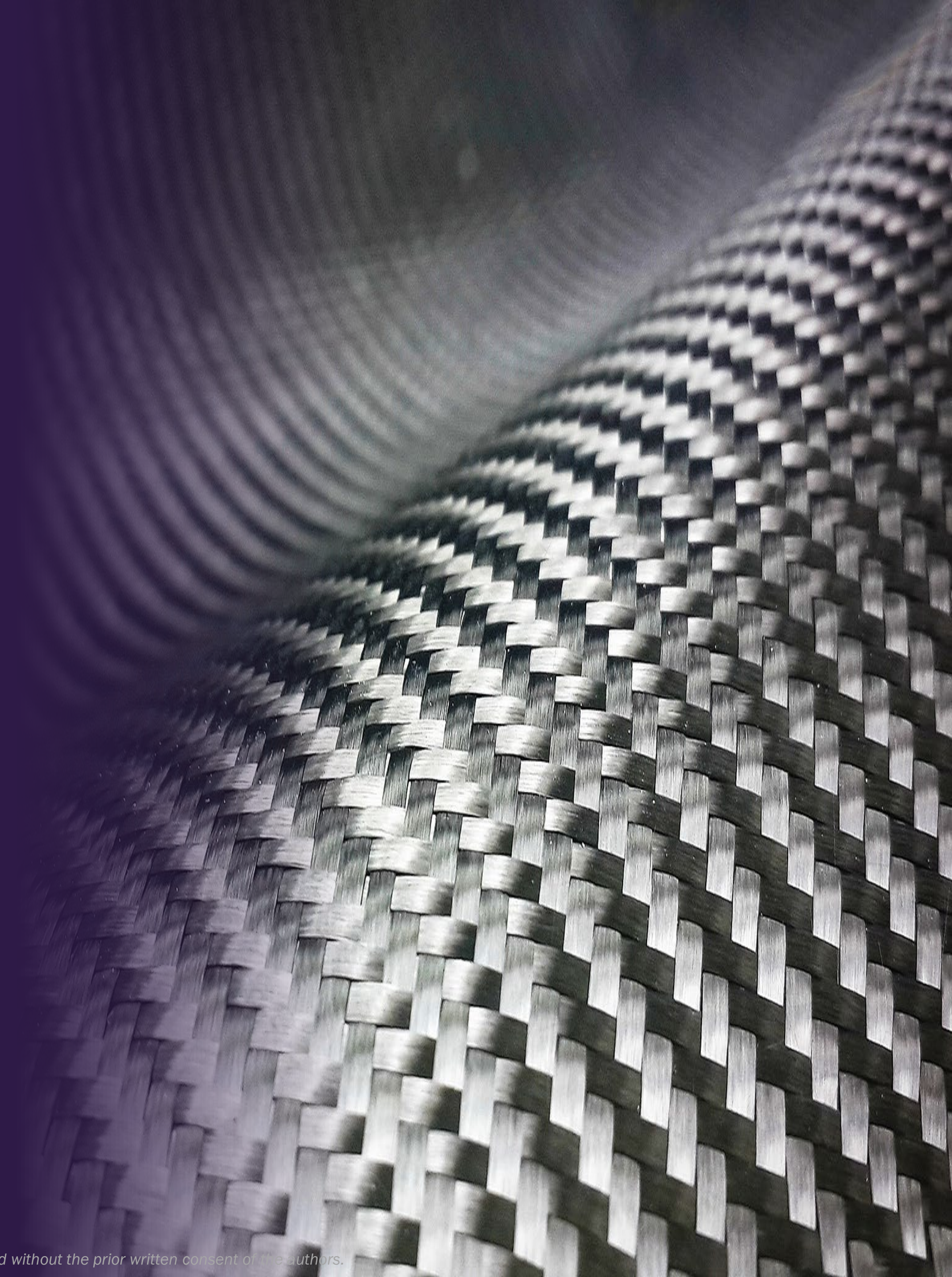
Clemson | CECAS | CCC | neXt

Composites Manufacturing

Ramy Harik

Director, Clemson Composites Center
Professor, School of Mechanical and Automotive Engineering
ExxonMobil Employees Endowed Chair
harik@clemson.edu



[1] https://www.siempelkamp.com/products-and-technologies/machine-and-plant-engineering/composites/?L=1

Outline

History of Composites

CLEMSON COMPOSITES CENTER

next

[1] https://coventivecomposites.com/Materials-Examples

History of Composites

- Composites have been arguably around in nature for millions of years

- Materials such as wood and bone can be classified as composites

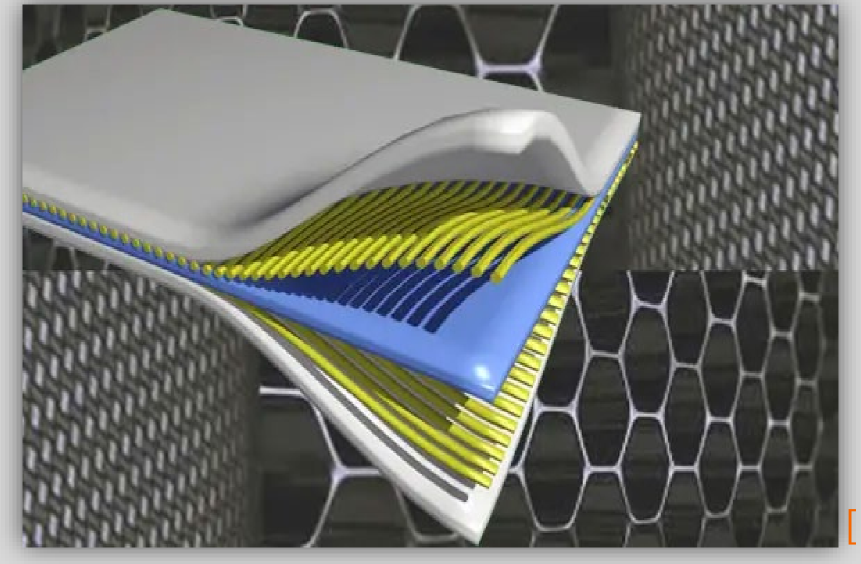
[1]

[2]

[1] https://www.popularmechanics.com/science/green-tech/a40231102/lab-grown-wood/
[2] https://www.sciencenews.org/article/ancient-hominid-bone-serves-dna-stunner

What is Composite Material?

- Composite materials are heterogeneous combinations of two or more constituents with different mechanical, physical, and/or structural properties.
- The fundamental concept is:
  - The combination of the different constituents provides superior properties for a specific engineering application compared to the individual constituents' performance.
- Typically, a composite contains two main components:
  - Reinforcement material
  - Matrix material



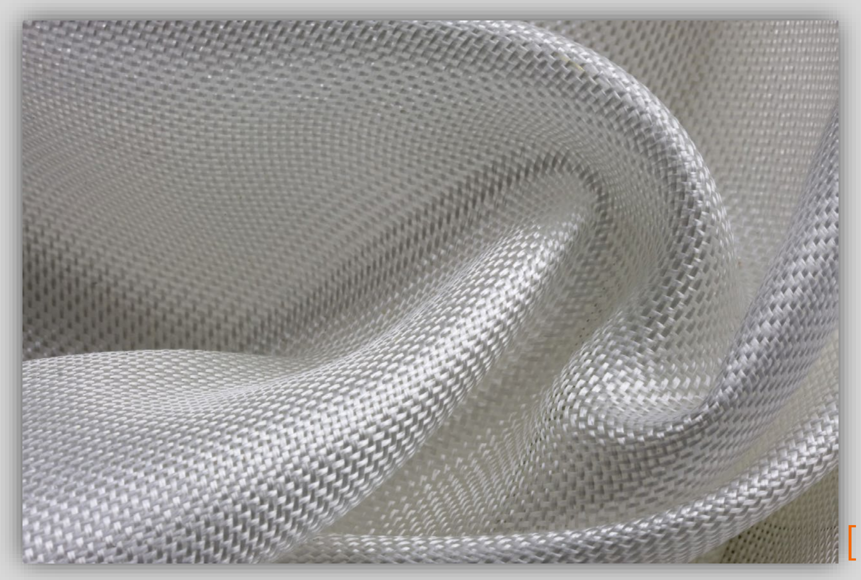
[1]

[2]

[1] https://www.innovativecomposite.com/examples-of-composite-materials/
[2] https://www.textileblog.com/composites-types-processing-and-application/

Example of Composite Material - Fiberglass

- Fiberglass is one of the most frequently used composite materials.
- In fiberglass composites, the reinforcement is made out of continuous glass fibers while the matrix is made out of a resin system.
- In the aerospace world, Carbon Fiber Reinforced Polymers (CFRP) are one of the most advanced engineering materials, possessing highly desirable properties when designed and manufactured correctly.
- The high strength and high stiffness provided by the carbon fibers (reinforcement component) provides un-matched properties.


[1]

[2]


[1] https://smicomposites.com/the-fiberglass-properties-to-know-in-composite-manufacturing/
[2] https://www.milesfiberglass.com/about-fiberglass-composites/

Composite Products

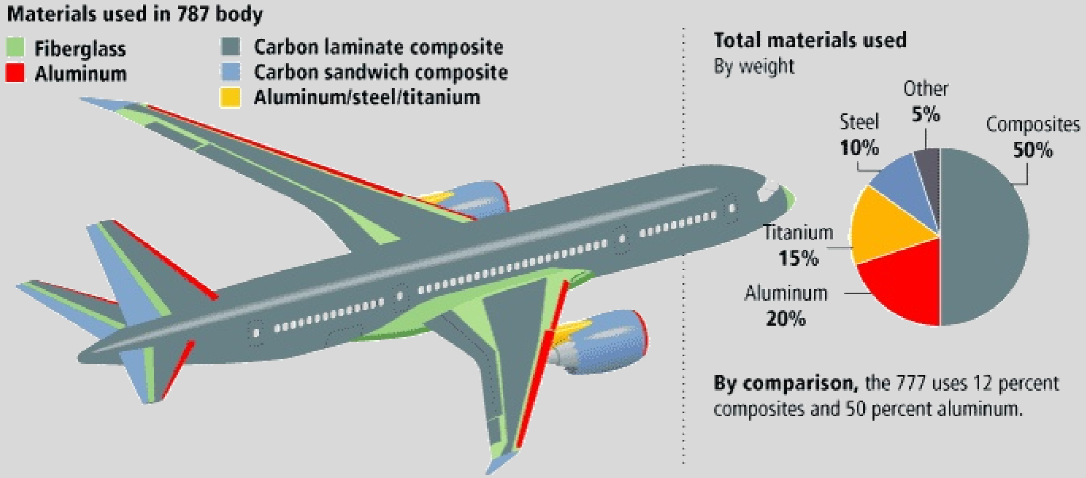
- The usage of composite products has been on the rise since the 1960s.
- The aerospace world has been a pioneer in the adoption and dissemination of composites and composite products.
    - The novelty in the use of composites is to obtain quality aerospace parts that are also lightweight, reliable, and consistent.
- Several industries are pushing the boundaries of composites design and manufacturing today.

- Major industries that use composite materials:

Aerospace
Automotive
Energy
Sports
Biomedical
…

Example of Composite Products - Aerospace

[1]

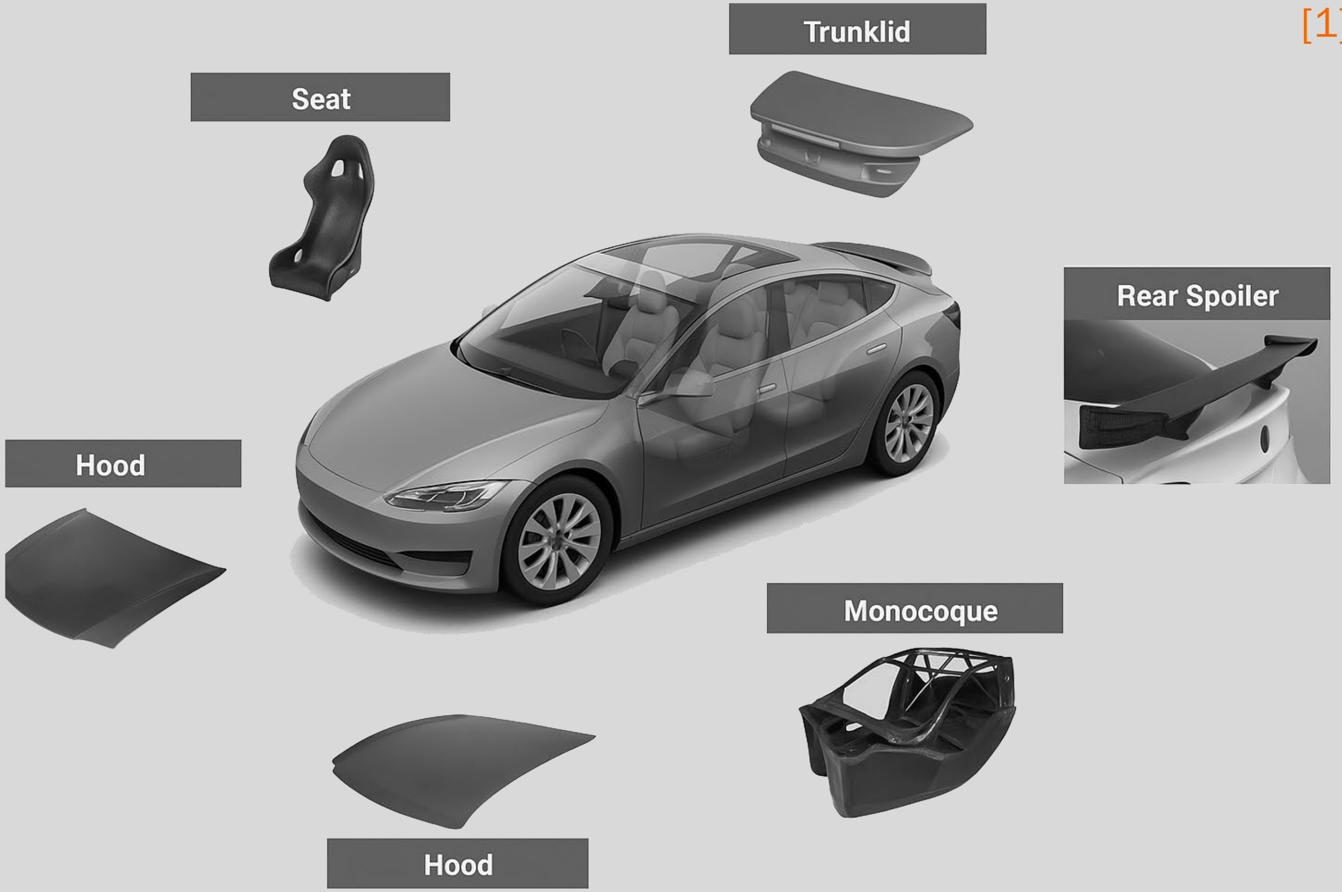


[2]

