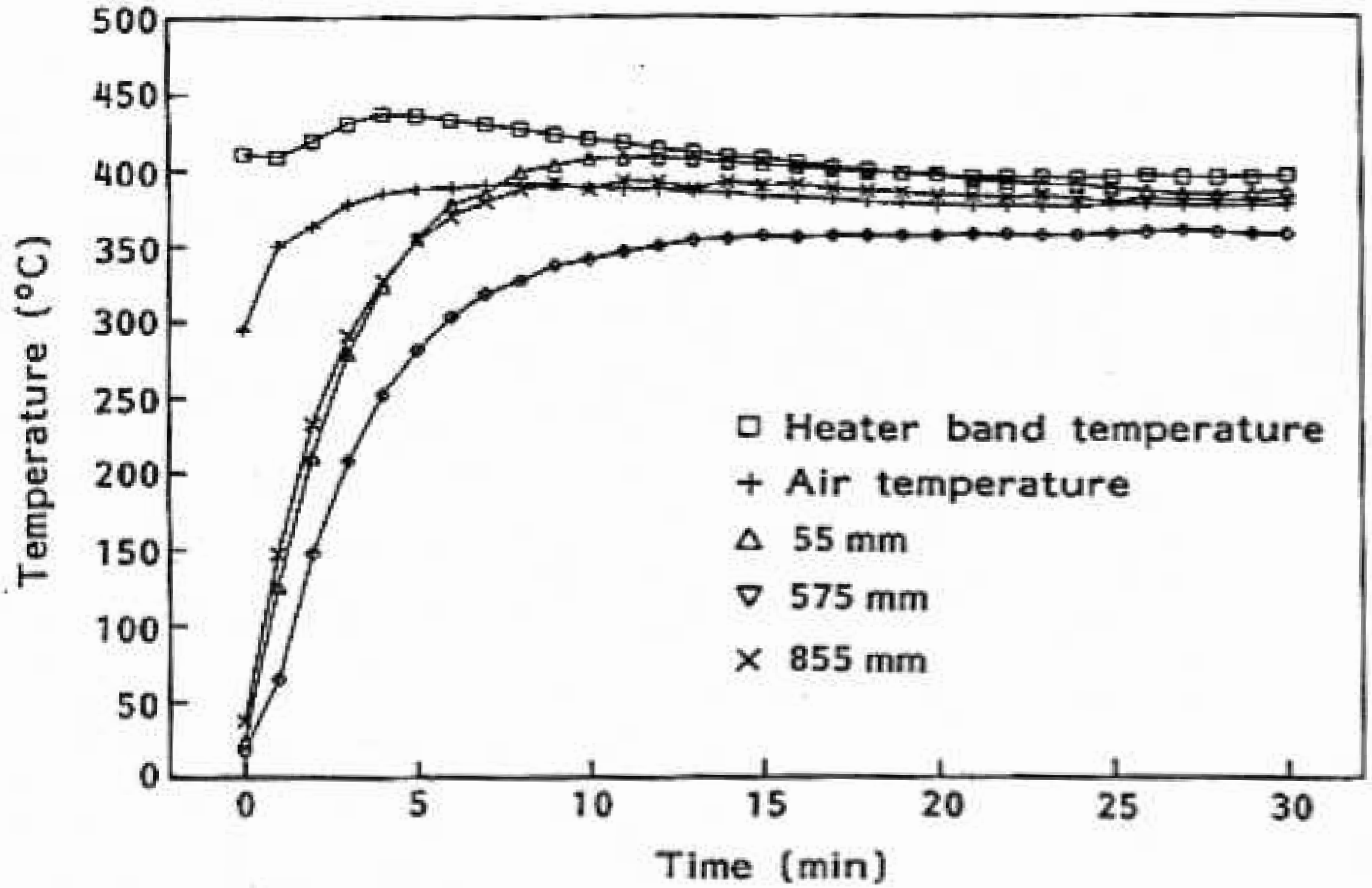


Figure 9 Temperature against time for high emissivity plate ($\varepsilon = 0.95$), heated in a preheated autoclave, for three different distances from the door

Source: PF Monaghan, MT Brogan, PH Oosthuizen, Heat transfer in an autoclave for processing thermoplastic composites, Composites Manufacturing Vol 2 No 3/4 1991

