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Automated composites manufacturing: Critical issues, Challenges and Opportunities

CONCOM

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Presented at the on-line webinar organized by the Bristol Composites Institute—July 11-2023

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Outline

1. Conclusion from ACM5
2. Thermoset matrix composites
    1. Inspection
    2. Fibre steering and wrinkles
    3. Thin ply laminates
3. Thermoplastic matrix composites
    1. Temperature distribution
    2. Interlaminar strengths
    3. Distortion
4. 4D printing of composites (mouldless manufacturing)
    1. CONCORDIA
    2. Leaf springs made by 4D printing of composites
    3. Corrugated core for flexible wing
5. Future outlook.

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Conclusions from ACM5- on line & at the National Composites Centre, Bristol, April 2021 & 2022

Thermoset composites:

- Have been successfully used in making aircraft structures.
- Improvements can be made on:
  - Speed of deposition
  - Automated Inspection
  - Understanding wrinkles
  - Understanding the performance of structures containing defects such as laps, gaps.

Thermoplastic composites:

- Low interlaminar shear strength
- Distortion of structures with free edges.

Future outlook:

- To expand, the technique needs to be adaptable to commercial products.
- Smaller AFP machines
- 3D printers with continuous fibers

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Thermoset matrix composites

- Inspection to detect defects
- Fibre steering and Wrinkles
- Processing with thin plies

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Defect detection

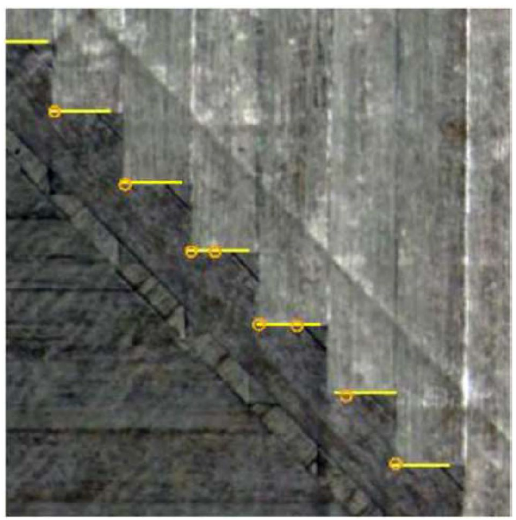
Photos by Electroimpact

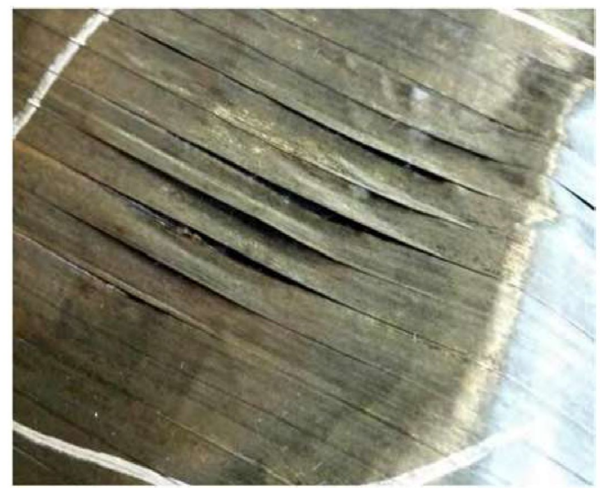
Laps-Gaps

FOD

Tow ends

Delamination
Tow twists
Puckering





Bridging

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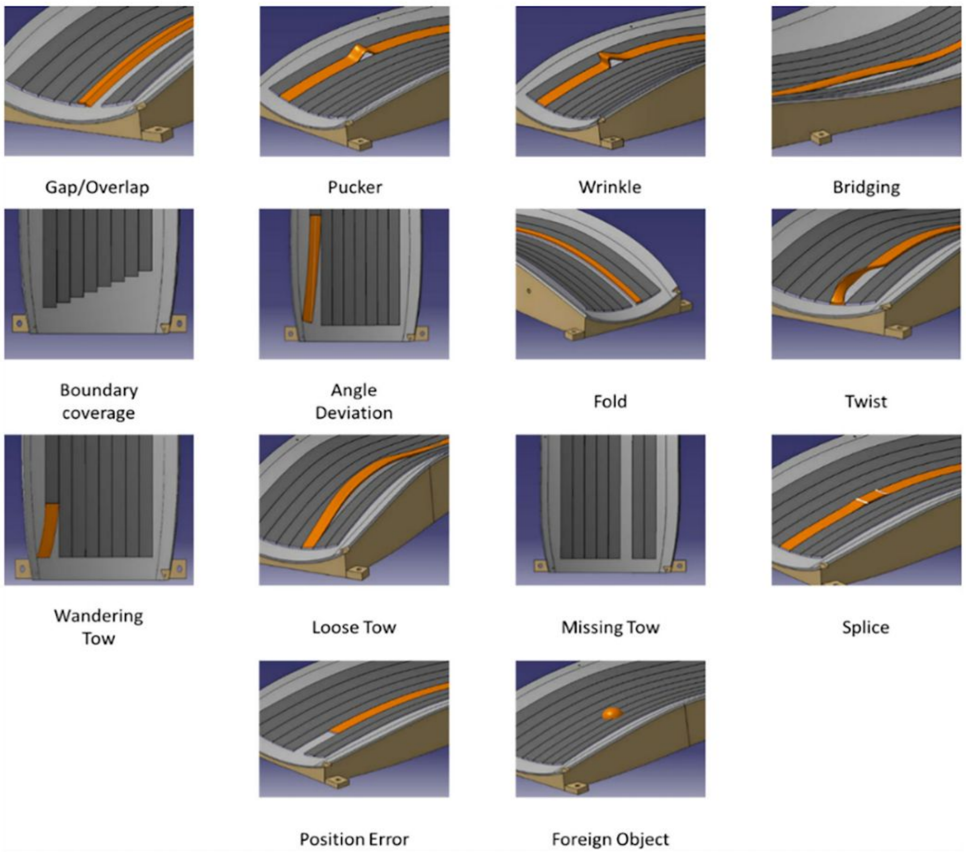
Defects