[1] https://www.researchgate.net/figure/Usage-of-various-materials-in-the-Boeing-787-Dreamliner-Katunin-et-al-2017-Rosato_fig6_332090040
[2] https://www.mhi.com/products/air/boeing_787.html

Example of Composite Products - Automotive

[1]



[1] https://www.cf-composites.toray/products/processed/automotive.html

Example of Composite Products - Sports

[1]

[2]

[1] https://dansfabulouswebsite.weebly.com/aerodynamic-golf-balls.html
[2] https://www.open.edu/openlearn/science-maths-technology/toys-and-engineering-materials/content-section-2.3

Manufacturers of Composite Materials

- Textiles and textile manufacturing are often seen as precursors to composite manufacturing.
- Toray Industries, for example, today one of the major companies in the composite materials market, had its roots in textiles and fabrics.
- Toray acquired TenCate, another company whose roots are also in the textile industry.
- Other major composite materials manufacturers include Hexcel and Solvay.

[1]

[2]

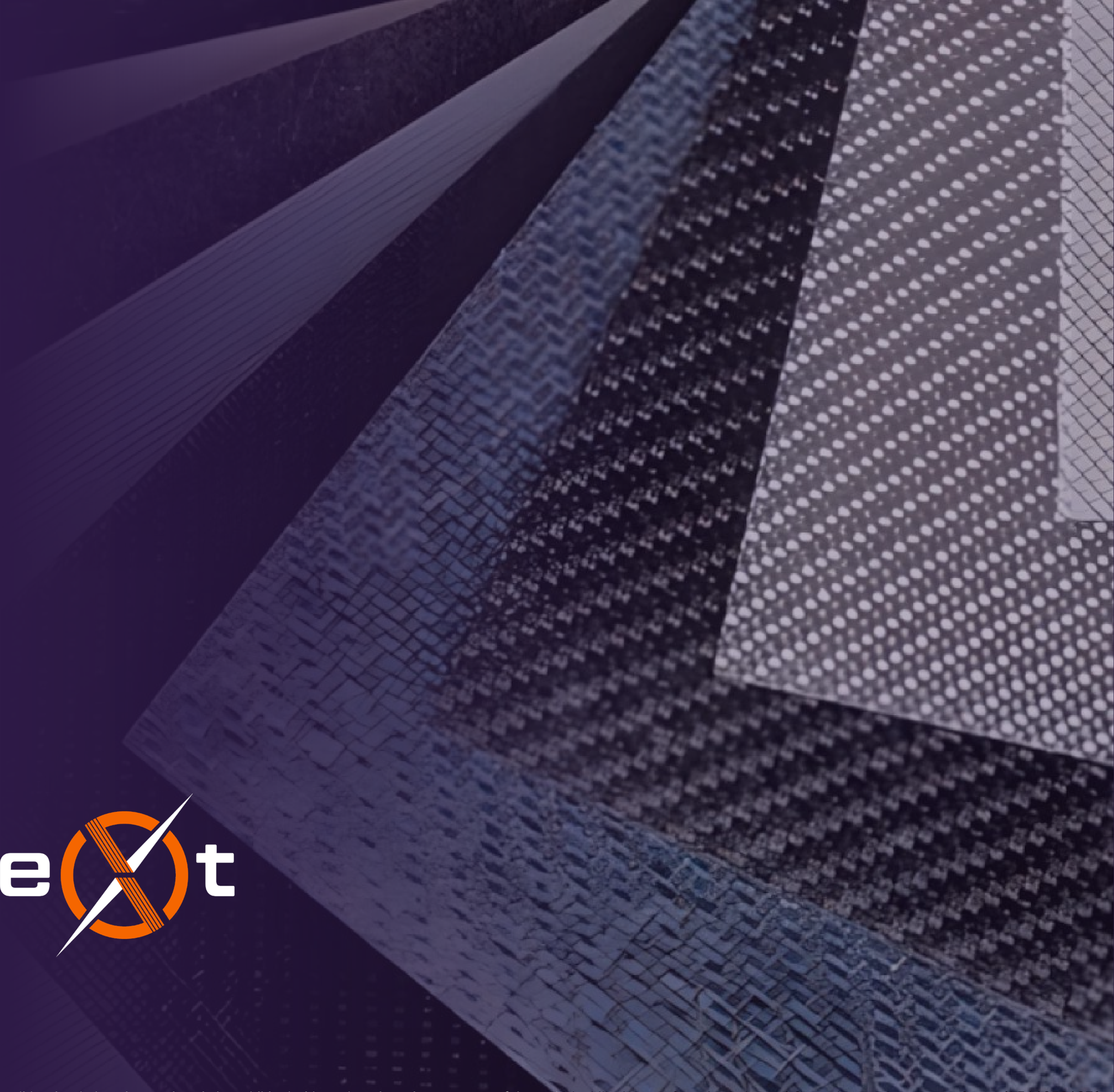
[3]

[1] https://www.water.toray/
[2] https://www.compositesworld.com/suppliers/hexcel
[3] https://www.compositesone.com/product/suppliers/solvay/

Clemson | CECAS | CCC | next

Composites Terminology

Section I



[1] https://www.rapiddirect.com/blog/what-is-composite-material-types-uses/

...ability-in-manufacturing-industry-4-0-a-path-towards-a-greener-future-4b511053137f

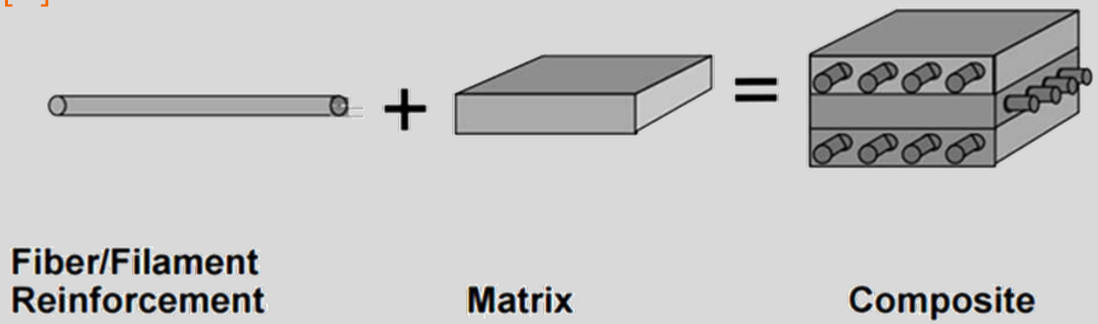
I | Components of Composite Material: Reinforcement

- It provides stiffness and/or strength component to the final material
- Reinforcement can be:
    - continuous fibers
    - chopped fibers
- With respect to manufacturing, continuous fibers are more demanding and required additional control and physical mechanisms to ensure appropriate manufacturing compared to chopped fiber

I | Components of Composite Material: Matrix

- It provides the shape/adhesion component
- It surrounds the reinforcement component and holds the composite in its final shape
- It can be of any material:
  - Metal
  - Ceramic
  - Polymers

[1]



[1] https://caeassistant.com/blog/all-about-composite-analysis/

I | Possible Reinforcement/Matrix Material Combination

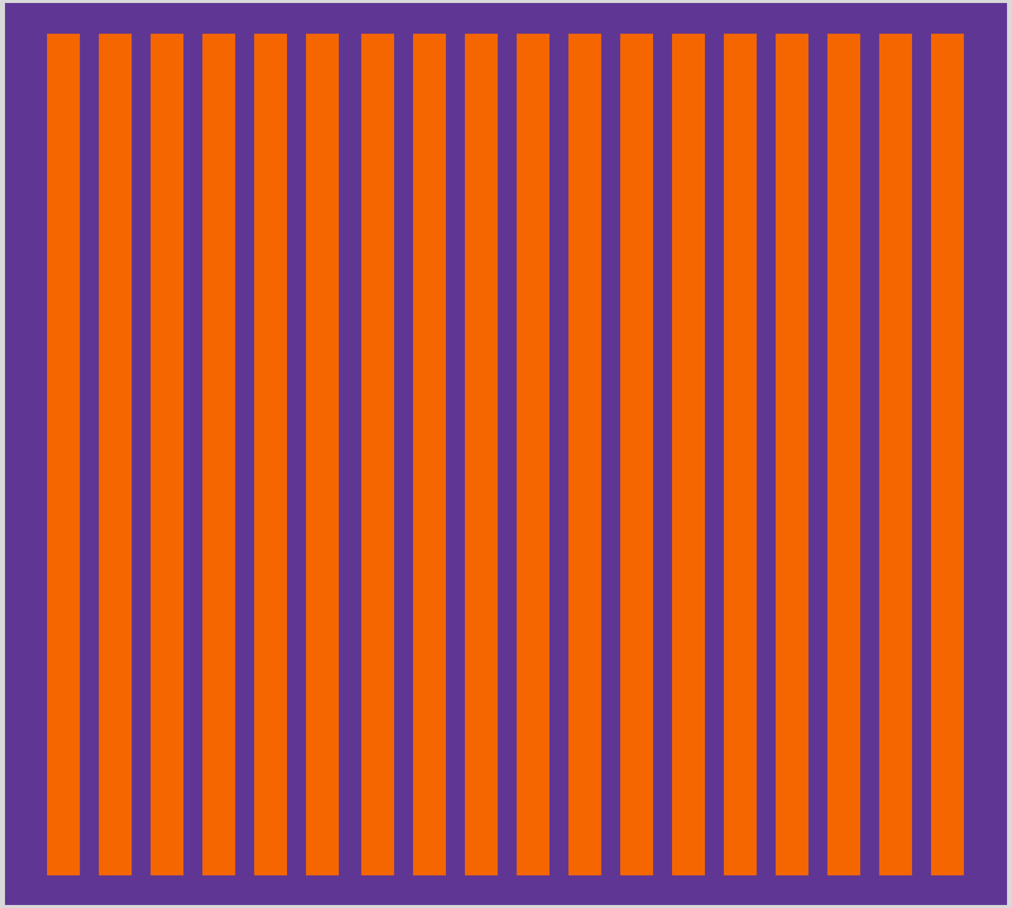
		Reinforcement		
		Metal	Ceramic	Polymer
Matrix	Metal	Metal-metal composites	Metal-ceramic composites	Metal-polymer composites
	Ceramic	Ceramic-metal composites	Ceramic-ceramic composites	Ceramic-polymer composites
	Polymer	Polymer-metal composites	Polymer-ceramic composites	Polymer-polymer composites

I.A | Material Forms

- Many material forms that are used to manufacture composite parts:
  - Unidirectional Tape
  - Slit Tape
  - Woven Fabric
  - Non-crimp Fabrics
  - Resin Systems
  - Adhesives

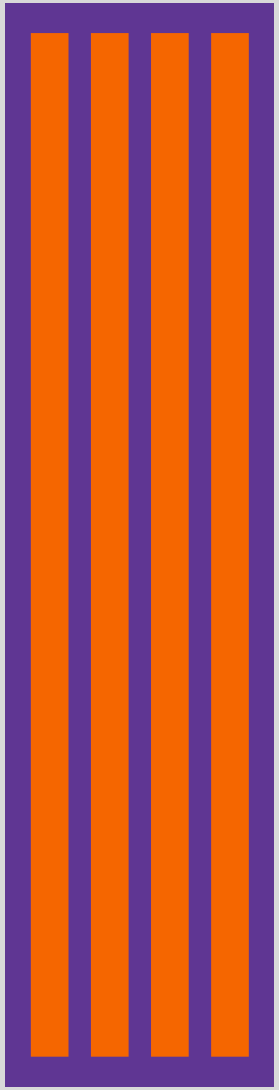
I.A | Material Forms: Unidirectional Tape

- All fibers within the tape layer have the same orientation.
- Unidirectional tape is used during Automated Tape Layering (ATL) process.
- Unidirectional tapes generally have widths of 3 inches and more.
- Example of unidirectional tape:
  - IM7-8552: It is one of the most common unidirectional tape.
  - IM7 stands for "Intermediate Modulus" carbon fiber reinforcement material and 8552 is a thermoset resin system.