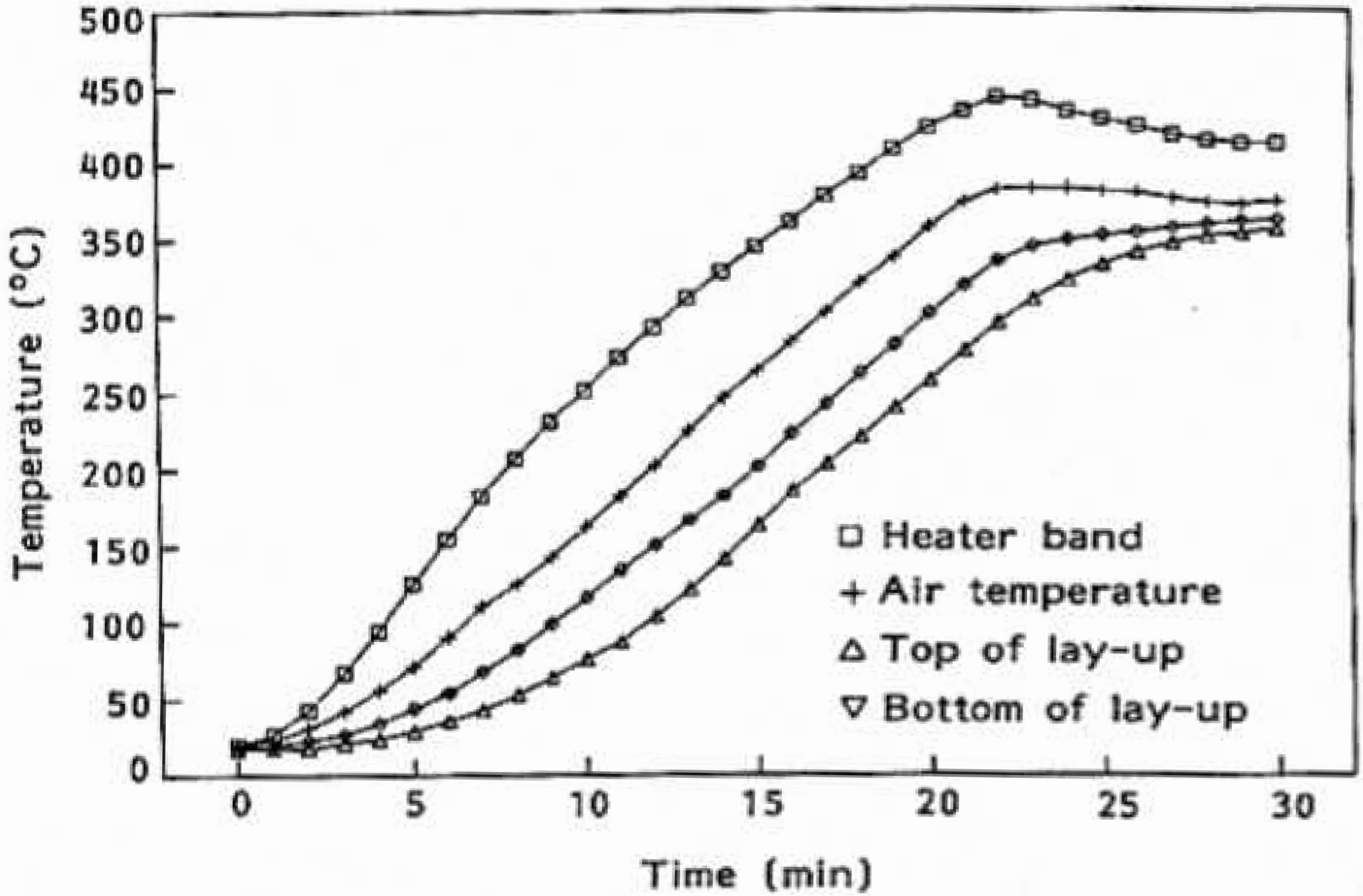


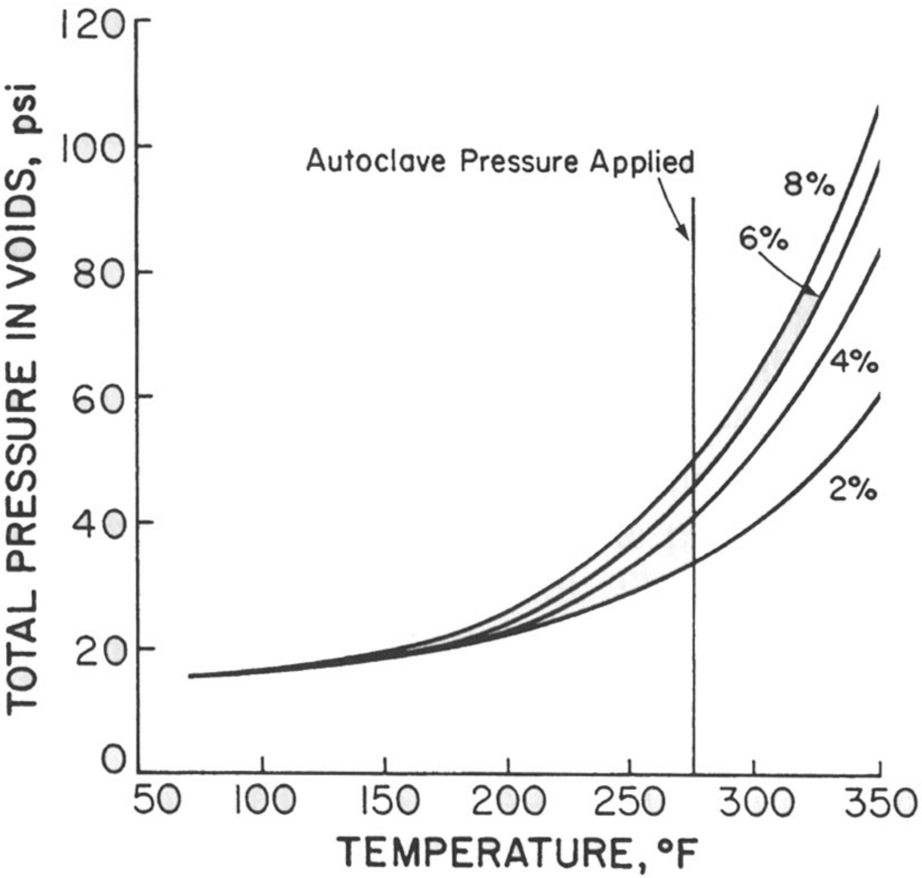
Figure 10 Temperature distribution of mould and unconsolidated lay-up heated within a non-preheated autoclave

Source: PF Monaghan, MT Brogan, PH Oosthuizen, Heat transfer in an autoclave for processing thermoplastic composites, Composites Manufacturing Vol 2 No 3/4 1991

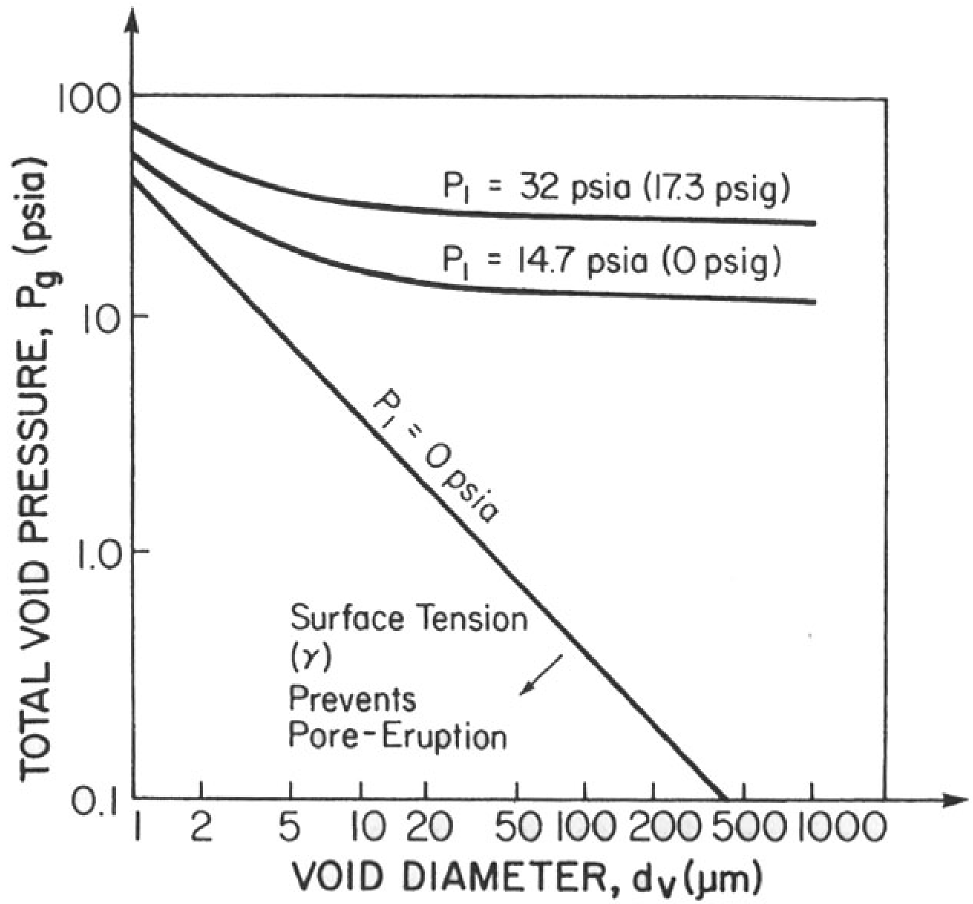
Leitfaden

- Introduction
- Heat Exchange Mechanisms
- Void formation and void growth
- Tooling

Porenbildungsmechanismen (Grundlagen)



Gutowski, T.G.: Advanced Composites Manufacturing; John Wiley & Sons, Inc. New York 1997



Gutowski, T.G.: Advanced Composites Manufacturing; John Wiley & Sons, Inc. New York 1997

Leitfaden

- Introduction
- Heat Exchange Mechanisms
- Void formation and void growth
- Tooling

Selection criteria for manufacturing process

Selection Criteria

Economical aspects

Investments

- Equipment
- Tooling

Labour costs

Material Costs

Series volume

Cycle time

Safety and health aspects

Technical aspects

Structural features

- Design and fabrication of highly integrated monolithic structures (reduction of single parts)
- Manufacturing of highly complex shapes
- Easy integration of doublers, inserts damping materials and functional elements such as actuators and sensors.

Surface quality

Laminate features

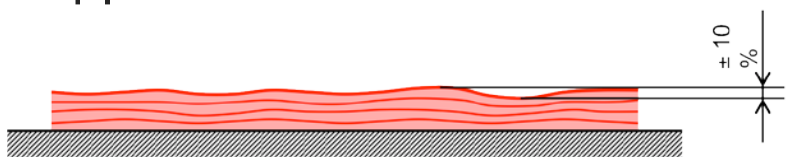
- Mechanical properties
- Fibre architecture
- Fibre volume content