Chevalier P.L., Kassapoglou C., Gurdal Z., “Fatigue behavior of composite laminates with automated fiber placement induced defects- a review”, Int. J. Fatigue, 2020, 140, 105775.



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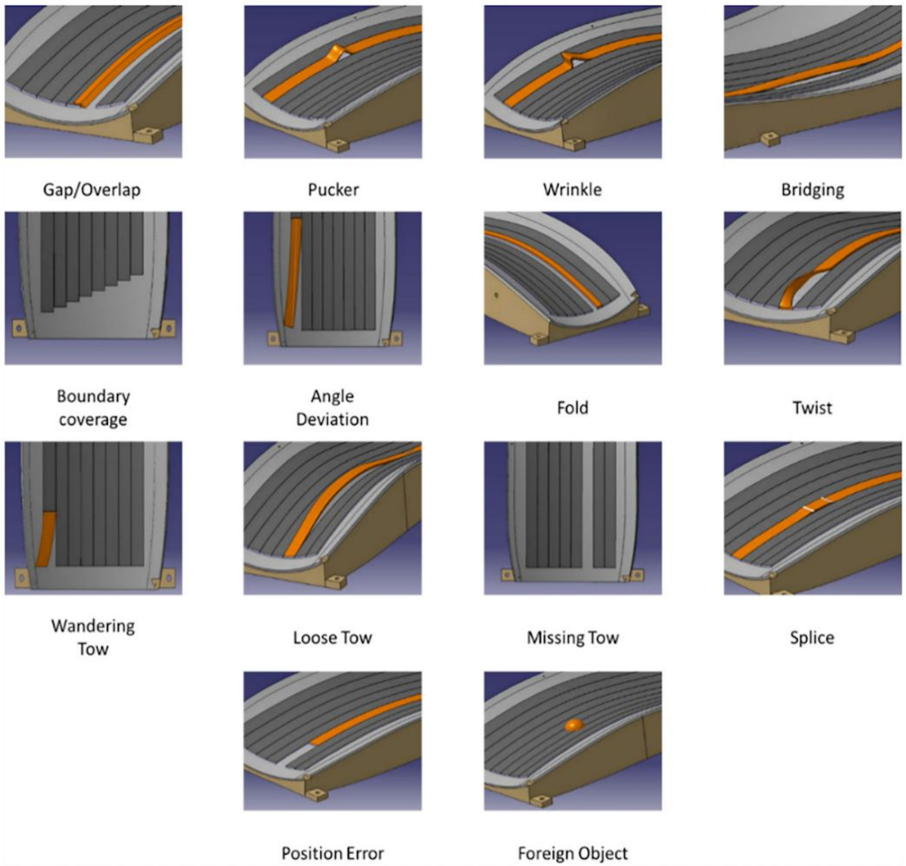
Five perspectives:

- **Anticipation: Predicting occurrence**
- **Existence: Inspection**
- **Significance: Effect on performance**
- **Progression: Potential evolution**
- **Disposition: Defect treatment**

Effect of defects on performance

Chevalier P.L., Kassapoglou C., Gurdal Z., “Fatigue behavior of composite laminates with automated fiber placement induced defects- a review”, Int. J. Fatigue, 2020, 140, 105775.