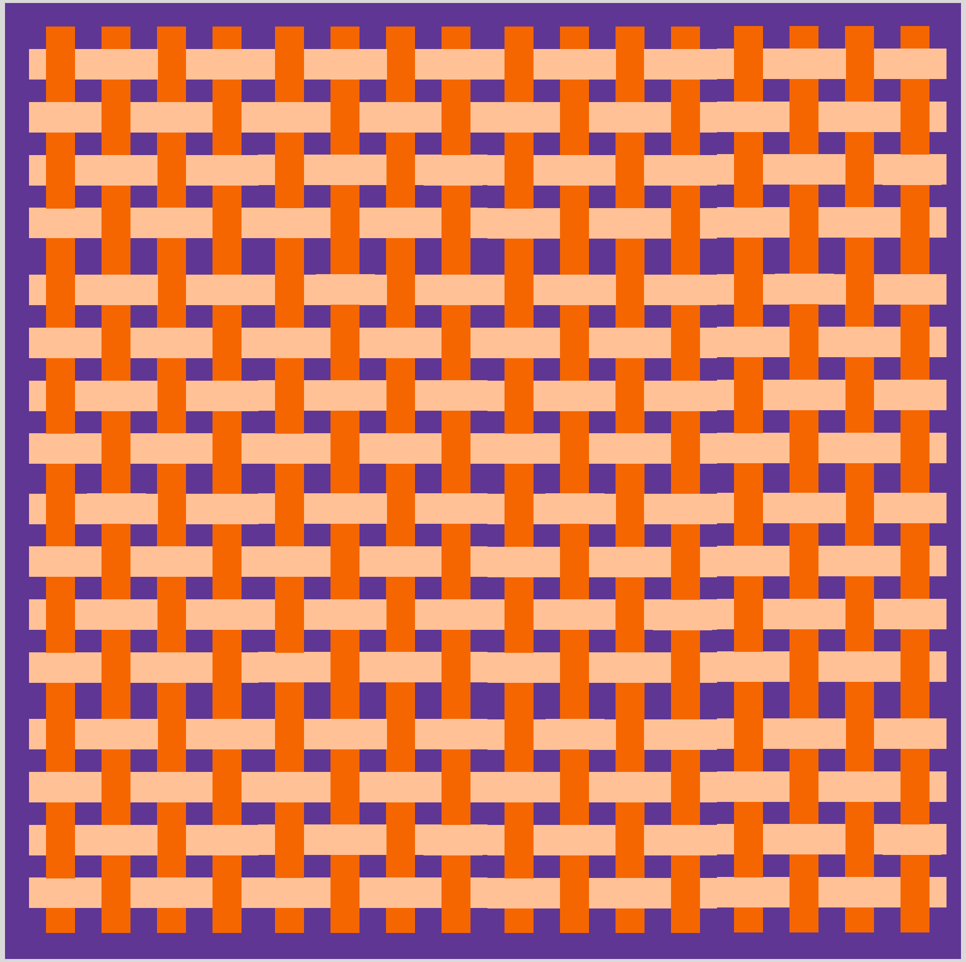
I.A | Material Forms: Slit Tape

- Slit tapes are unidirectional tapes that are slitted into smaller dimensions that can be used for specific manufacturing process.
- Slit tapes used for the creation of more intricate features and dimensions of machinery required.
- The fundamental difference between unidirectional tape and slit tape resembles the associated processes: ATL (unidirectional tape) and AFP (slit tape).
- The dimensions of slit tape are typically resembling 1/8 , ¼, ½, and 1 inch in width.



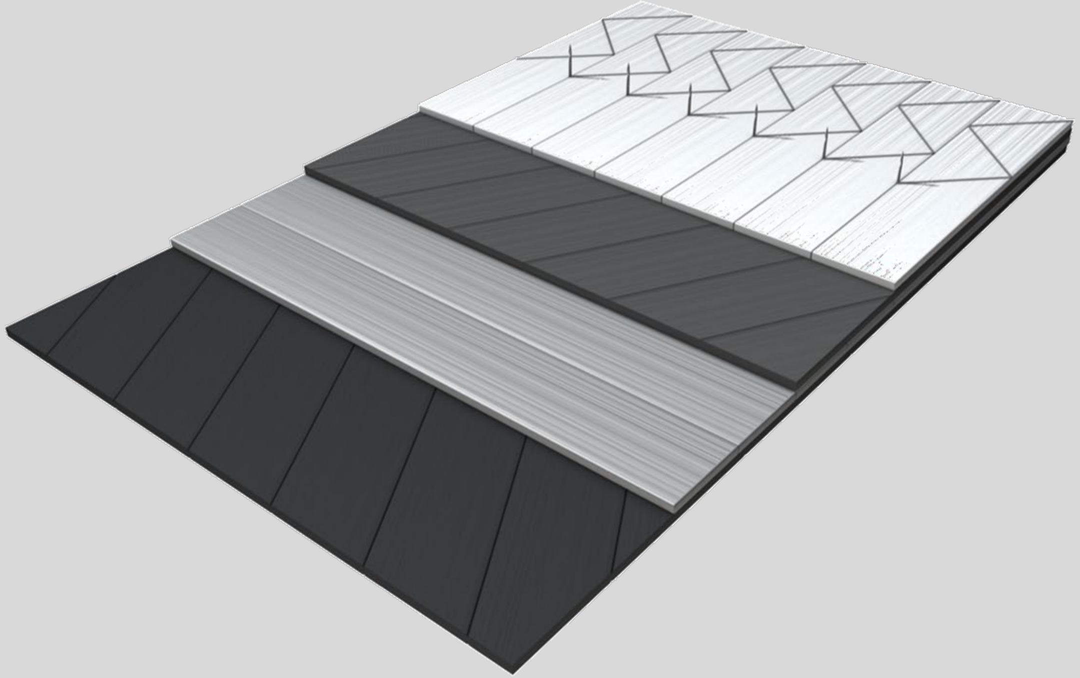
I.A | Material Forms: Woven Fabric

- Woven fabric is one of the most commonly used formats that is mainly used for hand/manual layup techniques in composite manufacturing.
- Woven fabrics are very similar to materials used in textiles and clothes.
- Woven fabric typically integrates fibers oriented in two or more directions in the same ply, woven into each other.
- Woven fabrics do not necessarily require prepreg material and are often used as dry fabrics.
- The resin system is applied in a second step to fill the spaces between the fibers of the woven fabrics to create the intended shape.



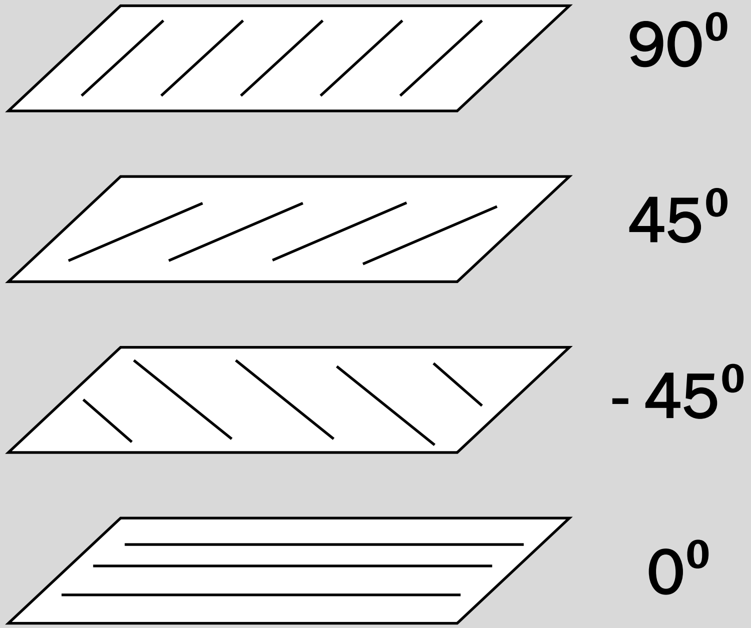
I.A | Material Forms: Non-crimp Fabrics

- Pre-forms that include several orientations of the in-plane fibers (reinforcement) are being created where the fibers are not woven together.
- The layers of dry unidirectional fibers are stacked on top of one another and held together by a thin thread through the thickness.
- Theoretically, fibers of any orientation can be used in this arrangement.
- This grouping of fibers is created on a machine and provides by the number of piles in each “stack” of material.
- This approach can also increase the quality by reducing human error which can cause fiber misalignment and/or missing layers.



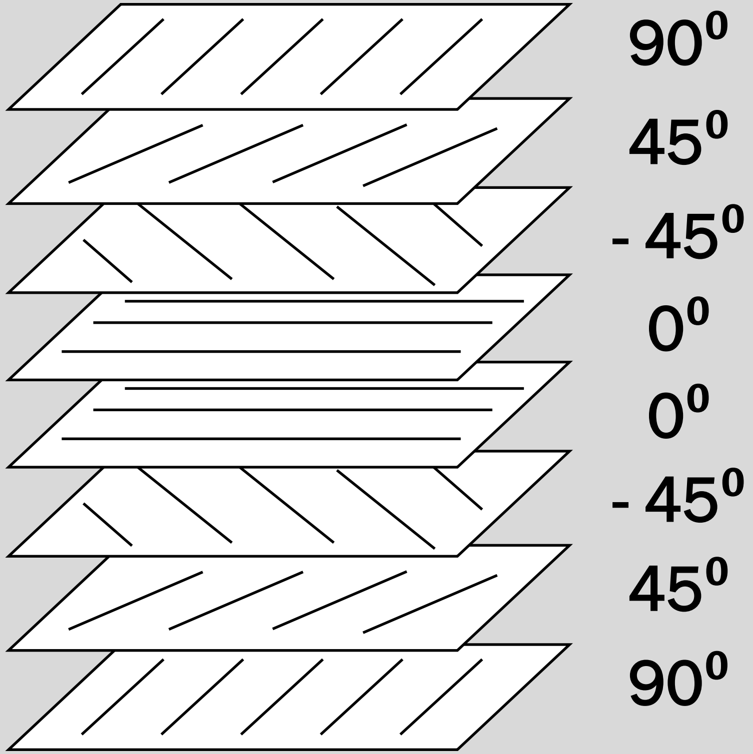
I.B | Stacking Sequence: Traditional Orientations

- In principle, a composite part is a collection of multiple plies stacked on top of each other in a layer-by-layer fashion.
- Any unidirectional tape has its "along the fibers" orientation. A single layer of a unidirectional tape is referred to as a ply or laminate. These layers can be used to create a laminate where each ply may be oriented in a different direction.
- To define the ply orientations of the laminate, we set a reference orientation of 0° as the orientation along the longest side of the panel (or complex shaped part), or alternatively, as selected by design to achieve a specific property of the composite part. Subsequently, any other ply is labeled with respect to this original reference orientation.
- If the "along the fibers“ orientation of a new ply deviates at a 45° angle from the reference orientation, this ply is classified as a 45° ply.
- Eventually, all individual plies are classified based on their angle with respect to the reference orientation.



I.B | Stacking Sequence: Nomenclature

- We define the stacking sequence by listing the orientations from the first layer to the last in sequence. The stacking sequence for the composite in the figure is defined as [90, 45, -45, 0, 0, -45, 45, 90].
- This nomenclature can be simplified by taking advantage of specific characteristics:
    - If a composite laminate is symmetrical, the subscript s can be used to reduce the annotation. Since the composite in the figure is symmetrical around its centerline, it can be annotated as ⟦"[90, 45, −45, 0]" ⟧_***s***.
    - When the same orientation occurs in the sequence for adjacent plies but with the opposite sign, the notation for two plies can be merged by introducing the ± sign. The annotation is then ⟦"[90, " ±"45, 0]" ⟧_***s***
    - Laminates are considered "balanced" when the laminate contains only pairs of plies at each orientation, i.e., for each +theta ply, there must be a-theta ply. In the figure, the laminate includes a -45° ply for each +45° ply and is therefore considered balanced.
    - If the composite panel includes repetition, we can use parenthesis and numerical subscripts to indicate this repetition. As such, [..., **90**, **0**, **90**, **0**, **90**, **0**, ...] becomes [..., ⟦(**90**,**0**)⟧_**3**, ...].
    - In case the composite includes an asymmetrical middle layer, we can include a bar above that layer to indicate it is not repeated. As such, [**90**, **0**, **45**, **0**, **90**] becomes $[\mathbf{90}, \mathbf{0}, \overline{(\mathbf{45})}]$.
    - Sometimes a subscript "**T**" is added to the end of a stacking sequence to enforce the idea that the entire (total) laminate is defined so that the reader does not question whether an "s" subscript was merely forgotten.