Quality and reproducibility

Pressure redistribution during curing

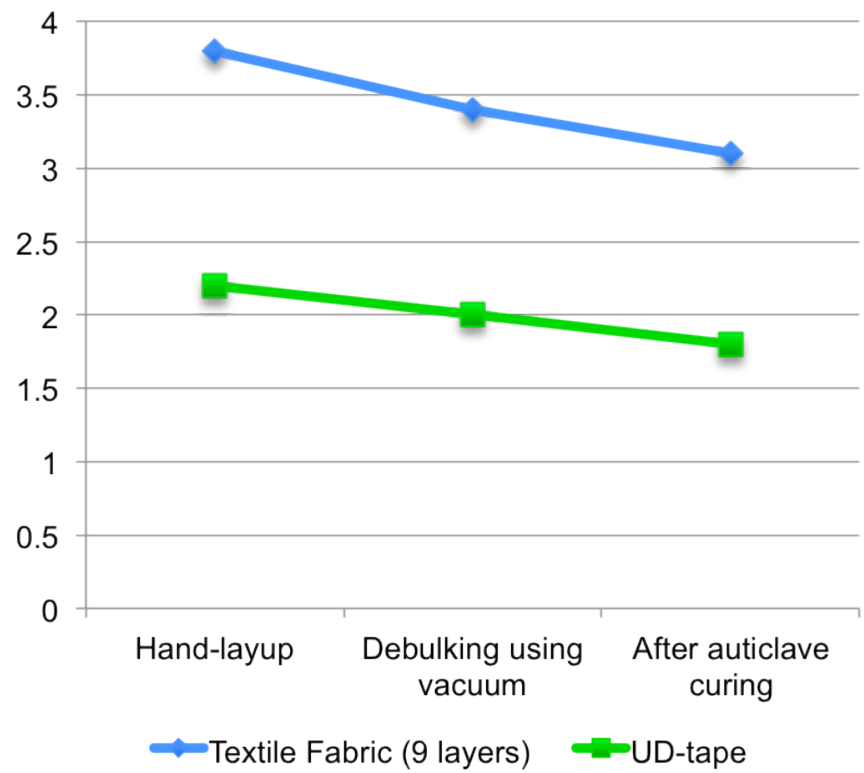
Thickness scattering during processing

- Good accuracy on mold-side
- Large scattering (up to 10% of laminate thickness) on the opposite side



- Uniformly-distributed (isostatic) pressure distribution on both laminate side is mandatory

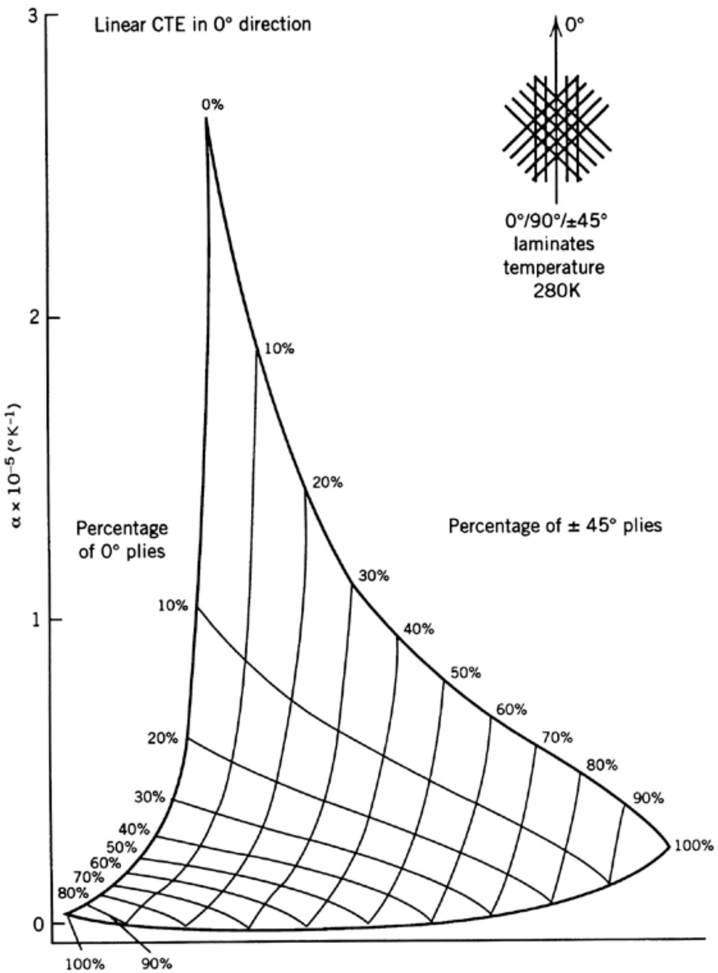
Laminate compaction during the manufacturing-process



Tooling: Design and material selection aspects

Criteria	**Influencing parameters**
Quality of the part to be manufactured: ■ Dimensional accuracy ■ Laminate quality ■ Surface quality	Thermal behavior: • Temperature stability • thermal mass, • thermal conductivity, • CTE of tooling material • Appropriate design to enhance heat transfer Tooling design: • Supporting structure • Vacuum-integrity • Dimensional stability under processing conditions Surface quality
Economical aspects ■ Handling ■ Cost efficiency	Tooling design (weight and volume) Tooling costs Material durability Design-life Tooling design

Coefficient of thermal expansion (CTE)



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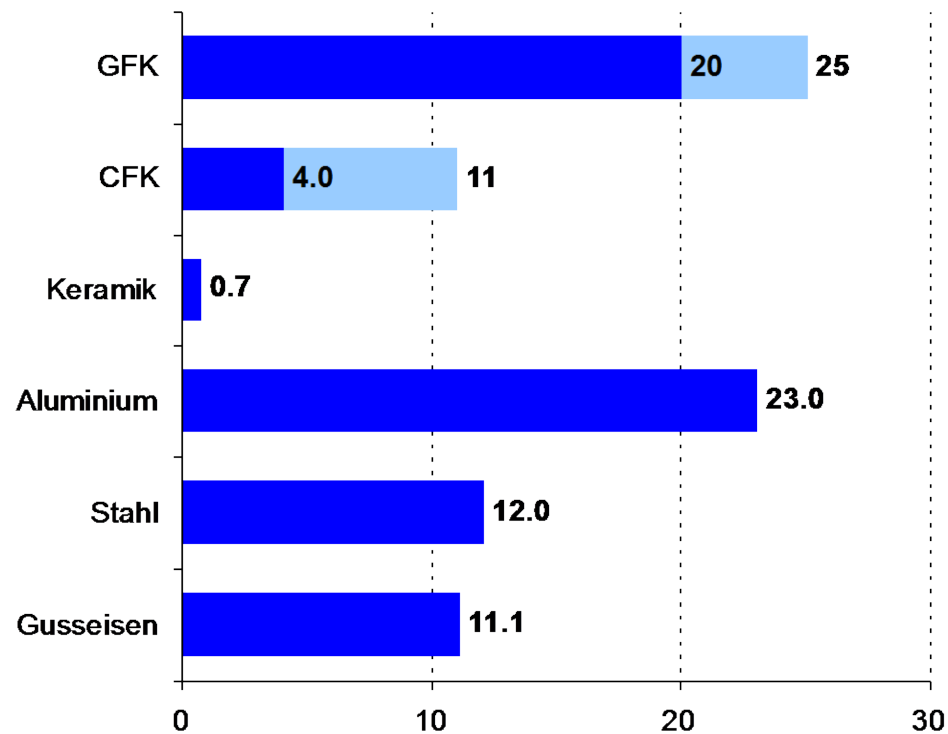
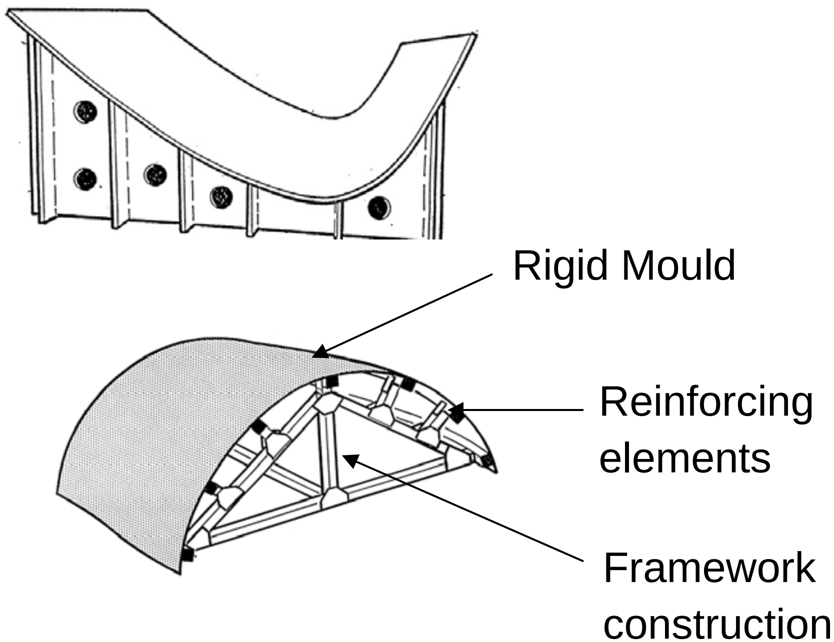