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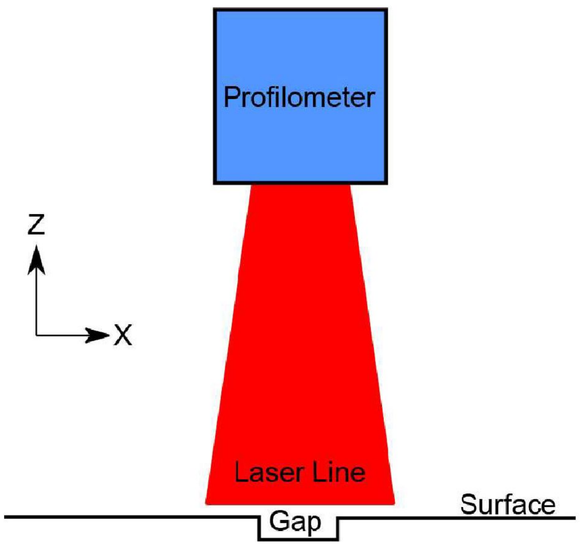
- **Quasi-static loading in unnotched unidirectional laminates:** Not significant effect.
- **Fatigue loading:** More influence
- **More work required:** Large variety of geometry configurations, large number of type of defects, loading conditions.

Defect detection

- **Detection system consists of cameras, laser profilometers, optical systems, etc., to gather raw data.**
- **A suite of software programs to process the data to create meaningful measurements for the location of ply boundaries, and widths of overlaps and gaps.**
- **The processed data is stored in a data base which acts as the interface between different software programs for interaction and data sharing.**
- **An extensive interface ties all the data together and displays the results.**



- **Inspection data consumes a large amount of hard drive space. The data can approach 1 TB per part for complex parts.**

- **Application of statistical analysis and control to make decision on how to use the inspection data. Must decide what conditions are acceptable for gaps or laps, placement end accuracy, individual tows, courses, plies, or individual parts.**

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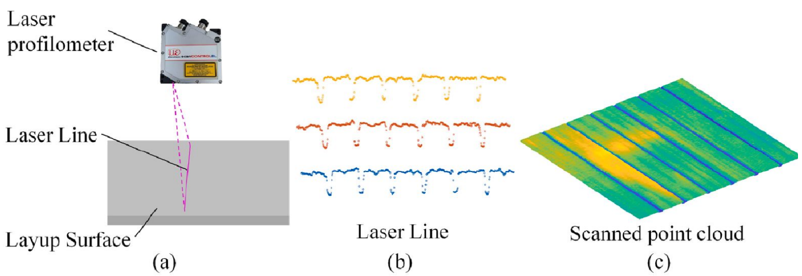
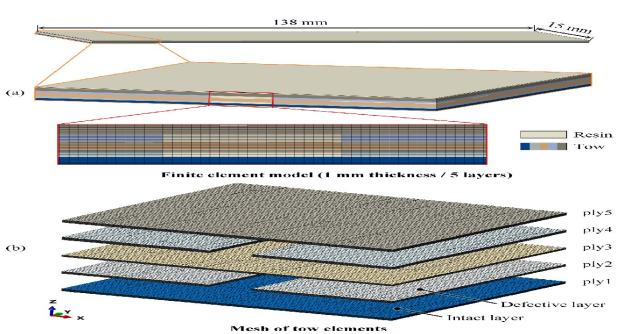
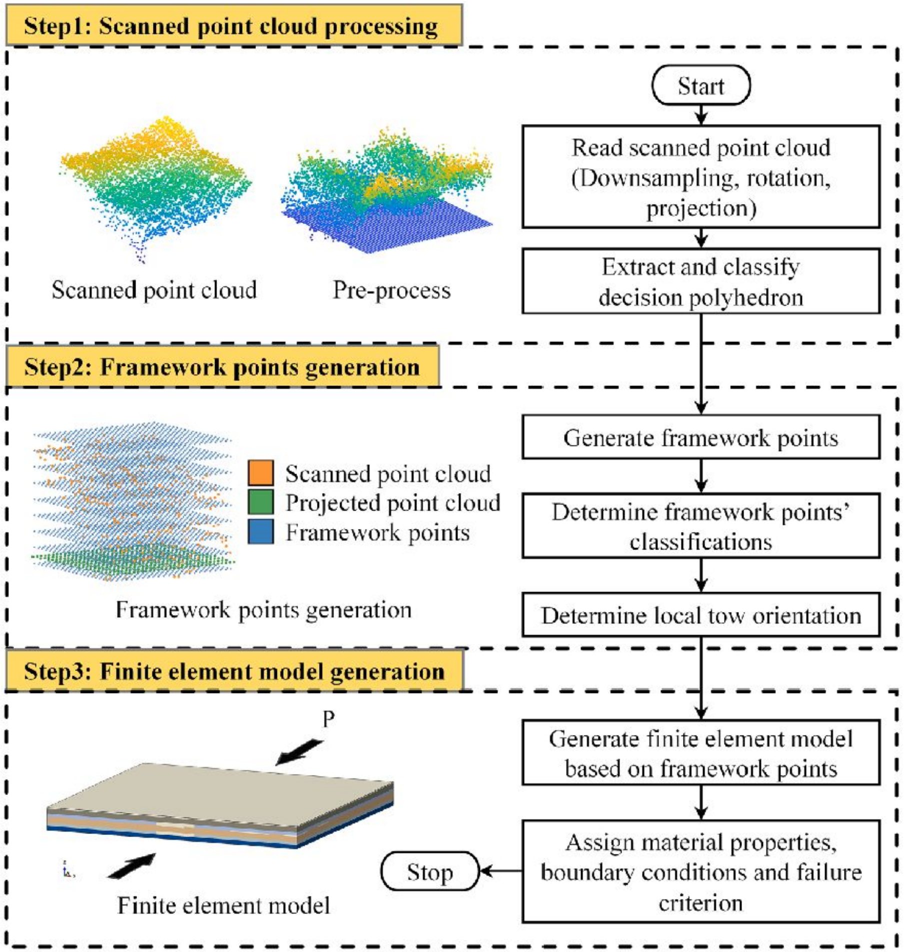
Integration of defect detection and analysis