Knowledge Check

Reinforcement Fiber Are

A. Chopped Fibers
B. Continuous Fibers
C. All of the Above

Knowledge Check

Reinforcement Fiber Are

A. Chopped Fibers
B. Continuous Fibers
C. All of the Above

Knowledge Check

Matrix Material Can Be

A. Metal
B. Ceramic
C. Polymer
D. All of the Above

Knowledge Check

Matrix Material Can Be

A. Metal
B. Ceramic
C. Polymer
D. All of the Above

Clemson | CECAS | CCC | next

Micro-Mechanics of Composite Structures

Section II

CLEMSON COMPOSITES CENTER

neXt

[1] https://cen.acs.org/materials/inorganic-chemistry/s-fiberglass-does-delicate-material/96/i38

II.A | Theory

- Consider a composite (C) with mass m_c, volume V_c and constituents: reinforcements (m_r, V_r), matrix (m_m, m_c) and voids (m_v, V_v). Then the total mass m_c and volume V_v computed as:

$$m_c = m_r + m_m + m_v$$

$$V_c = V_r + V_m + V_v$$

- If an advanced manufacturing technique is properly used, such as an autoclave or and innovative Out-of-Autoclave process, we can update the equations by assuming the void volume is less than 1% leading to the following simplified equation:

$$m_c = m_r + m_m$$

$$V_c = V_r + V_m$$

II.B | Volume Fractions

- Let us define the volume fractions of the matrix (f_m) and reinforcing (f_r) phases to be:

$$f_m = \frac{V_m}{V_c}$$

$$f_r = \frac{V_r}{V_c}$$

- Considering the prior condition of "no void" (=1% void space) composite, the volume fractions can be expressed as:

$$f_m + f_r = \frac{V_m}{V_c} + \frac{V_r}{V_c} = \frac{V_c}{V_c} = 1$$

II.C | Density of Composite Structures

- The density of a composite part ρ_c can be calculated using the rule of mixture:

$$\rho_c = \rho_r \times f_r + \rho_m \times f_m$$

- Example:
  - Let's look at a composite structure made from IM7/8552 with a 40% volume fiber.
  - IM7 is a continuous, high-performance, PAN-based fiber having a density of 1.78 g/cm^3.
  - 8552 is a high-performance tough epoxy matrix primarily used in aerospace structures. It has a density of 1.3 g/cm^3.
  - The density of the resulting composite structure is computed as:

$$\rho_c = 1.78 \times 0.4 + 1.3 * (1-0.4) = 1.492 \text{ g/cm}^3$$

II.D | Modulus of Elasticity

- Orthotropic composites are a subset of general anisotropic composites.
- The properties of orthotropic composites are derived based on the individual properties along the orientation of the fiber and its perpendicular orientation.
- Unlike density, the modulus of elasticity is orientation dependent.
- Along the orientation of the fibers, we compute the modulus of elasticity as:

$$E_c = E_r \times f_r + E_m \times f_m$$

- Along the perpendicular orientation of the fibers:

$$E_c^p = \frac{E_r \times E_m}{E_m \times f_r + E_r \times f_m}$$

Knowledge Check

Calculate the density of a thermoplastic composite containing 40% by volume of glass fiber. Assume no voids, ρ_m=1.1g/cm^3, ρ_r=2.5g/cm^3

A. 1.66
B. 1
C. 2
D. 3

Knowledge Check

Calculate the density of a thermoplastic composite containing 40% by volume of glass fiber. Assume no voids, ρ_m=1.1g/cm^3, ρ_r=2.5g/cm^3

A. 1.66
B. 1
C. 2
D. 3

$$\rho_c = \rho_r \times f_r + \rho_m \times f_m = 2.5 \times 0.4 + 1.1 \times 0.6 = 1.66$$

Knowledge Check

Fiberglass is a composite structure made from silica fibers (*E = 74 Gpa*) and epoxy resin (*E = 4.3 Gpa*) with a fiber volume of *60%*. What would be the resulting Modulus of Elasticity of Fiberglass along the perpendicular orientation of the fibers?

A. 15.32 GPa
B. 44.12 GPa
C. 9.89 GPa
D. 61.65 GPa

Knowledge Check

Fiberglass is a composite structure made from silica fibers (*E = 74 Gpa*) and epoxy resin (*E = 4.3 Gpa*) with a fiber volume of *60%*. What would be the resulting Modulus of Elasticity of Fiberglass along the perpendicular orientation of the fibers?

A. 15.32 GPa
B. 44.12 GPa
C. 9.89 GPa
D. 61.65 GPa

$$E_c^p = \frac{74 * 4.3}{4.3 * 0.6 + 74 * 0.4} = 9.89\ GPa$$

Clemson | CECAS | CCC | next

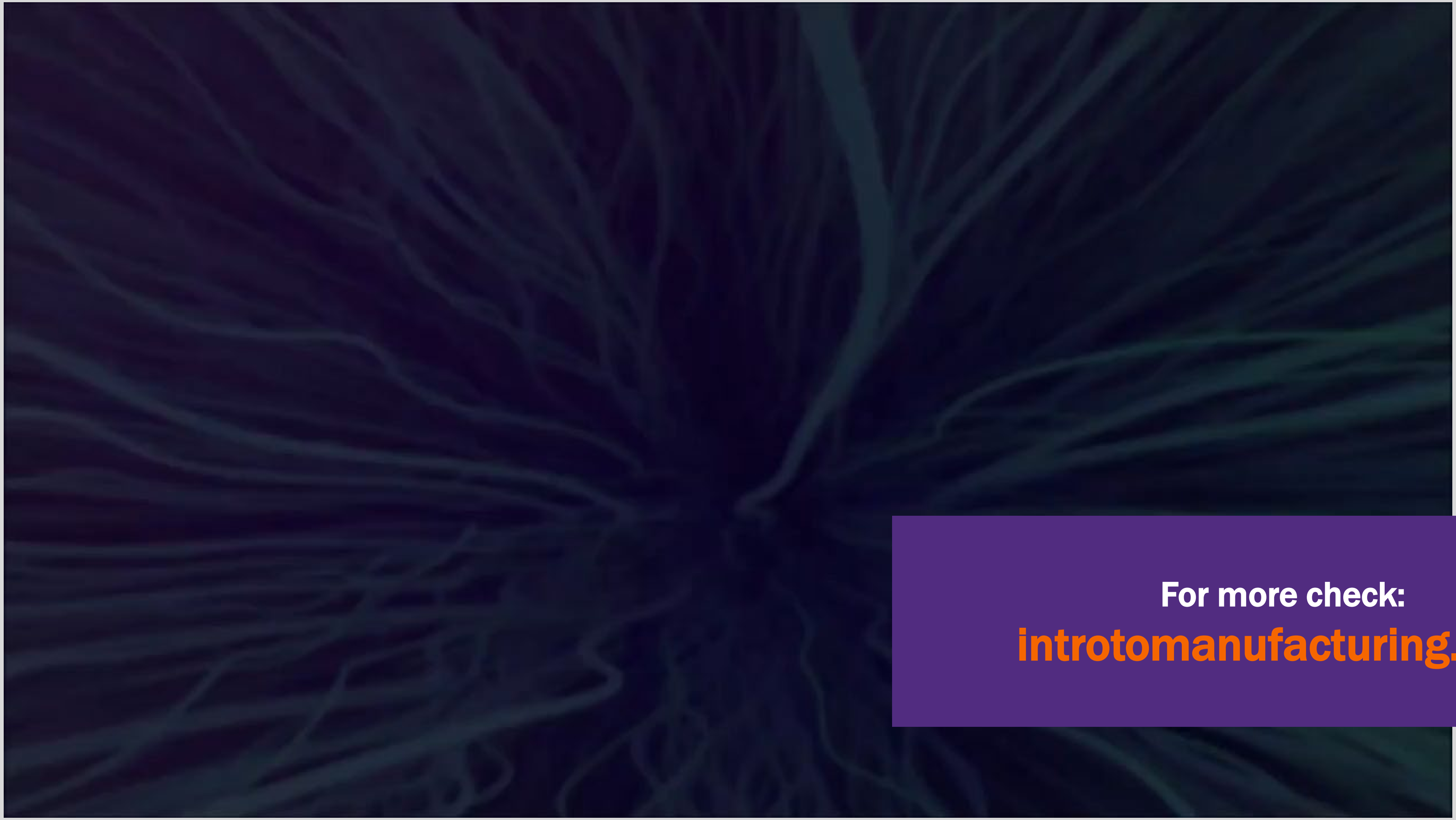
Composites Manufacturing

Section III

[1] https://www.compositesworld.com/articles/why-does-my-composite-mold-leak-under-vacuum-or-applied-pressure

III.A | Hand Layup

- Hand Layup is the manual stacking of composite layers according to the design.
- It is the most common and widespread manufacturing techniques for composites today.
- The typical steps in hand layup are:
    1. Individual layer preparation (Layers can be of different sizes)
    2. Bagging material preparation and placement on the tool surface
    3. Projection of boundary (not always required)
    4. Positioning of materials
    5. Application of resin system
    6. Sealing of the bagging process
    7. Curing of the composite (typically in an autoclave or oven)

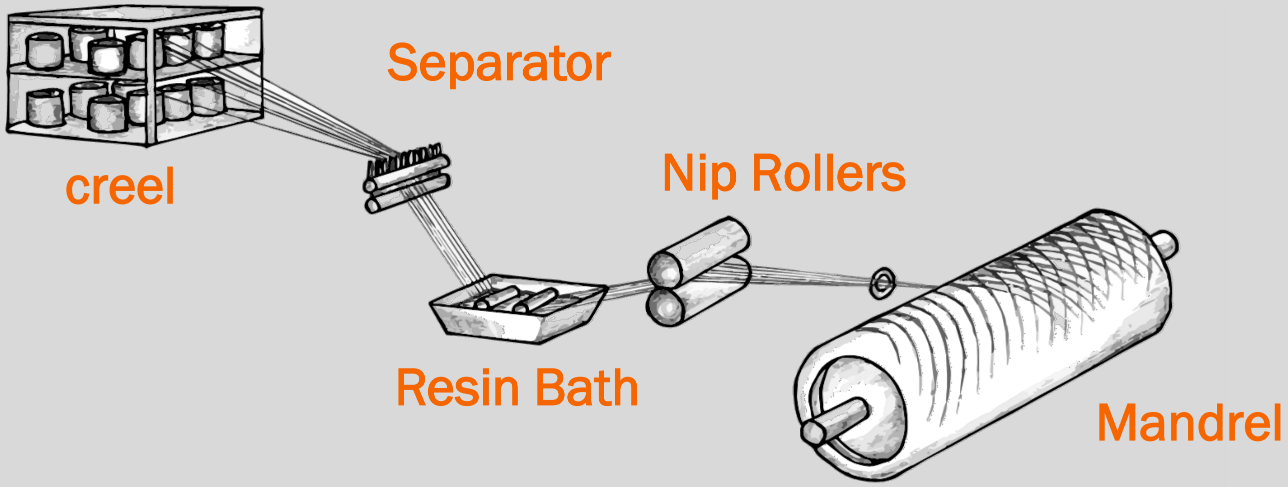


For more check:

introtomanufacturing.com

III.B | Filament Winding

- Filament Winding is particularly suitable for pressure vessels and structures with circular cross sections.
- The process is as follows:
    - A rotating mandrel pulls the fibers and places them
    - They are then impregnated with the resin by being dipped into a resin bath
    - The separators ensure uniform impregnation
    - The creel holds the fibers in their dry format

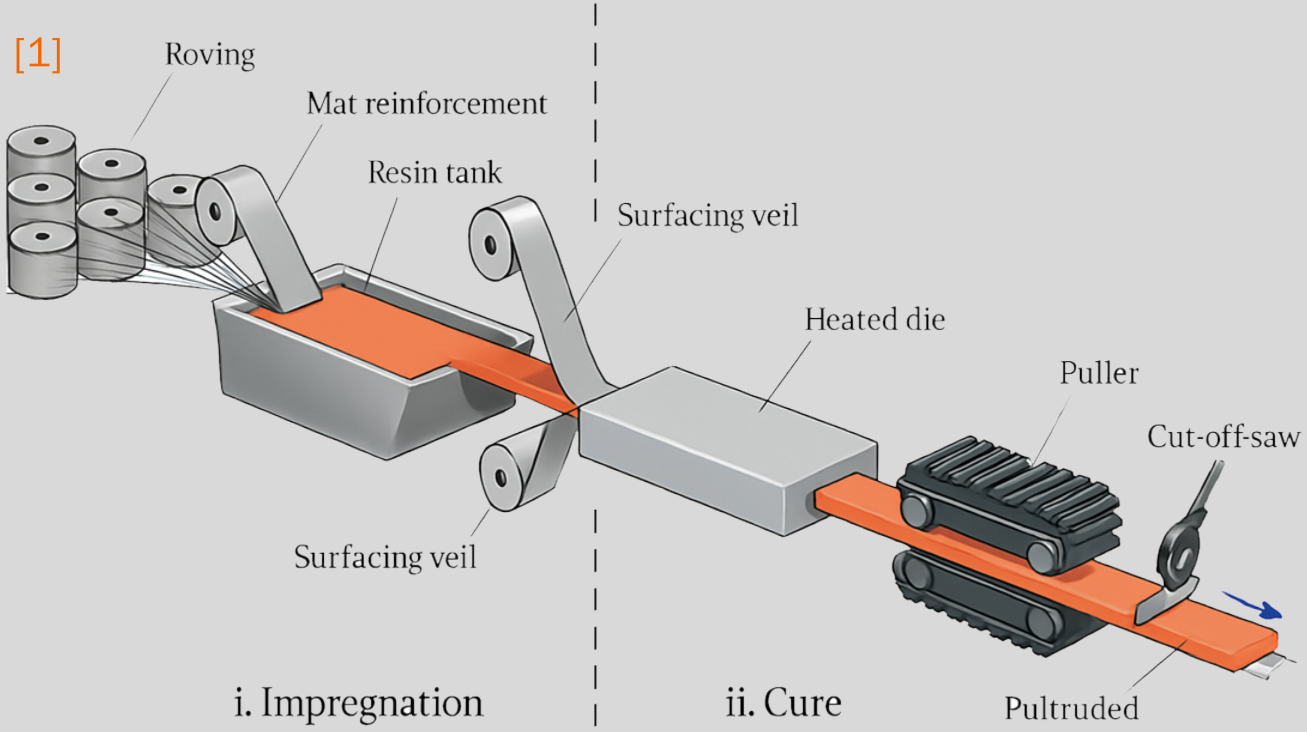


For more check:
introtomanufacturing.com

III.C | Pultrusion

- Pultrusion attempts to join several steps into one manufacturing process.
- The term is a hybrid between pulling and extrusion.
- The two main steps that pultrusion combines is the impregnation and collimation of fibers.