$\alpha\left[10^{-6}\, m / m\, ^{0}C\right]$

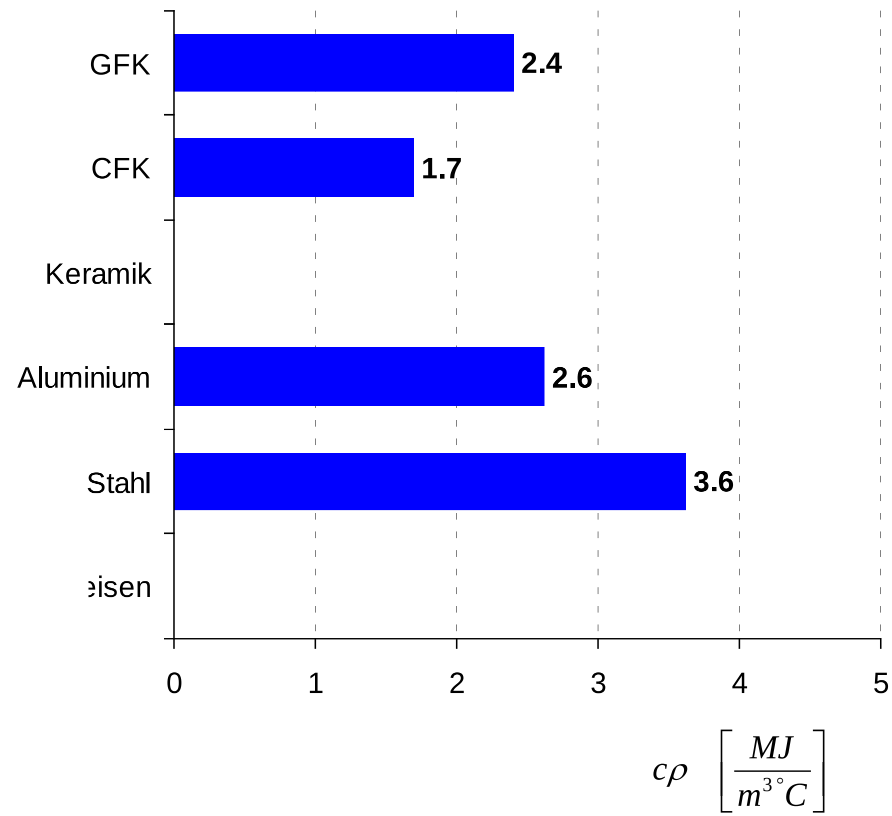
Reduction of the thermal mass is important in order to achieve faster heating and cooling cycles

Inflencing factors

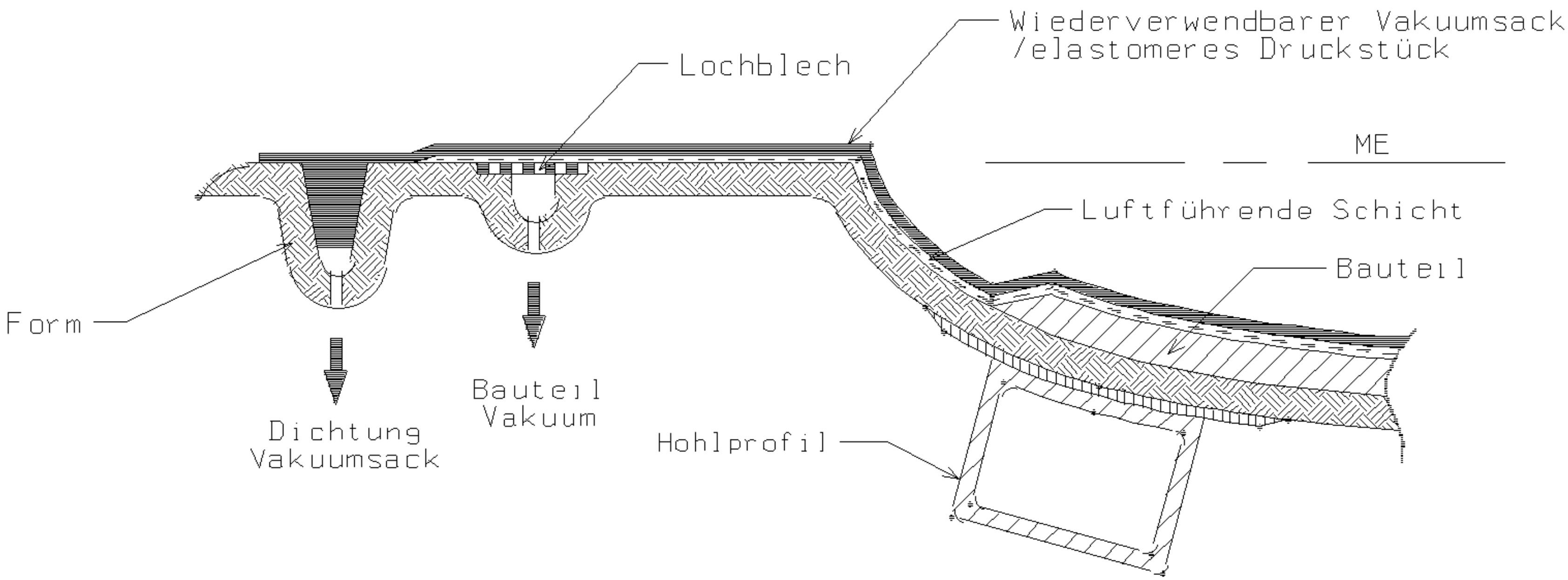
- Material selection
- Design of the supporting structure