“Modeling the effect of automated fiber placement induced gaps based on serial layer scanned point clouds” by Ye Hu, Ching Wang and 5 others. Composite structures, 2023, 116929.

Zhejiang University, China







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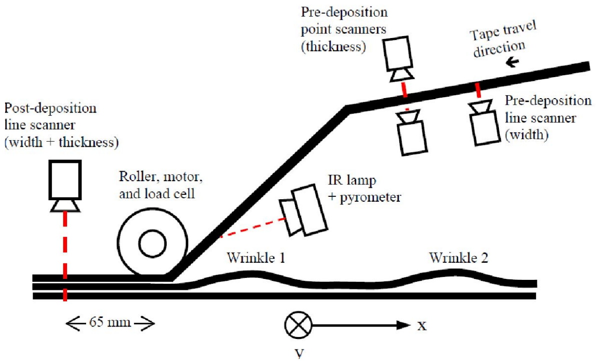
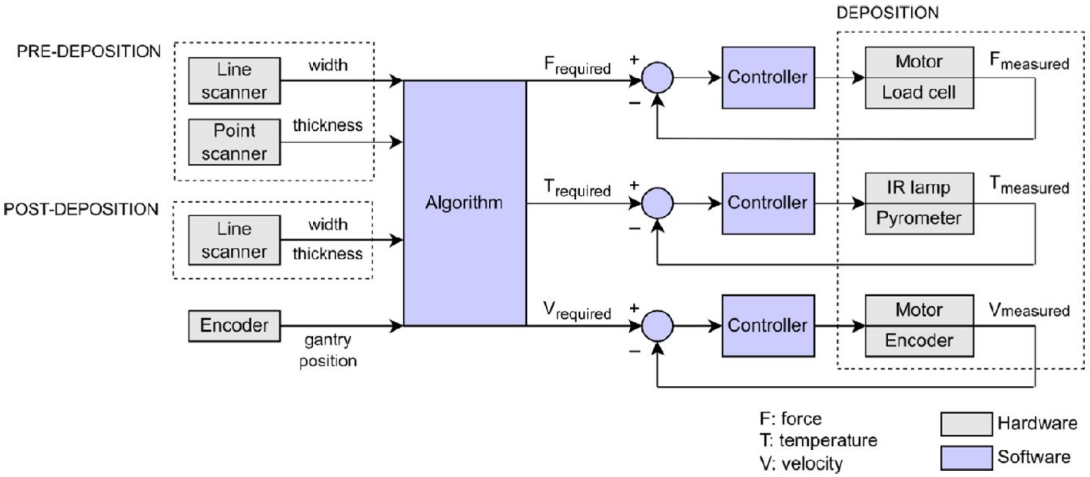
University of Bristol

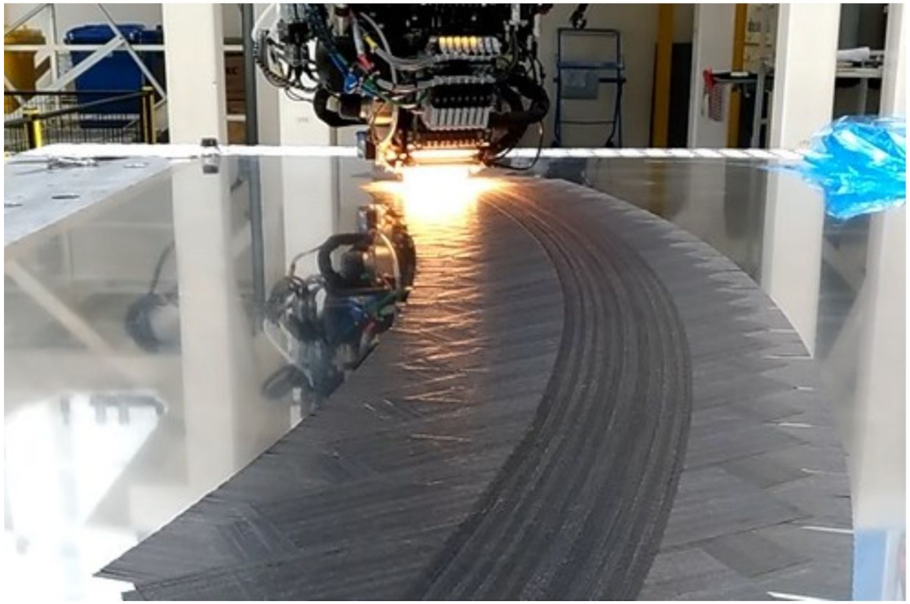
"Automatic process control of an automated fibre placement machine", by Duc H. Nguyen, Xiaochuan Sun, Iryna Trytiak, Mario A. Velverde, and James Kratz, Composites Part A, 168, 2023, 107465.