[1]

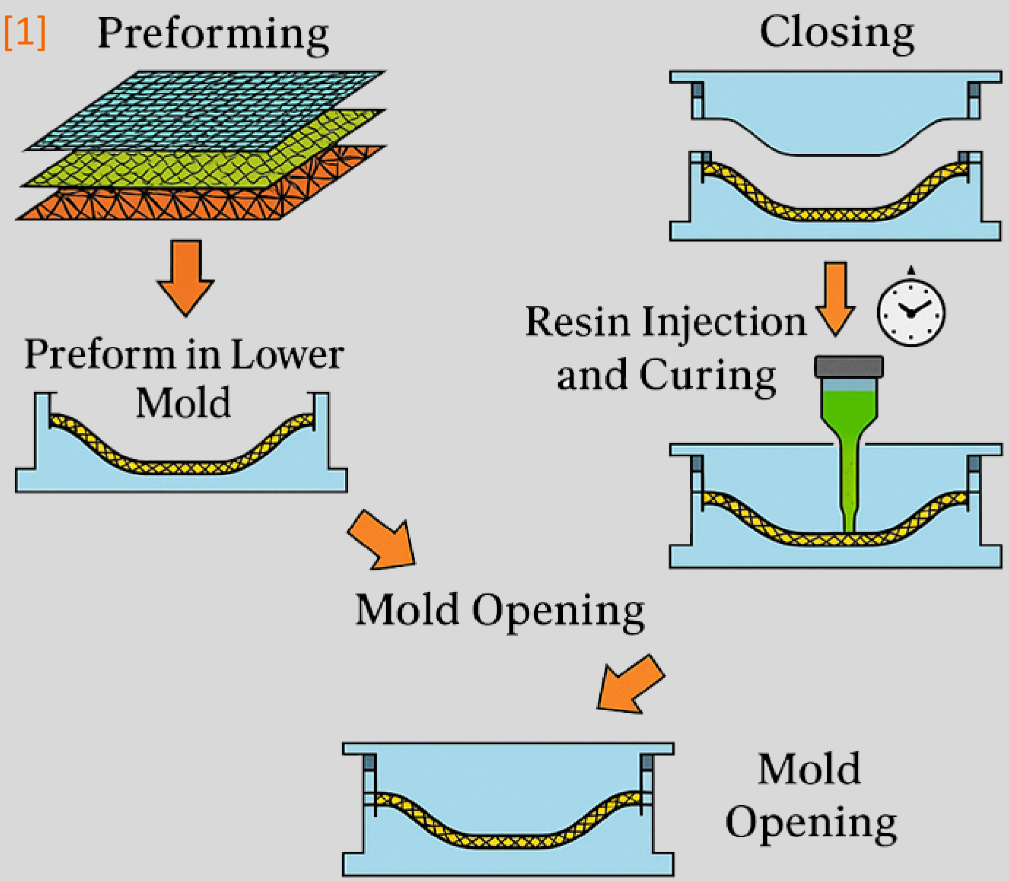


[1] https://www.researchgate.net/figure/Pultrusion-process-of-Glass-Fiber-Reinforced-Polymers_fig2_283555992. (Enhanced)

III.D | Composite Molding

- Similar to die casting processes, in Composite Molding a preform is pressed along a mold and heated or impregnated to initiate a curing process.
- The part is then de-molded and retrieved for further finishing processes such as drilling and trimming.

[1]



[1] F. Sánchez *et al.*, "A process performance index based on gate-distance and incubation time for the optimization of gate locations in liquid composite molding processes," *Compos Part A Appl Sci Manuf*, vol. 37, no. 6, pp. 903–912, Jun. 2006, doi: 10.1016/J.COMPOSITESA.2005.01.016. (Enhanced)

III.E | Automated Tape Laying (ATL)

- Automated Tape Laying (ATL) is a versatile manufacturing process that is shape dependent
- The starting material of ATL is unidirectional tapes.
- The width of those tapes is usually 3 in., which prevents the manufacturing of complex shapes with different curvatures.
- ATL was the precursor to the creation of Automated Fiber Placement (AFP).

[1]

[1] https://www.globalspec.com/learnmore/manufacturing_process_equipment/manufacturing_equipment_components/

Knowledge Check

What is the role of separators in a Filament Winding process?

A. Separate the fibers from the resin
B. Ensure an appropriate distance between the fibers
C. Ensure uniform impregnation
D. None of the above

Knowledge Check

What is the role of separators in a Filament Winding process?

A. Separate the fibers from the resin
B. Ensure an appropriate distance between the fibers
C. Ensure uniform impregnation
D. None of the above

Knowledge Check

The starting material in Automated Tape Laying is bidirectional Tape?

A. True

B. False

Knowledge Check

The starting material in Automated Tape Laying is bidirectional Tape?

A. True

B. False

Clemson | CECAS | CCC | next

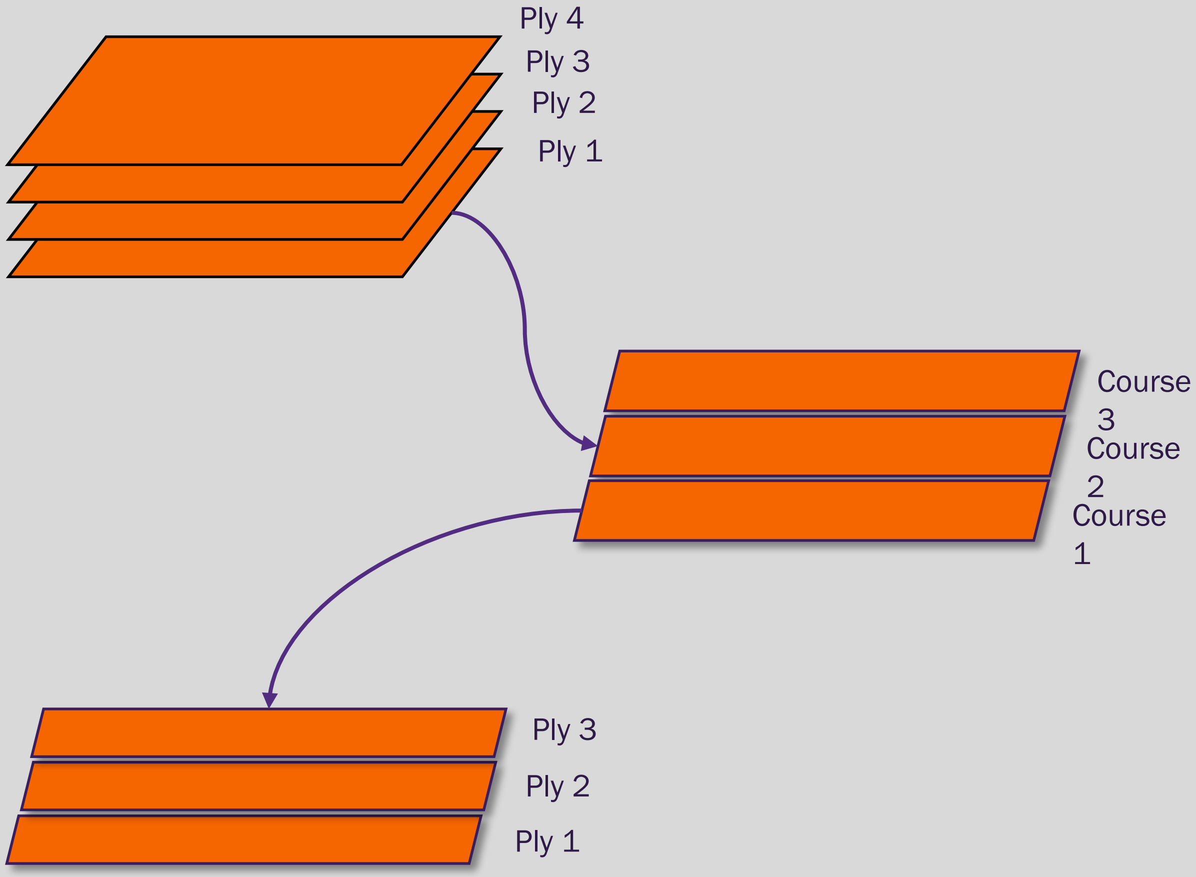
Automated Fiber Placement (AFP)

Section IV

[1] https://anisoprint.com/blog/advanced-composites-manufacturing-automated-fiber-placement/

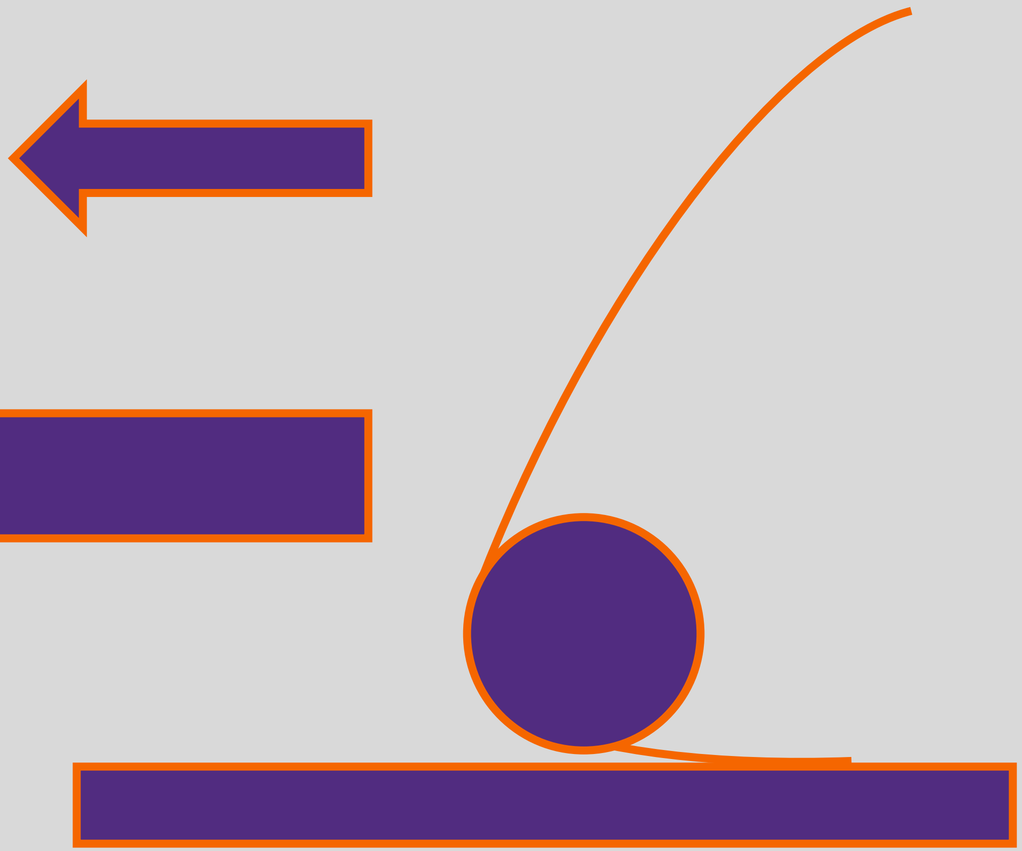
I | AFP Process

- AFP process offers high degree of flexibility as the laminate is built by aggregation of slit tapes with small width (1/2 or 1 in.)
- Aggregation of individual tows into one placement identifies a course.
- Succession of multiple courses creates a single ply.
- Placement of different plies creates the laminate.



I | AFP Process

- AFP Includes four basic components:
  - Feeding mechanism: Ensures that tension and a proper feed adjustment of the tows.
  - Cutting mechanism: Cut individual tows providing extreme flexibility in the context of laminate building.
  - Heating mechanism: Heats the underlying layer prior to placement of the new one.
  - Pressure mechanism: Applies pressure through the roller to squeeze out any voids.
- Basic AFP processes are continuously under investigation and there are no single method to provide any of the four elements.
- IR heating method is prominent throughout aerospace industry, producing ideal material offering better efficiency and less power consumption.