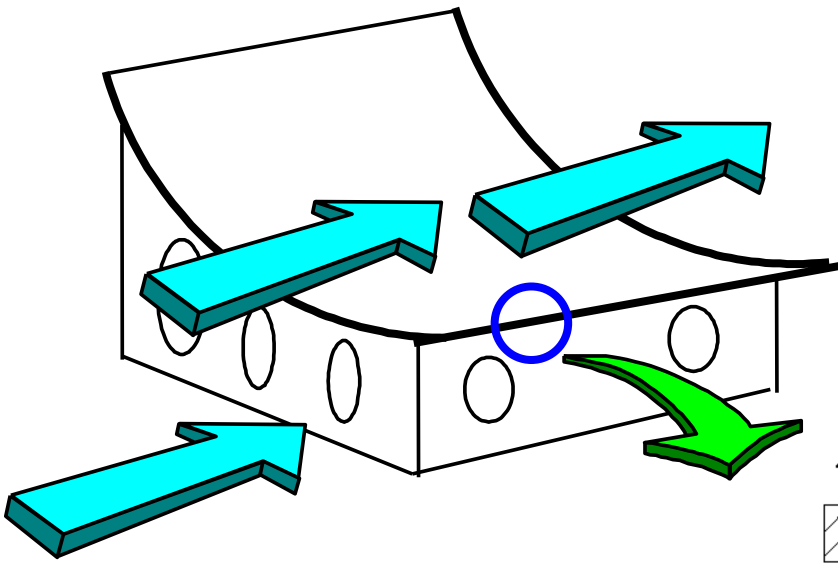
Thermal Mass

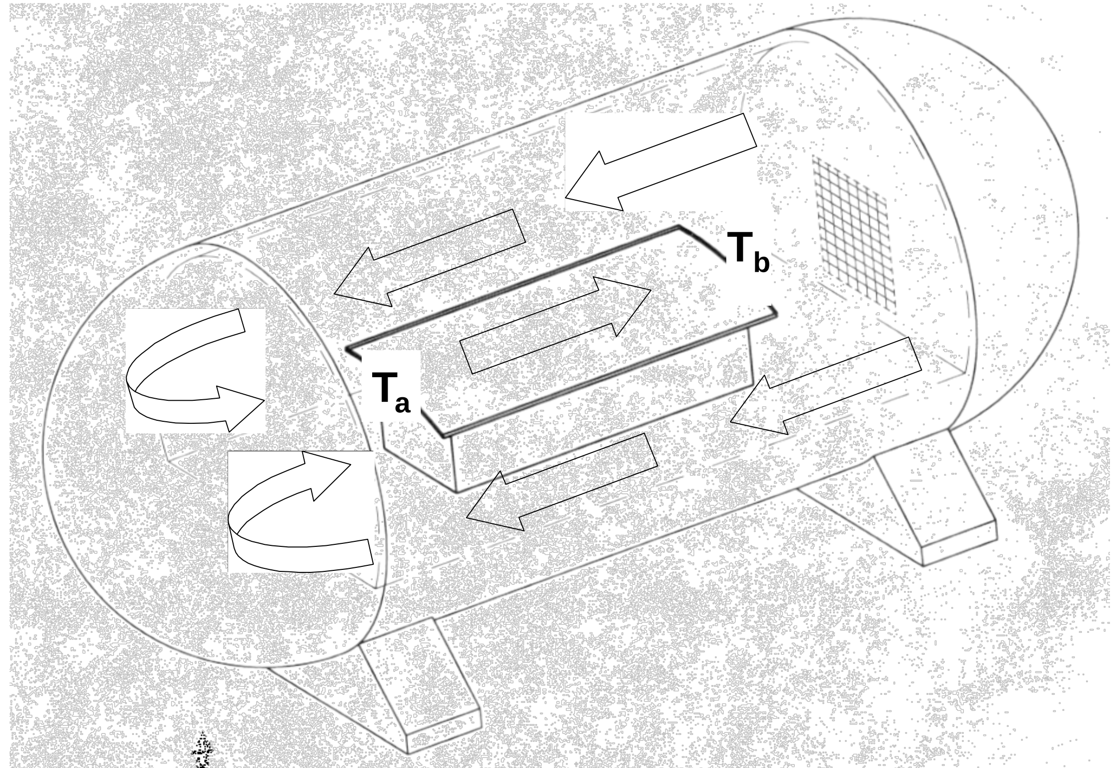


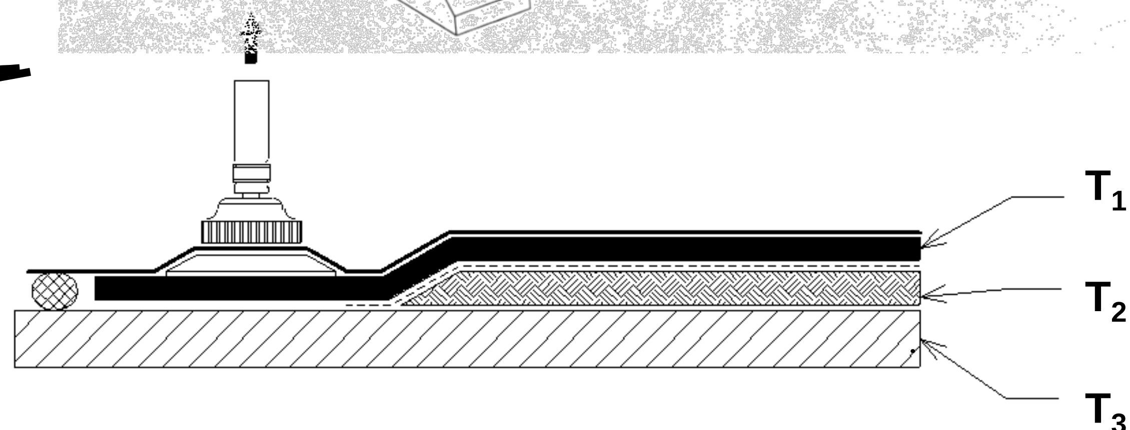
Detail design



Heat transfer control during curing







Requirements on Composite Tooling

Feature	Requirement
Porosite	< 1 %
Fibre volumen content	> 55 Vol. %
CTE	4 - 10 10^{-6} [°C^{-1}] CFRP 20 - 25 10^{-6} [°C^{-1}] GFRP
T_G	At least15°C above curing temperature
Surface quality	Surface porosity < 0.5 %
Shrinkage	< 0.03 % CFRP < 0.10 % GFRP
Warping	As low as poosile

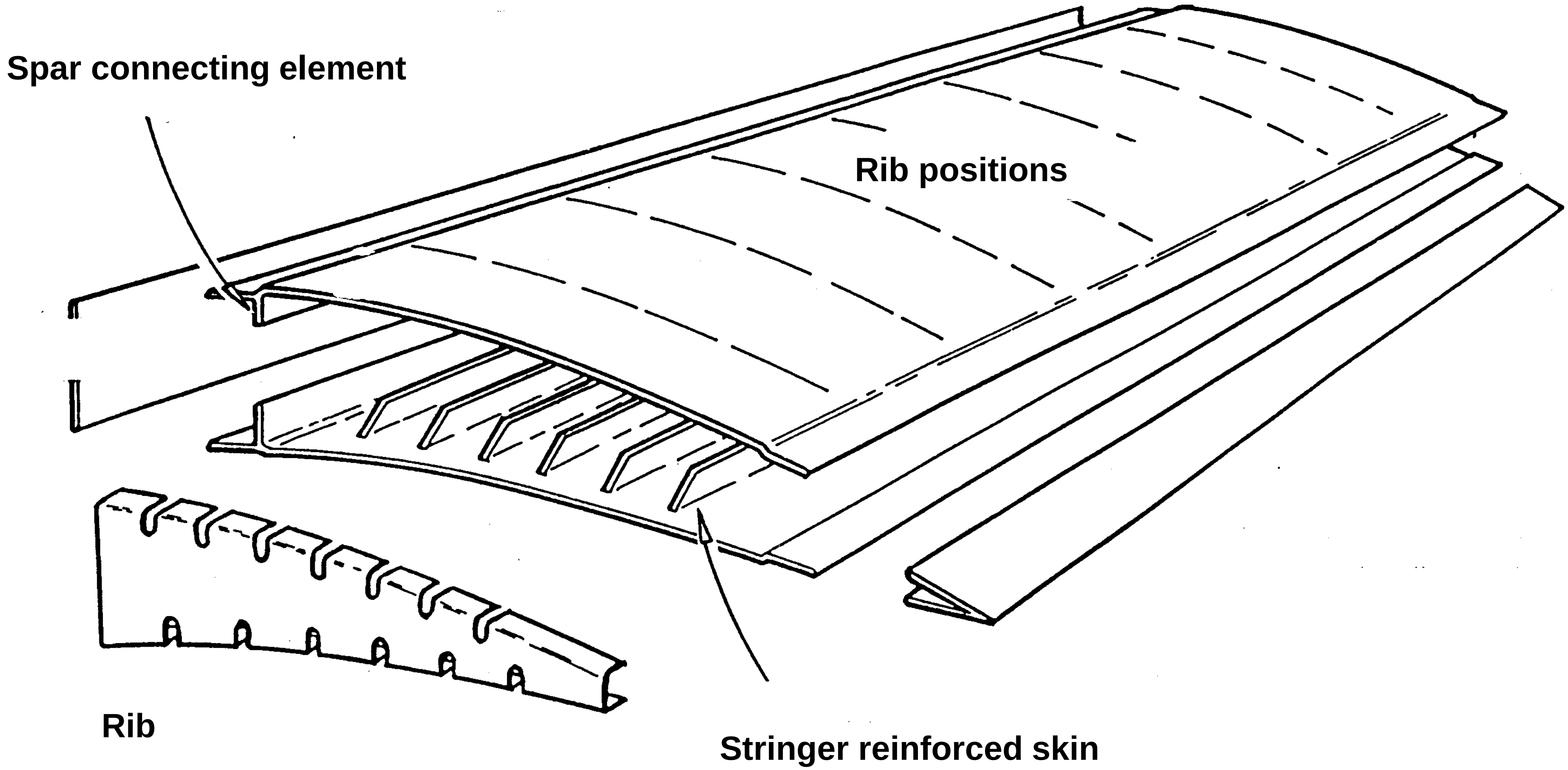
Composite tooling can be manufatured Hand- or Prepreg-layup