Inspect-Think-React





Fibre steering and wrinkles



Shown here is an Ingersoll Machine Tools AFP machine demonstrating a course of steered tows. While moderate steering is possible with infrared heating systems, smaller radii likely will require laser-based heating systems. Photo Credit: Ingersoll Machine Tools

Photos from Composites World magazine- Nov. 2020

Fiber wrinkles in CFRP may cause the materials to lose their tensile strength by 36-40%

R. Talreja, "Manufacturing defects in composites and their effects on performance", Polymer composites in the aerospace industry, ed. By P.E. Irwing and C. Soutis, Woodhead publishing 2015, pp. 99-113

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Prediction of occurrence of wrinkles

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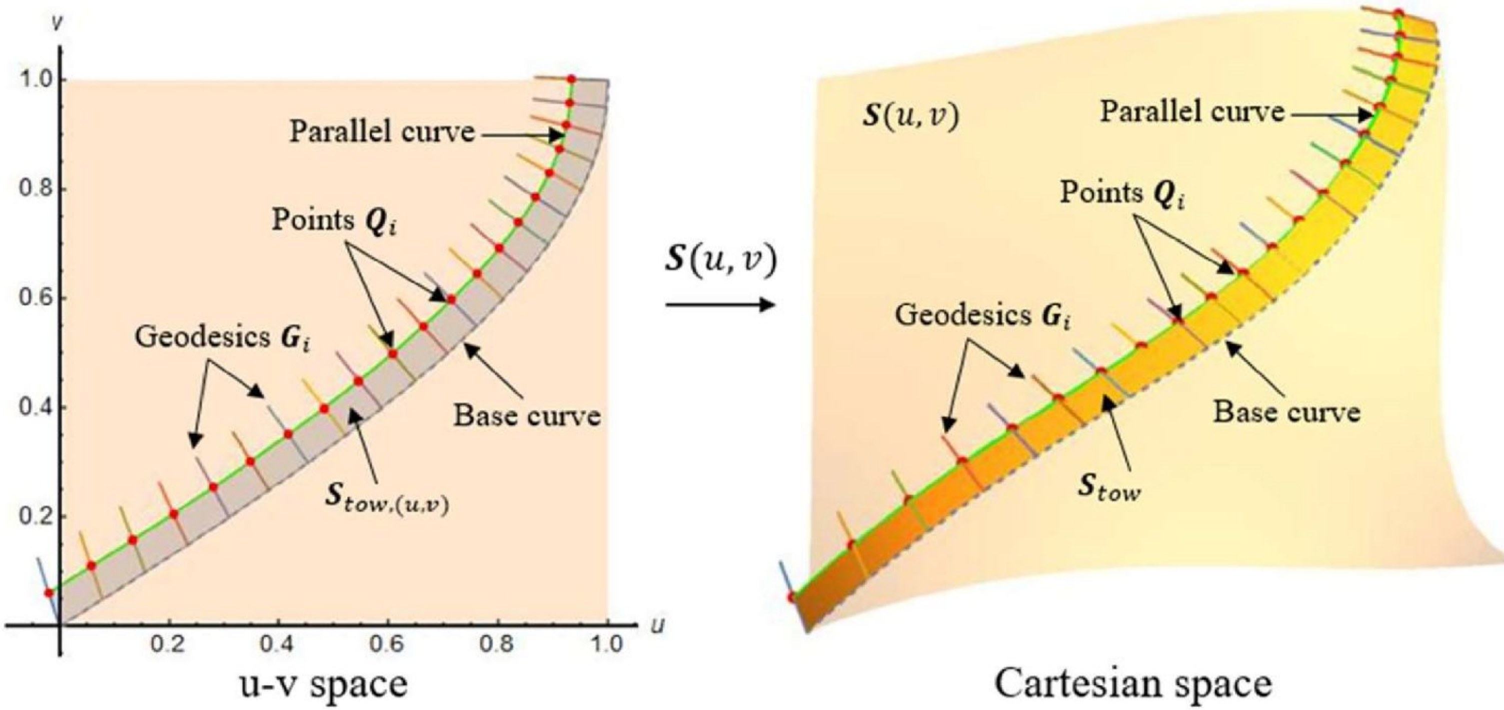