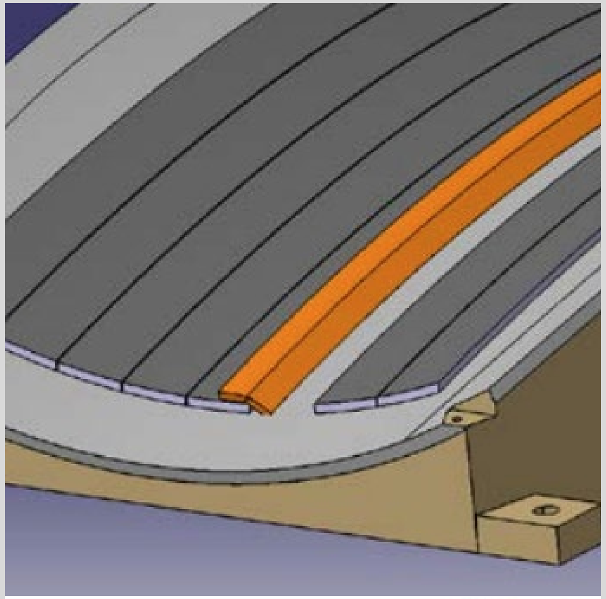
II | AFP Defects

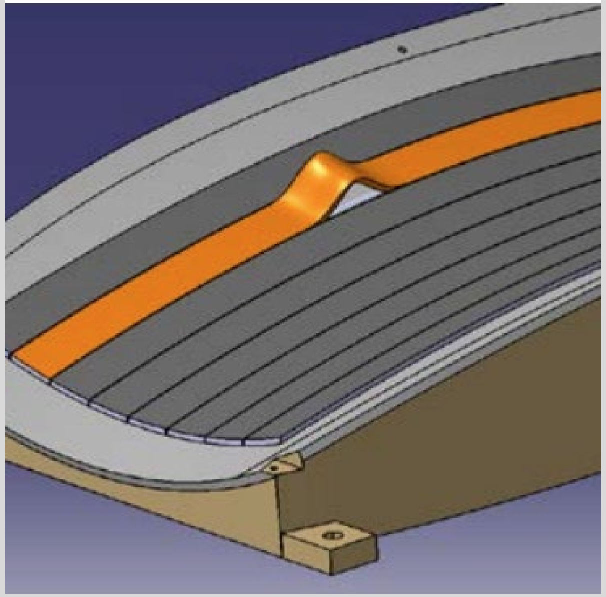
Defects in AFP results in reducing the final part's ability to withstand load so they must be corrected prior to the placement of the subsequent layer.

The Predominant AFP defects are:

- Gap/Overlap: A gap emerges when two adjacent tows are not perfectly placed next to each other. The common cause is steering during layup. It occurs as well when laying up complex 3D-shaped tool surface.

- Pucker: It initiate at the inside radius of a steered tow. It could occur either partially or over the entire tow width. It forms an arch of excess material that does not adhere to the substrate surface. It is caused by excess feed that gradually accumulate.

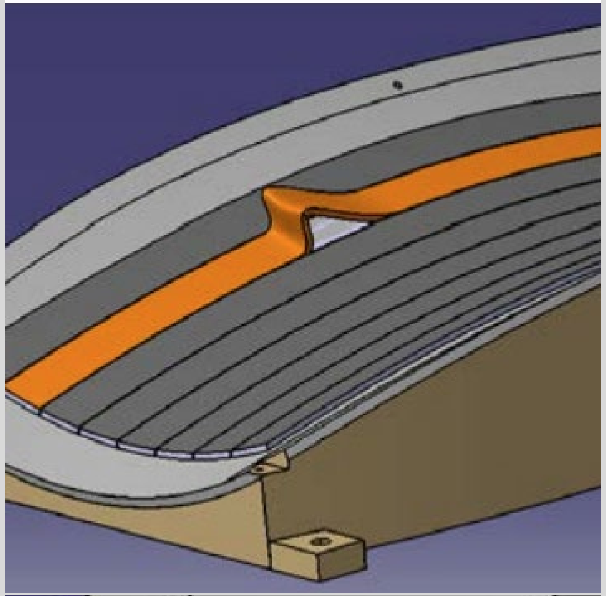


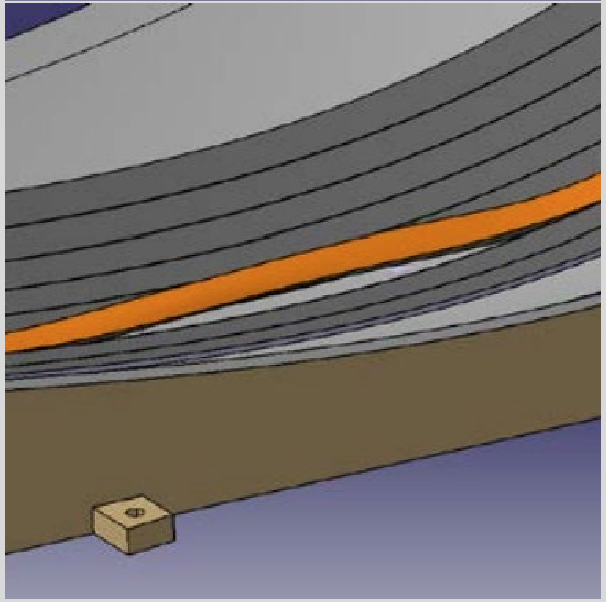


II | AFP Defects (Cont.)

- **Wrinkle:** A wrinkle is typically indicated by a wavy pattern of puckering along the edge of a tow. It occurs on the inner radius and remain out of plane after curing. Wrinkles are often caused by placing small steering radii, that delivers tows with equal edges, which results in puckers and wrinkles on parts with excessive differential length.

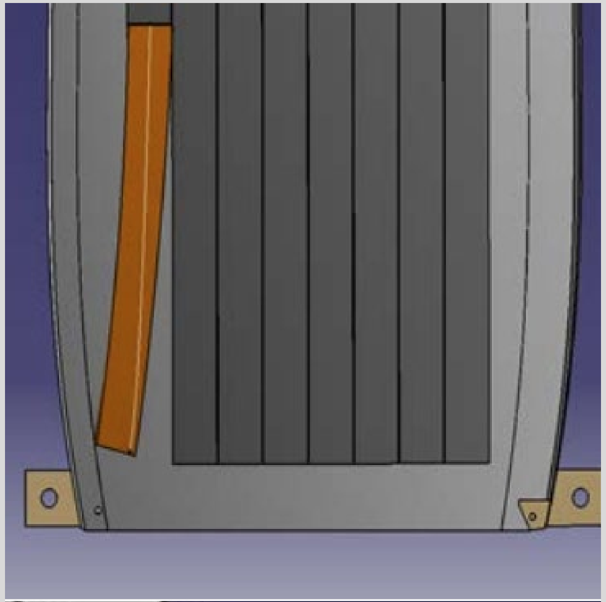
- **Bridging:** Occurs when tows does not fully adhere to the concave surface. It will result in a gap between the radius of the concave tool surface and the tow. Main causes are excessive tension of the tow, or insufficient tack adhesion to the surface.



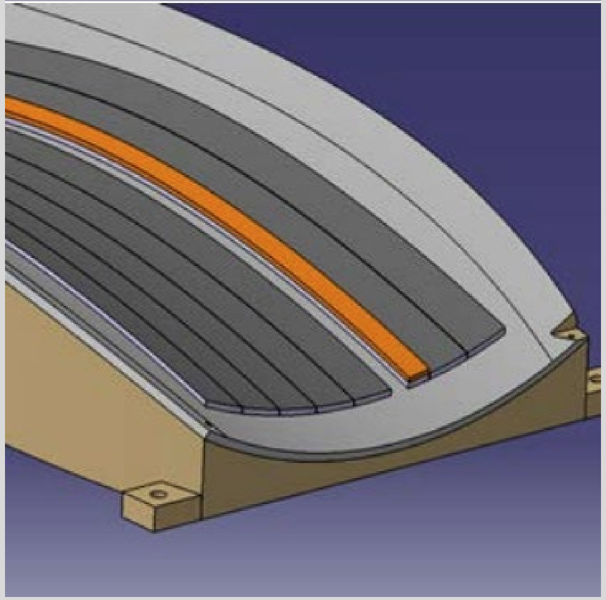


II | AFP Defects (Cont.)

- **Angle Deviation:** Occurs when the angle of the as-manufactured layup deviates from the as-designed one. It is caused by incorrect roller coverage or small radius steering as the tow may move after being steered.



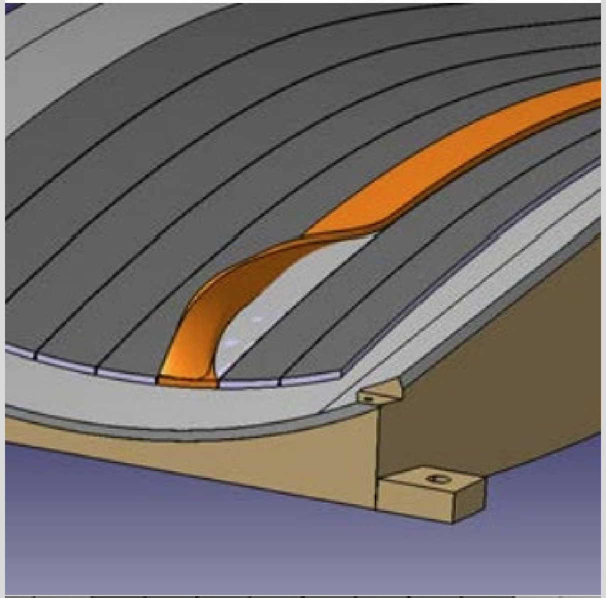
- **Fold:** Occurs when the tow folds in the transverse direction onto itself creating a gap in the surface and doubling the thickness over the folded part. Insufficient or excessive tension rises the possibility of tow fold. Long unsupported/complex tow paths can result in folding. In a steered/curved tow path outer segment fold towards the inner side due to tension of the outer edge.

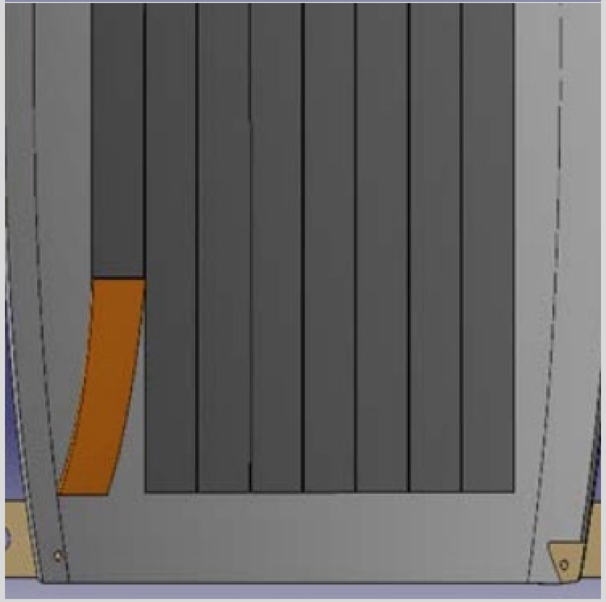


II | AFP Defects (Cont.)

- Twist: Occurs when a tow rolls axially 180^0 onto itself. Depending on the length over which twisting occurs, the shape will be determined. It could be a bow tie with bunching of the fibers and increased thickness in the center. It is initiated by folding. Friction between guide holes along a long/complex tow path may cause twisting.

- Wandering Tow: Occurs when the portion of the tow between the roller and the cutter wanders from the original fiber path after being cut. Unsupported portion of the tow between the compaction roller and the tow cutter may causes wandering tow. The angle deviation will be like the unsupported tow.

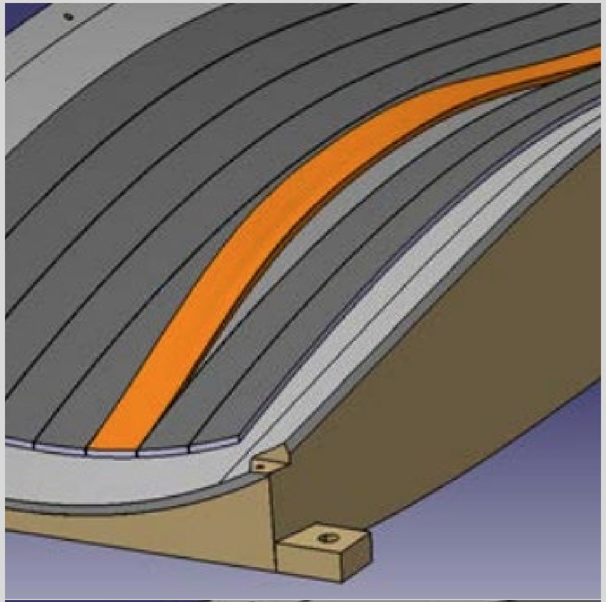


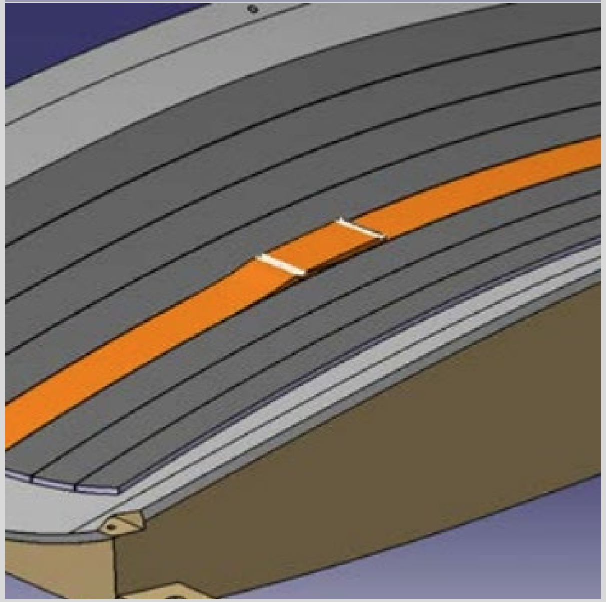


II | AFP Defects (Cont.)