	PRO	CONS
Hand Layup	• Curing at room temperature • No thermal expansion of the mold-shape • Cheap	• High shrinkage • Higher thermal deformation during curing
Prepreg	• Low shrinkage • Well-defined layup	• Modl fabrication is more expensive and time consuming

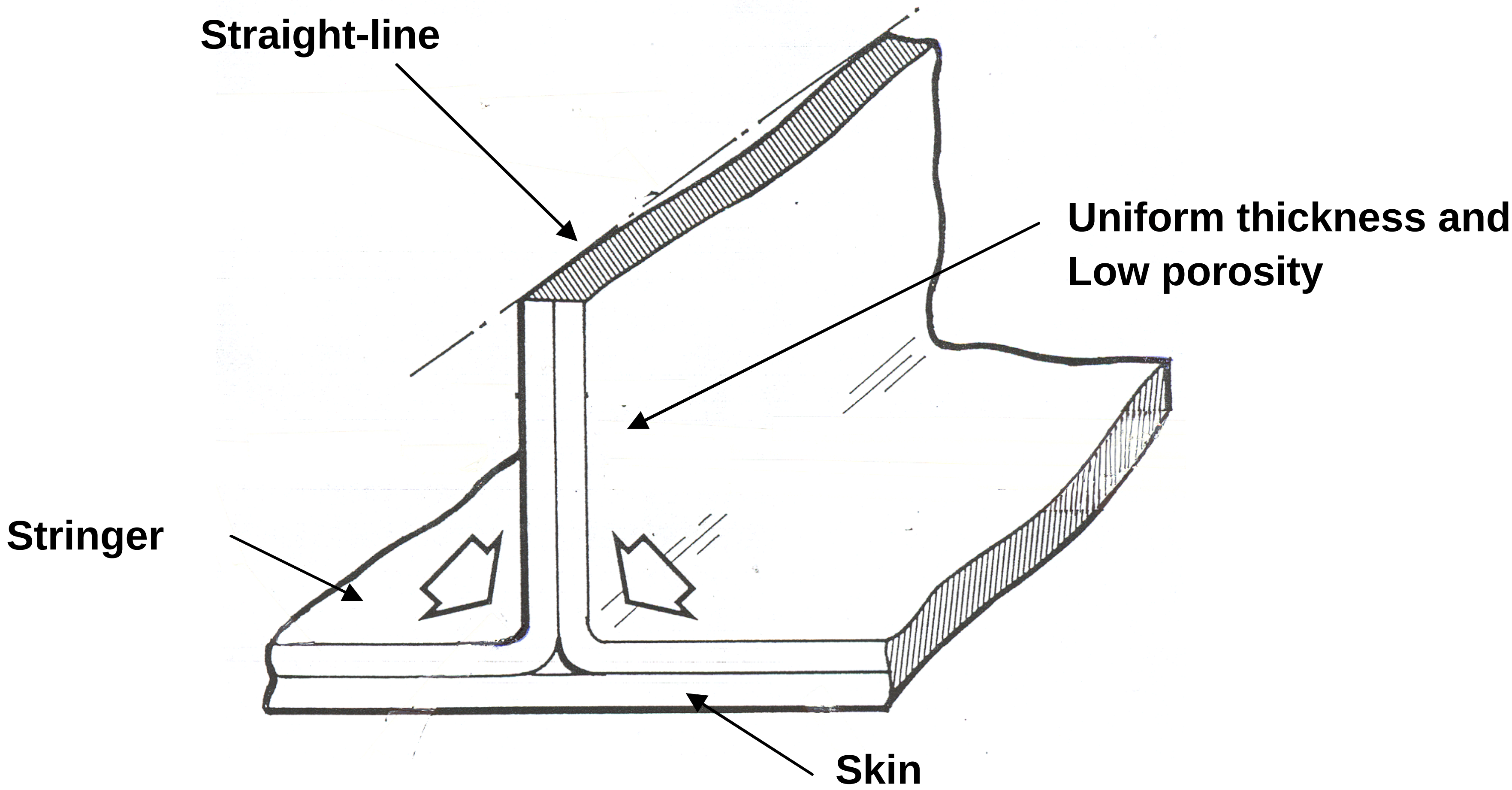
Achievable laminate quality

	Mold fabrication technology		
	Hand Layup	Hand layup + debulking	Autoclave
Fibre volume content	40%	55%	60%
Porosity in %	> 10	3-5	< 1.0
CTE	7.2	5.4	3.6
Shrinkage [10-6/°C]	-3.6	-0.9	-0.018
Curing cycles at 175°C	50	100	1000