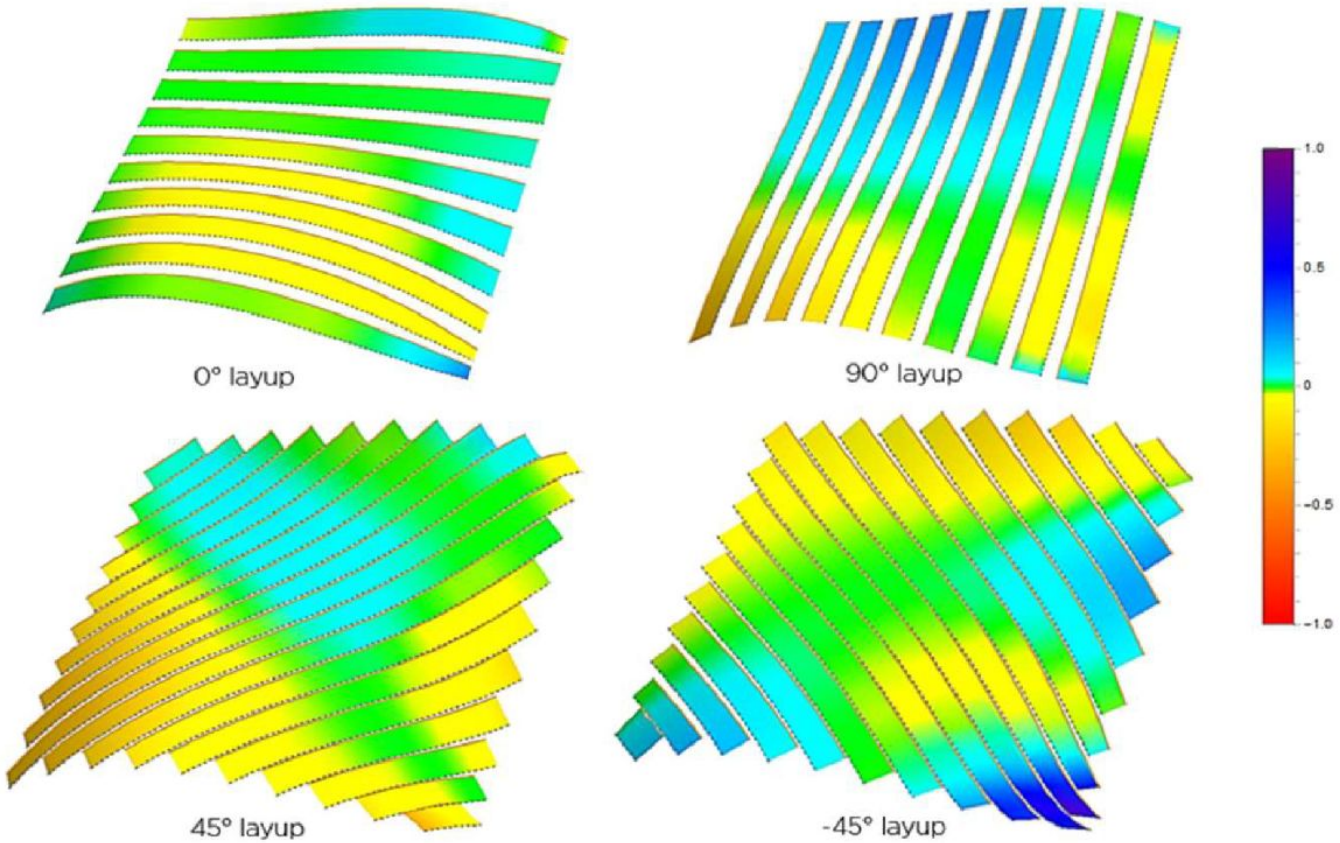
" Geometrical modeling of tow wrinkles in automated fiber placement", by Roudy Wehbe, Brian Tatting, Sreehari Rajan, Ramy Harik, Michale Sutton, and Zafer Gurdal. Composite Structures, 246, 2020, 112394





At the same location, the 0^{o} ply may not have wrinkles while the 45^{o} ply will have wrinkles.

This helps to plan process parameters in the design stage

Thin ply composites

- Plies of thickness less than 100 microns (0.1 mm) are considered thin plies Standard ply – 0.125 mm
- Better resistance to damage tolerance under applied stress when compared to standard ply laminates.
- Have the capability to suppress and/or delay microcracks onset and delamination damages.
- Whether they can processed using AFP?