- Loose Tow: Occurs when the machine does not have precise control over the placement of the tow. It occurs when the tow is longer than the tool path. If the tow is steered at the end, it may not follow the defined path.

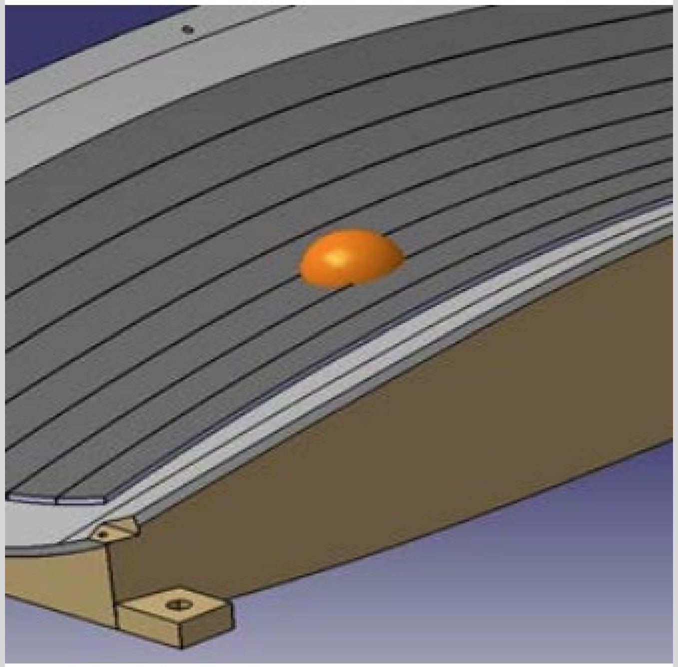
- Splice: Occurs when two tows are joined together end to end by overlapping. Tows usually have finite length. Typically, 1 to 3 in of the two tapes are connected resulting in a portion thicker than the rest of the tow.





II | AFP Defects (Cont.)

- Foreign Object Detection: Occurs when the fibers has collected on surfaces where there is debris. Generally, FOD includes any debris that ends up in a part.



III | Manufacturing Strategy (Material Selection)

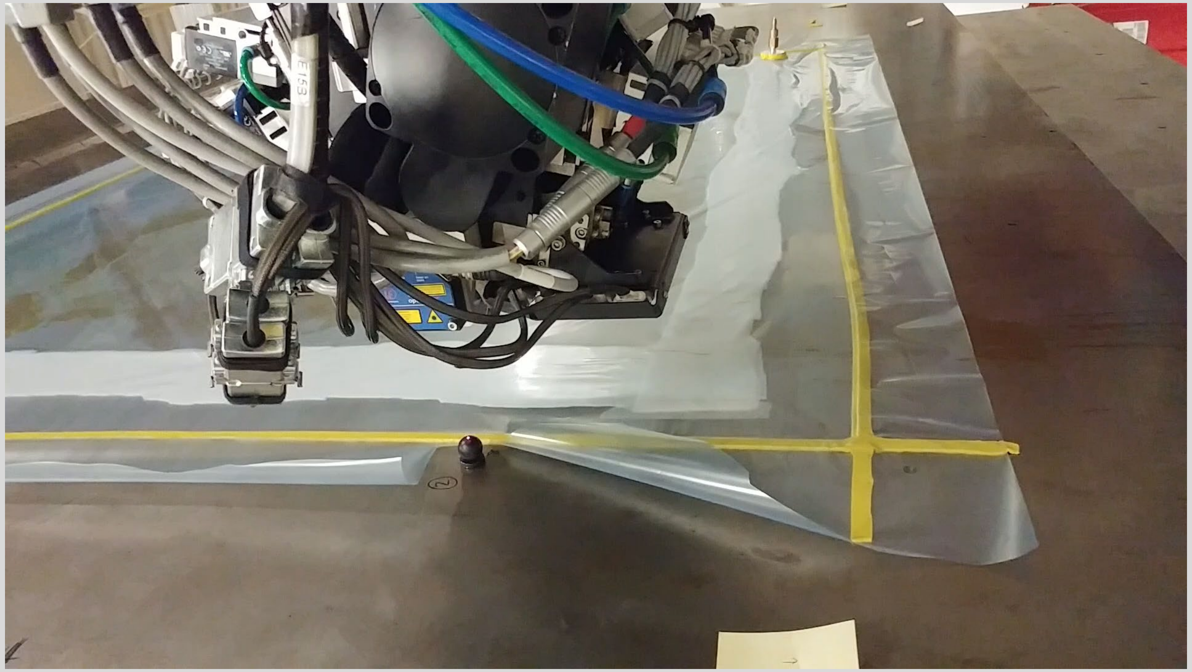
- Prepreg
  - Refrigeration required
  - Cured using Autoclave
  - Current Industry Standard
- Dry Fiber
  - No Refrigeration Required
  - Cured Using Vacuum Impregnation Techniques
  - Possibly The Future of Industry

III | Manufacturing Strategy (Tool Preparation)

- If the tool is used in the autoclave curing process, tackifier is used to help the first layer of prepreg adhere to the surface.
- Tackifier is resin from the prepreg material that is separated using acetone.
- Vacuum bags are used if tool cannot be removed from mandrel or will not fit in autoclave.
- Prepreg is laid up on the bag and then removed from mandrel and placed on caul plates to be cured.
- Dry fiber must always be laid up on vacuum bag to be removed and infused with resin.

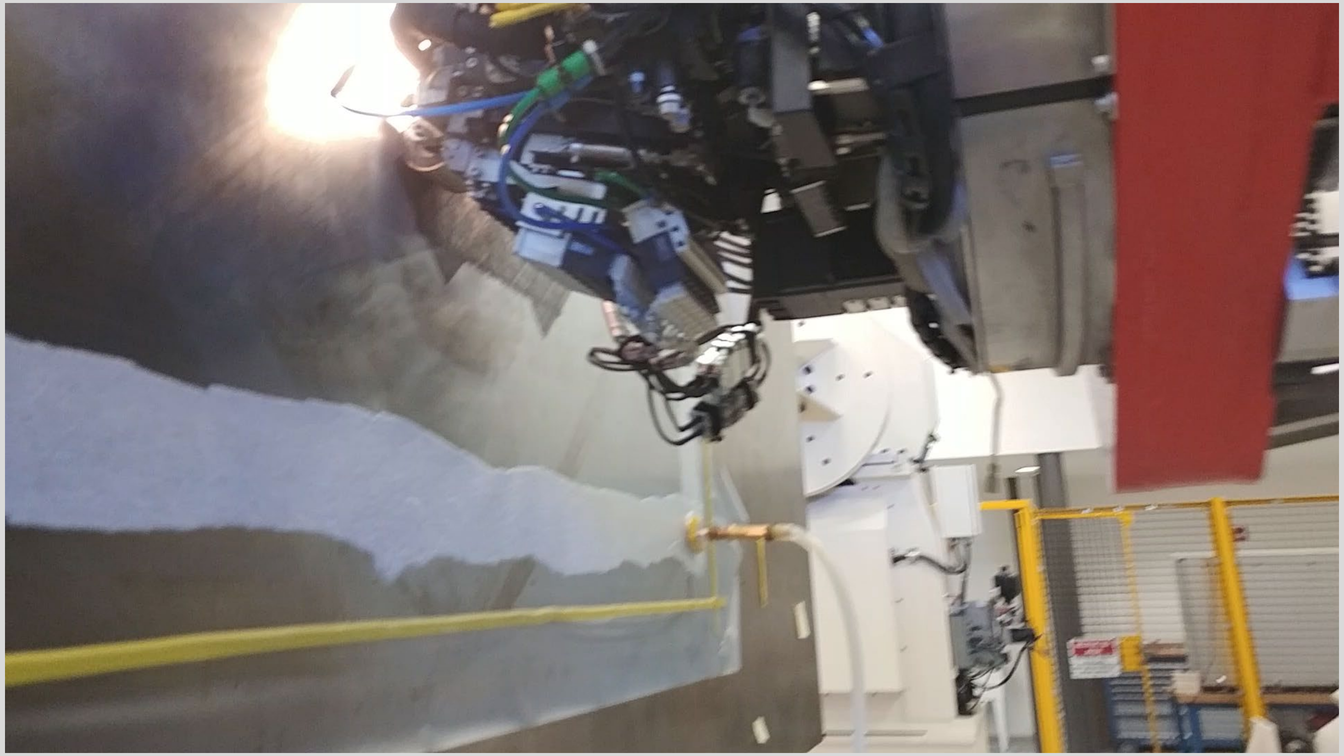
III | Manufacturing Strategy (AFP Layup Strategies)

- Manufacturing an optimal composite part requires the adaption of optimal layup strategy.
  - Geodesic Path
  - Constant curvature
  - Linear Variation
  - Use of control points
  - Following the constraints
- Tooling Processes:
  - Done to orient the machine
  - 3 points tooling ball technique
  - Laser distance finder calculates the center of each ball to create a theoretical surface for the machine to follow.



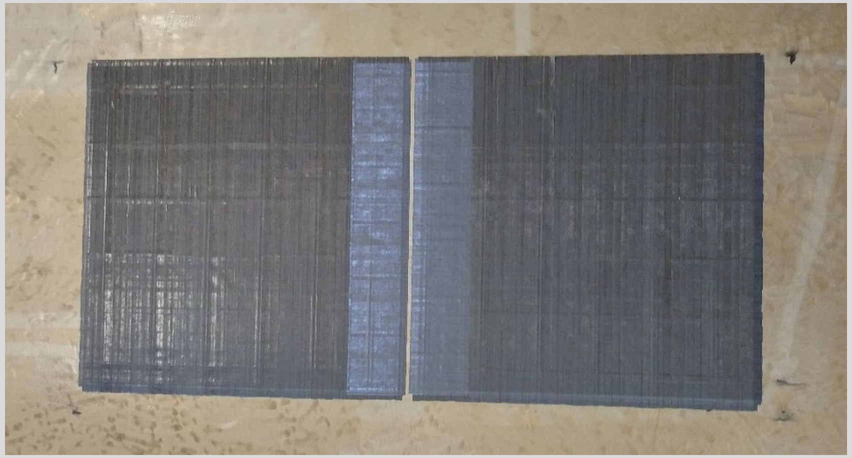
III | Manufacturing Strategy (AFP Layup Strategies) Cont.

- Prepreg Layup:
  - Done on vacuum bag to pull part off the mandrel for double caul plate curing in autoclave.

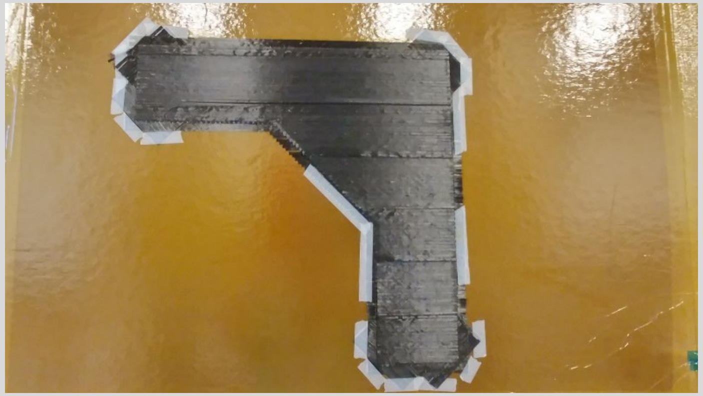


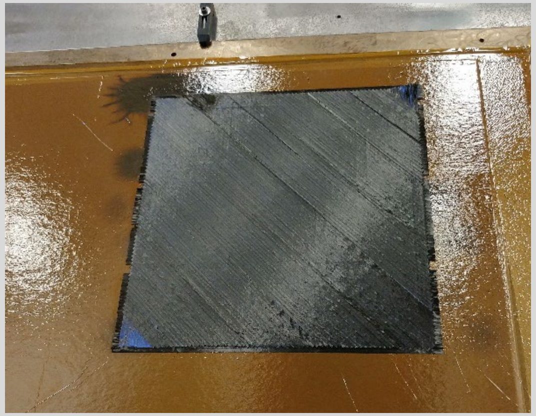
III | Manufacturing Strategy (AFP Layup Strategies) Cont.