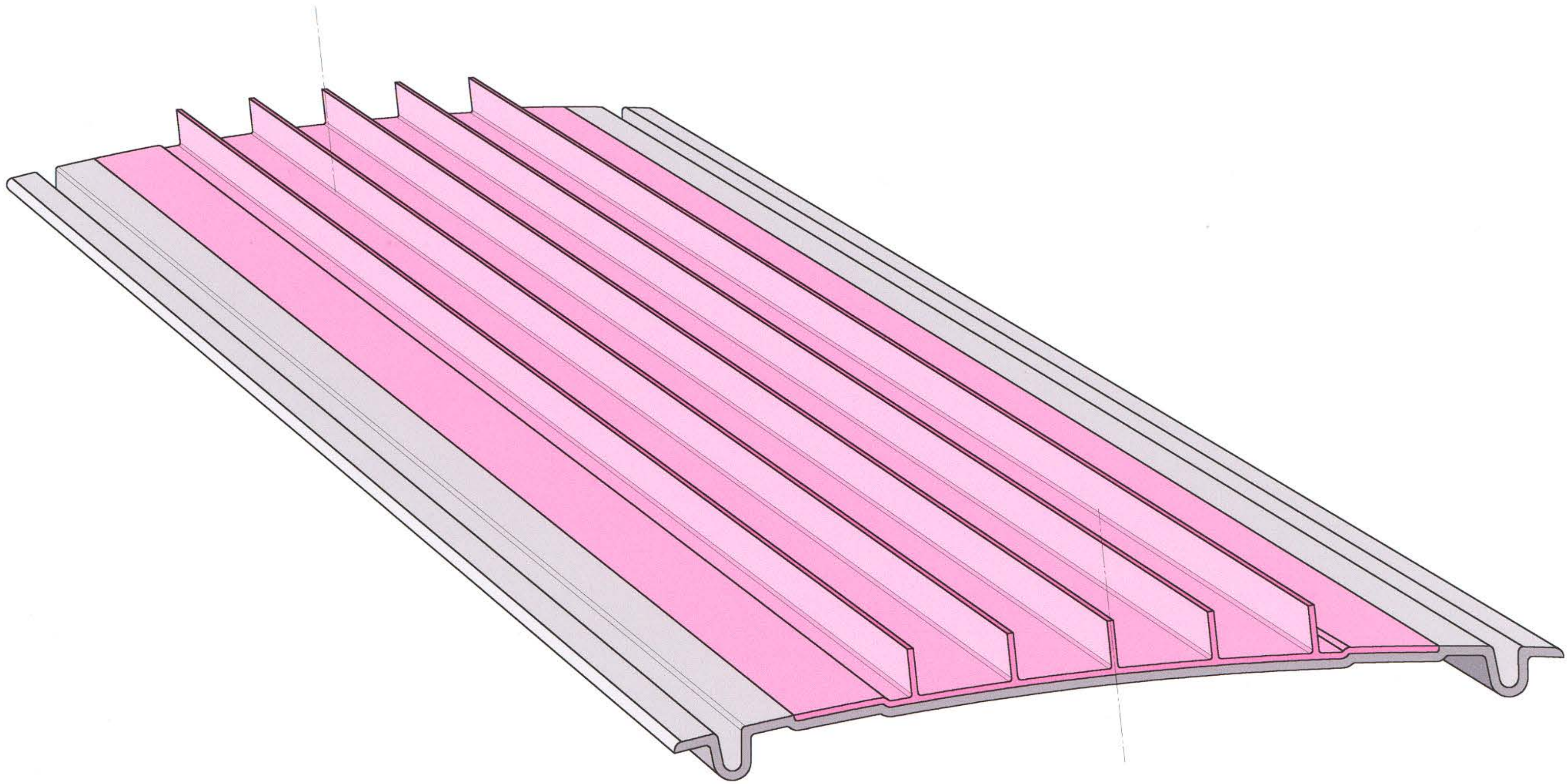
Airbus A320: Landing flap



Requirement on the stringer elements

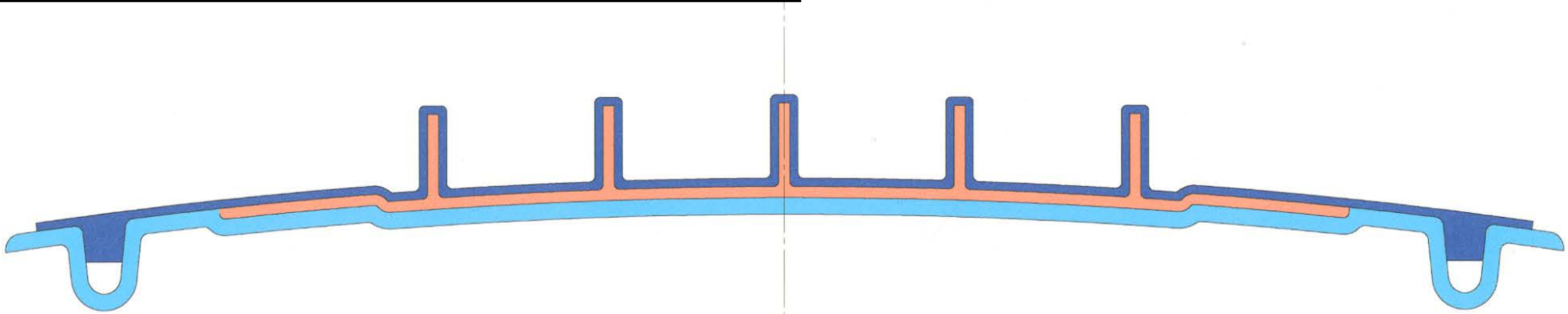


Airbus A320: Stringer-reinforced panel element

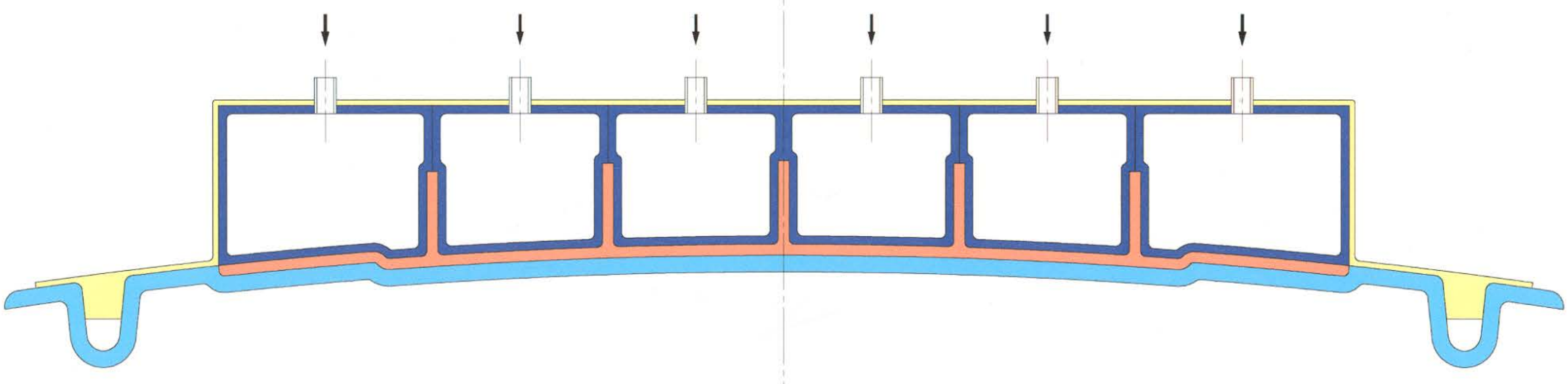


Airbus A320: Tooling concepts

Flexible Elastomeric tool

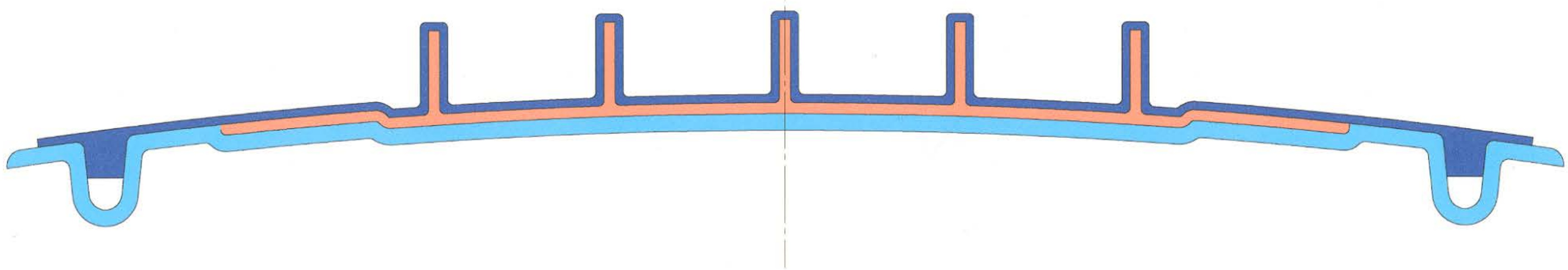


Inflatable core

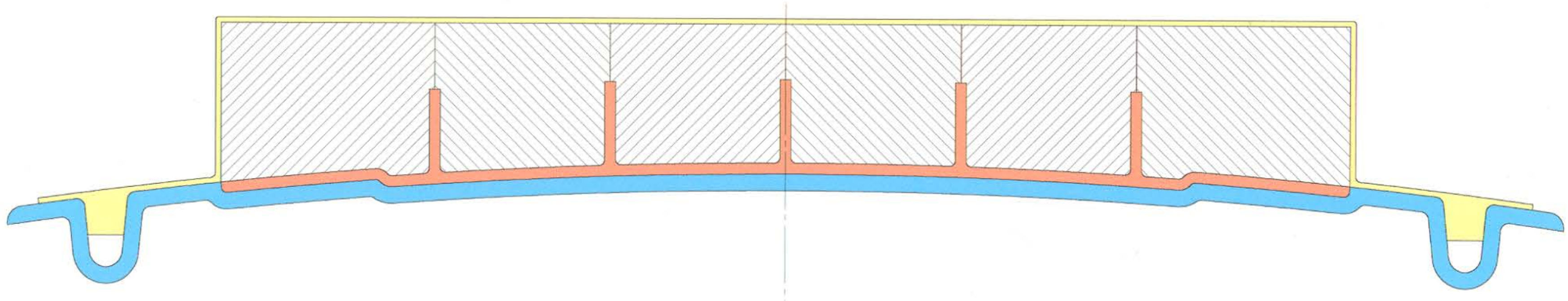


Airbus A320: Verschiedene Vorrichtungskonzepte

CFRP-Tool



Aluminum Cores



Example: Airbus A310 Vertical Tail

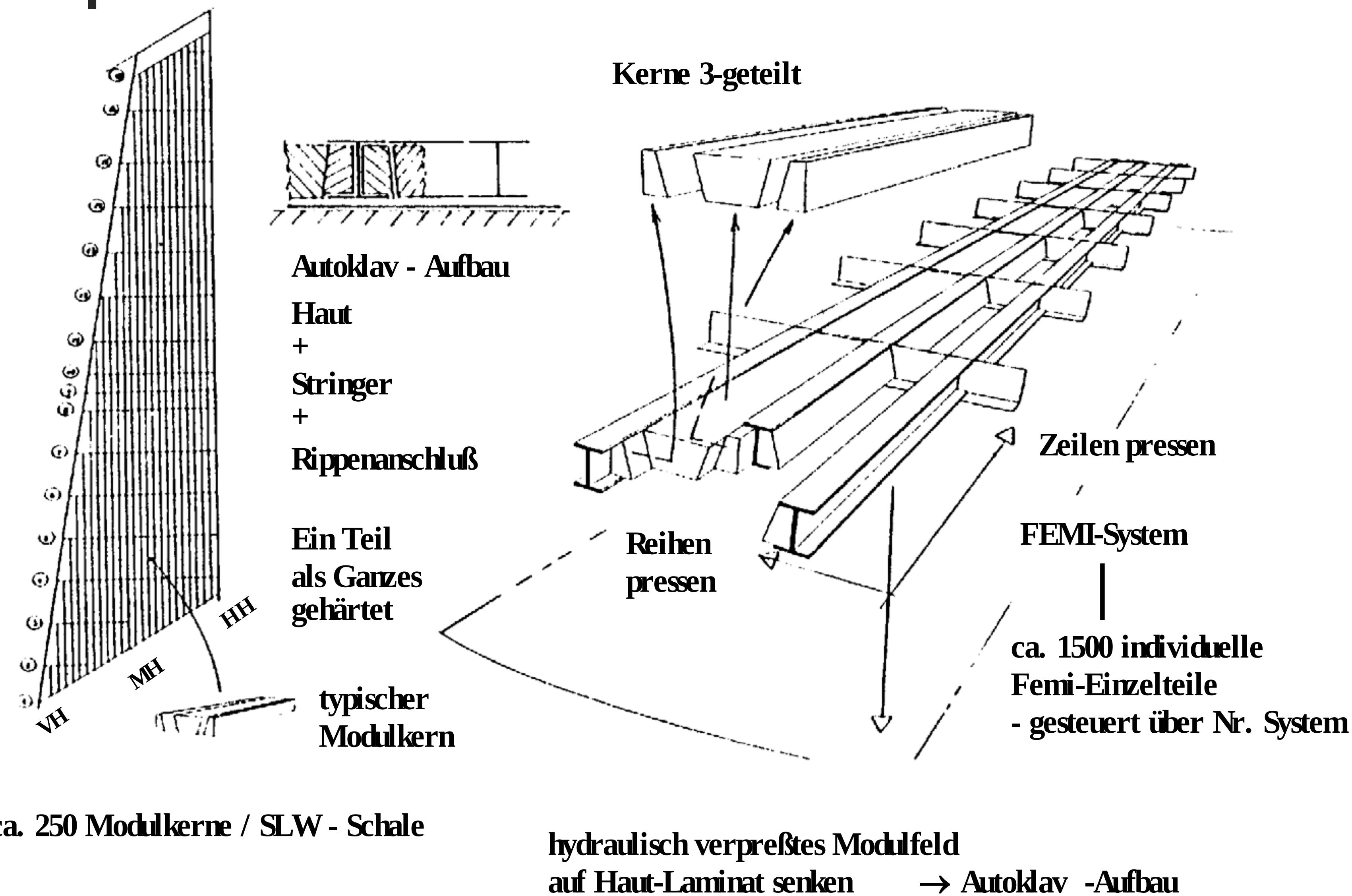
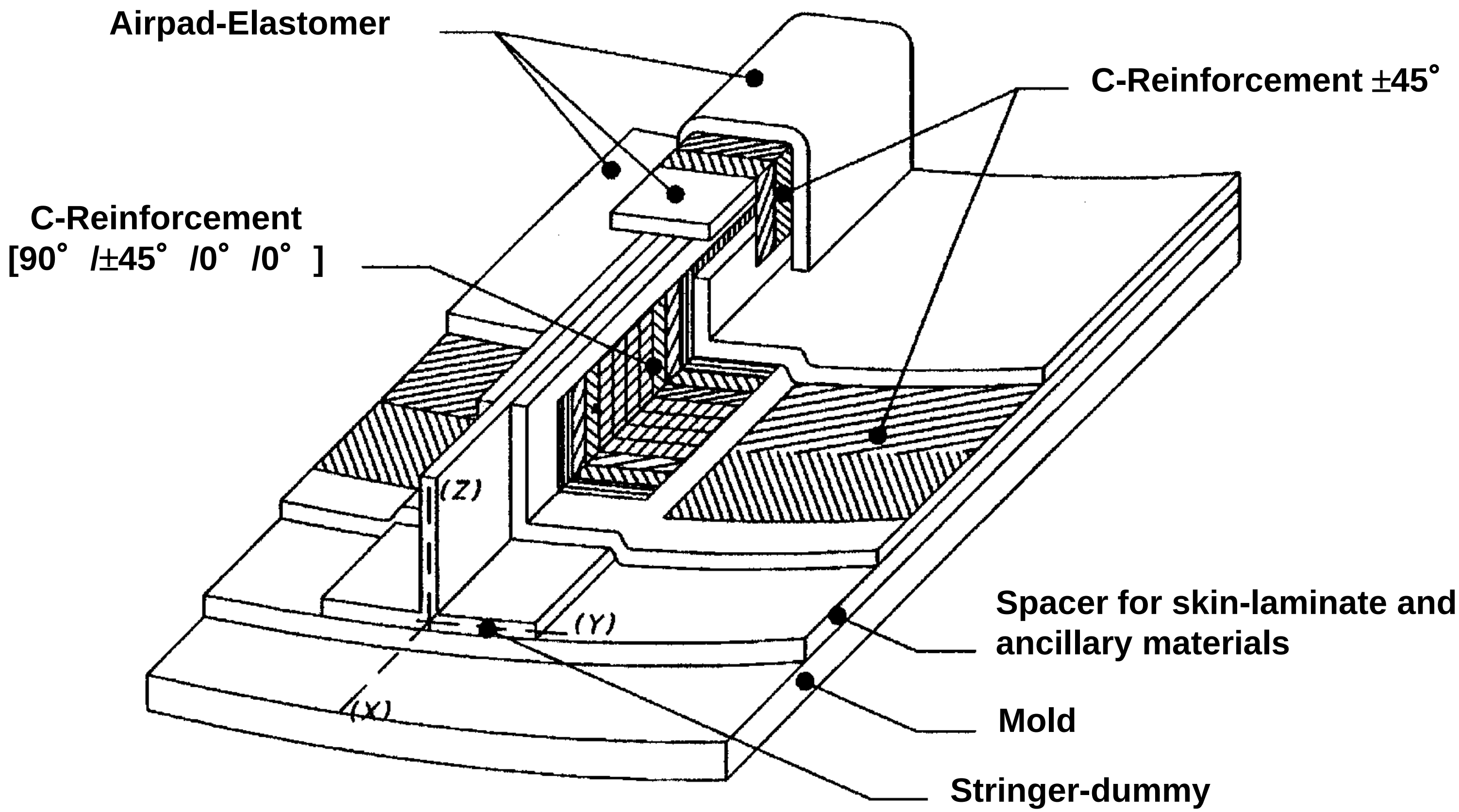


Bild: Bieling, H.: Serieneinsatz von Faserverbundwerkstoffen im Flugzeugbau, dargestellt am Seitenleitwerk des Airbus, Vortrag bei der 10. ICED-Konferenz, Prag 1995

Aufbau einer Airpadmatte im Bereich einer Längsversteifung



Comparison between Soft- and Hard-Core technique

	Hard Core	Soft Core
PRO	■ Surface quality ■ Precise geometry ■ Design-life	■ Laminate quality ■ Shape accuracy ■ No induced thermal loading
CONS	■ Thermal expansion of the cores is inducing loadingin laminate ■ High requirements on the tolerances of the tooling ■ Laminate porosity ■ Heavy and costly construction ■ Autoclave pressure redistribution is difficult	■ Limited design life