AFP with thin ply laminates

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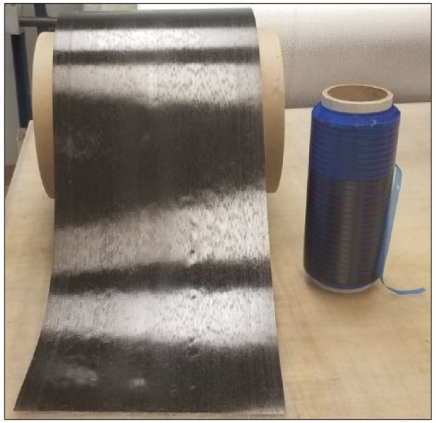
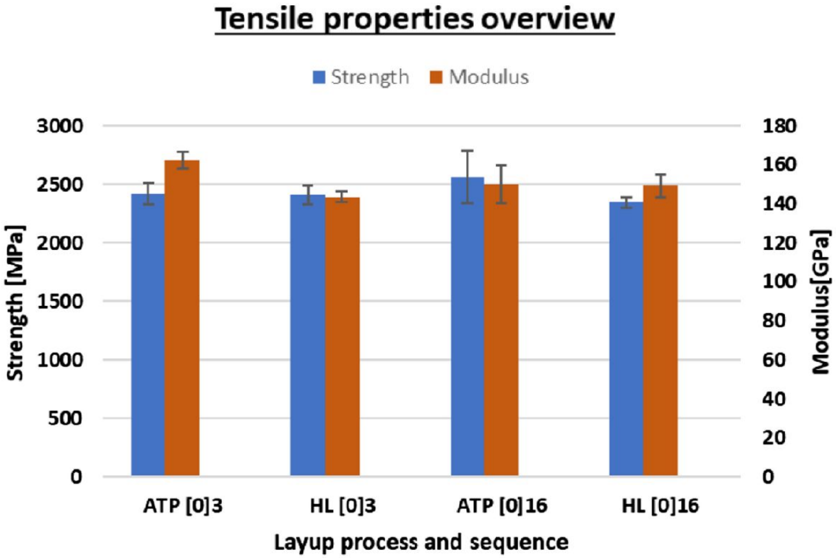
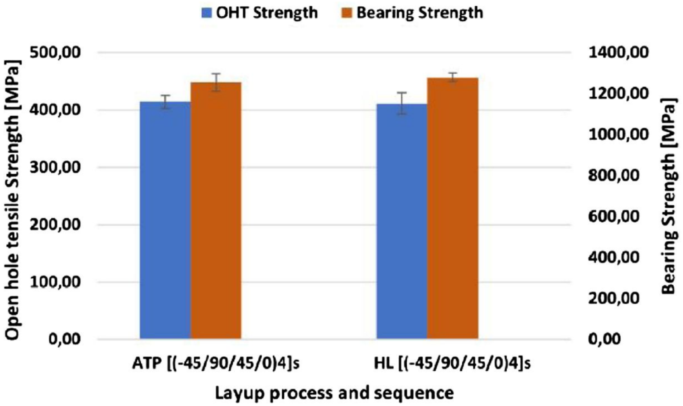
"Characterization and comparison of thin ply IM7/8852 composites processed by automated tape placement and hand lay up", by Uday Kiran Balaga, Verena Gargitter, Roger Crane, John Tierney, Shridha Yarlagada, Dirk Heida, and Suresh Advani, Journal of Composite Materials, Vol. 57, No.14, June 2023, pp. 2243-2260

University of Delaware



Unidirectional prepreg tape IM7/8552, 70 g/m^2, 12 inch wide, as received (left) and slit ¼ inch tape (right)





70 microns ply versus 130 microns ply

Basically, there is no difference

Thermoplastic composites

- **Determination of temperature distribution**
- **How to improve interlaminar strengths**
- **How to eliminate distortion on structures with free edges.**

Importance of temperature distribution

- Affects the bonding between the layers.
- Affects the residual stress development
- Affects the distortion of the structure.

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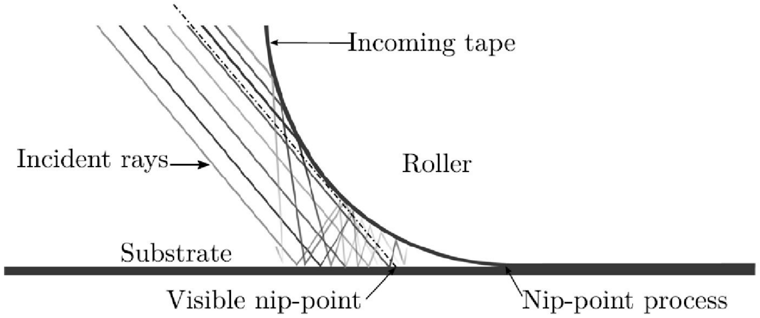
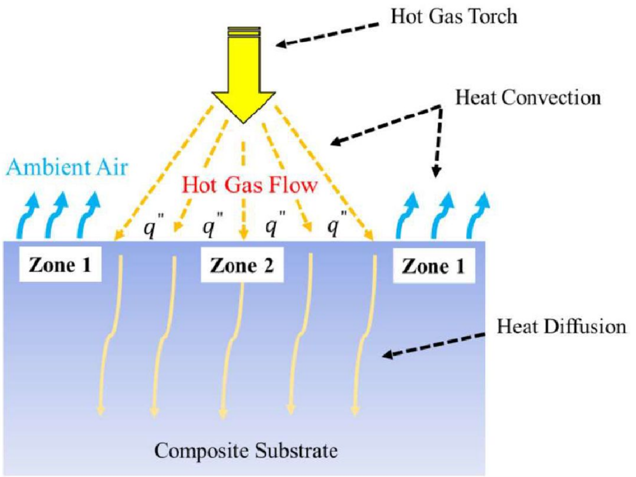
Issues with temperature distribution