- Prepreg completed layups



- Dry Fiber Completed Layups



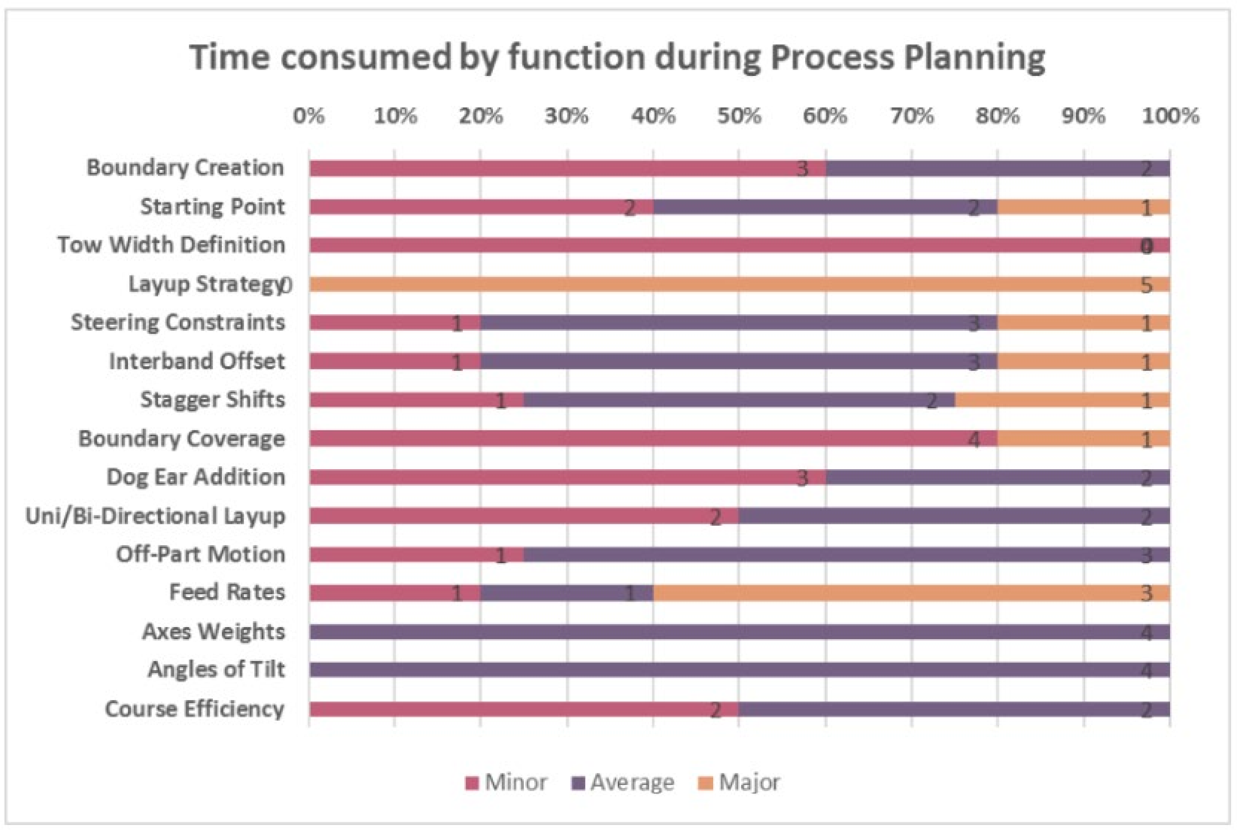


III | Manufacturing Strategy (AFP Layup Strategies) Cont.

Geometry of the surface					
Strategy for the reference curve	Coverage Strategy	Coverage percentage		Notable defects	Ranking
		% of gaps	% of overlaps		
Geodesic Path	Fast marching method Parametrical parallel curves Shifted curves Independent curves				
Constant Curvature	Fast marching method Parametrical parallel curves Shifted curves Independent curves				
Linear Variation	Fast marching method Parametrical parallel curves Shifted curves Independent curves				
Use of control points	Fast marching method Parametrical parallel curves Shifted curves Independent curves				
Following the constraints	Fast marching method Parametrical parallel curves Shifted curves Independent curves				

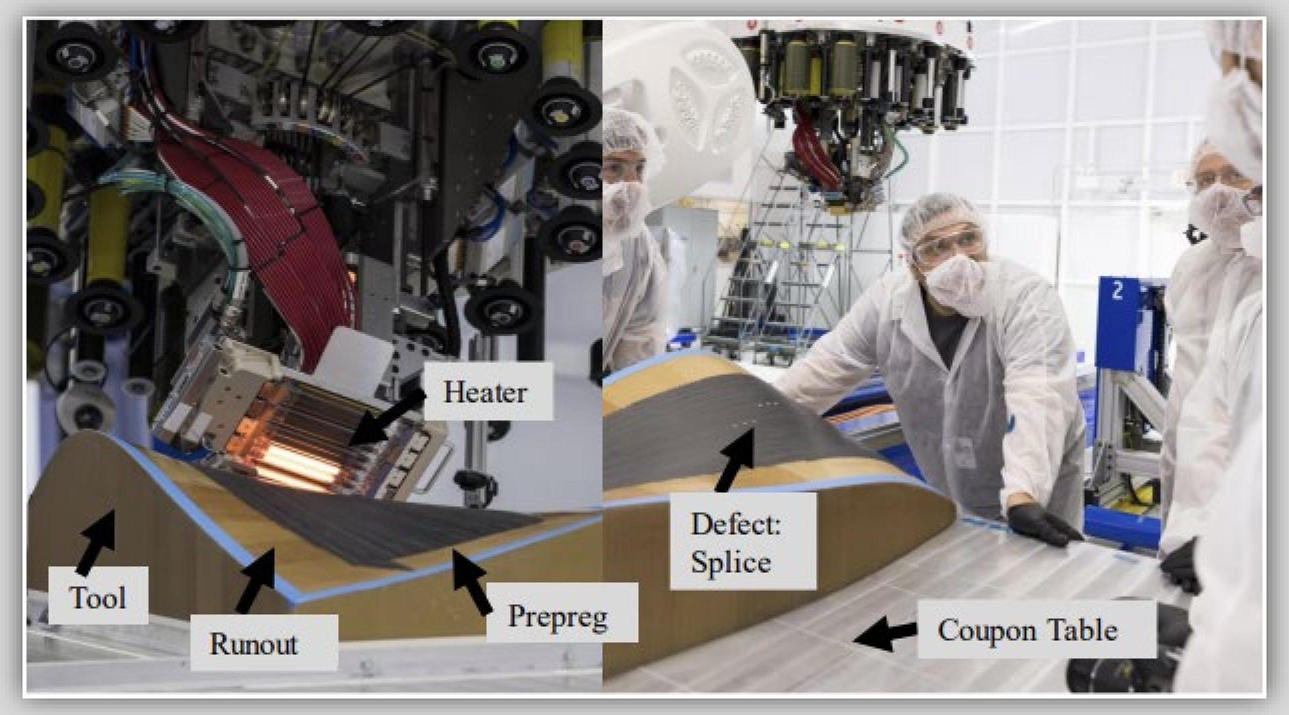
IV | AFP Process Planning

- Process planning is crucial in order to adequately manufacture complex geometrical structures.
- Large effort is required in process planning in order to reduce defect occurrence to the best extent possible.
- Computer Aided Process Planning can be used.



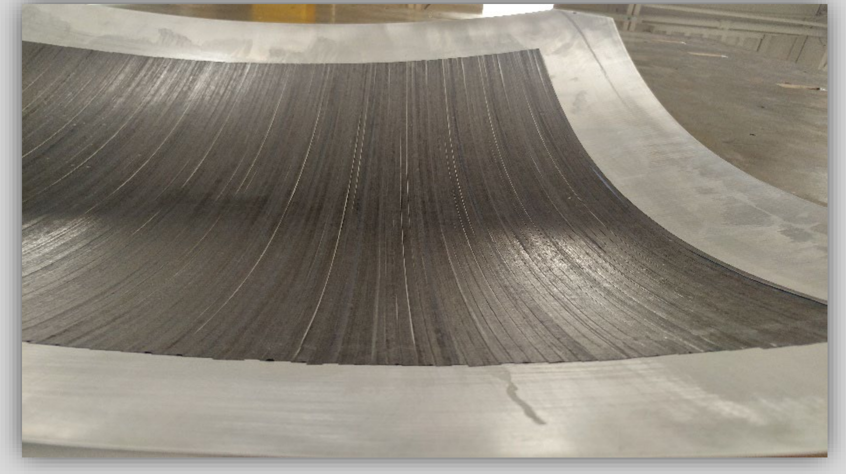
IV | AFP Inspection

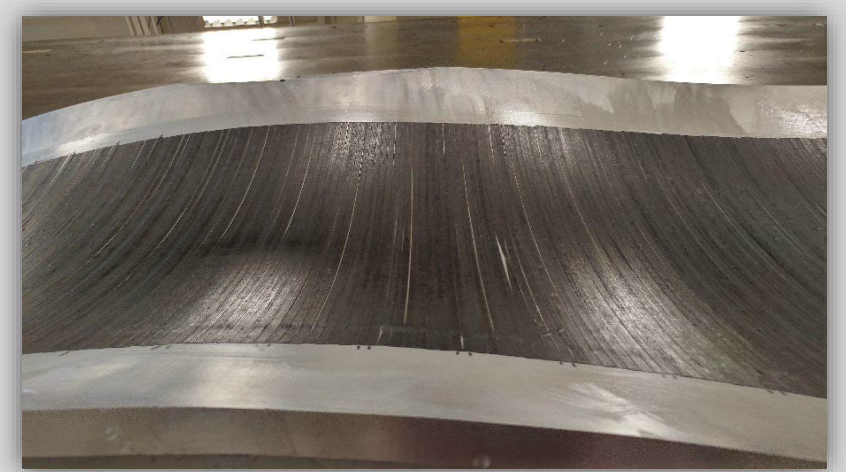
- AFP Quality
- Recognizing/classifying defects using machine learning algorithms.
- AFP inspection is very important.
- Currently is done manually.
- Efforts are toward automating the process.

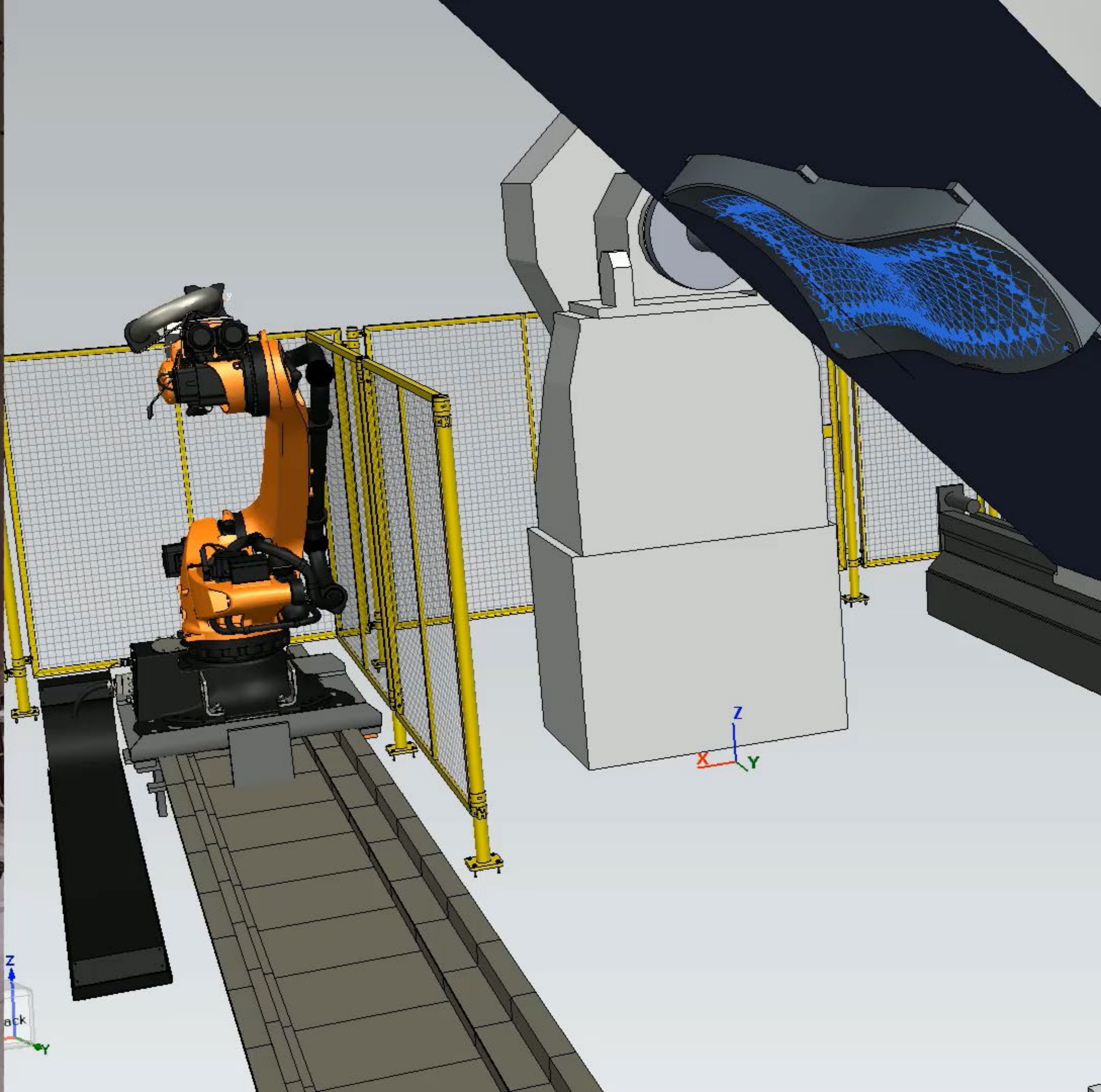


VI | AFP Products

Cool Stuff






-Z+

Z
X
Y

For More Information on AFP

Please watch the YouTube video titled “ISAAC Robotic System Demonstration with Ramy Harik” for more information on AFP.

Link of the video: https://www.youtube.com/watch?v=gT9vIFUeAyk

THANK YOU

- This set of slides is retrieved from the textbook: Intro to Advanced Manufacturing, Harik/Wuest, ISBN 978-0-7680-9327-8 978-0-7680-9327-8
- Link of the textbook: https://www.sae.org/publications/books/content/r-463/
- For more information:

  Email: harik@cec.sc.edu