- Temperature at the NIP point is critical.
- Can not measure temperature at the NIP point.
- Infrared camera cannot reach the NIP point due to shadow effect.
- Most work on measurement is done only in the substrate between layers.



- Heat transfer analysis for the case of hot gas torch uses coefficient of convection (h) for heat input.
- h value is assumed constant, and its value varies a lot from researcher to researcher.



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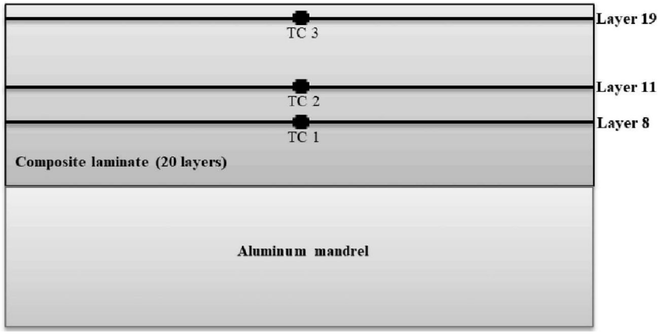
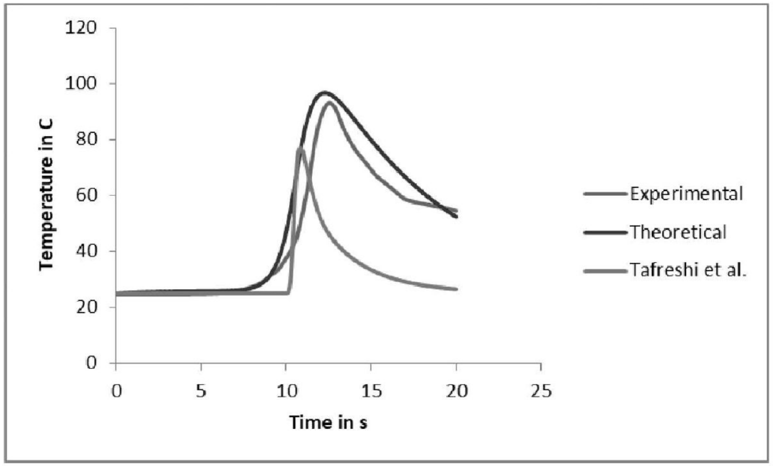
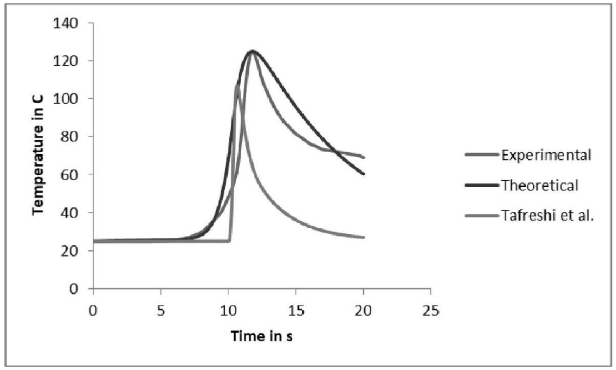
"Models for heat transfer in thermoplastic composites made by automated fiber placement using a hot gas torch", by Mehrshad Mogadamazad and Suong V. Hoa, Composites, part C: Open Access, 7, 2022, 100214. (Variable h)

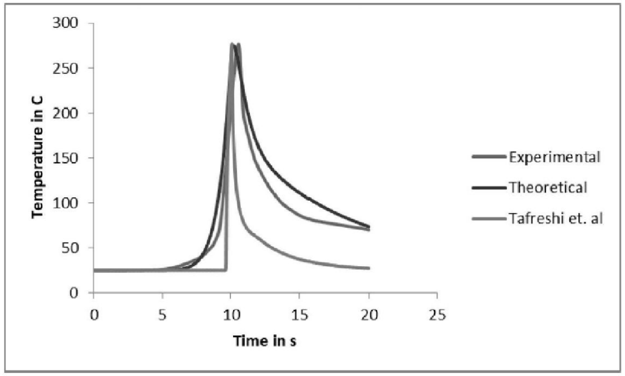




TC1

TC2





TC3

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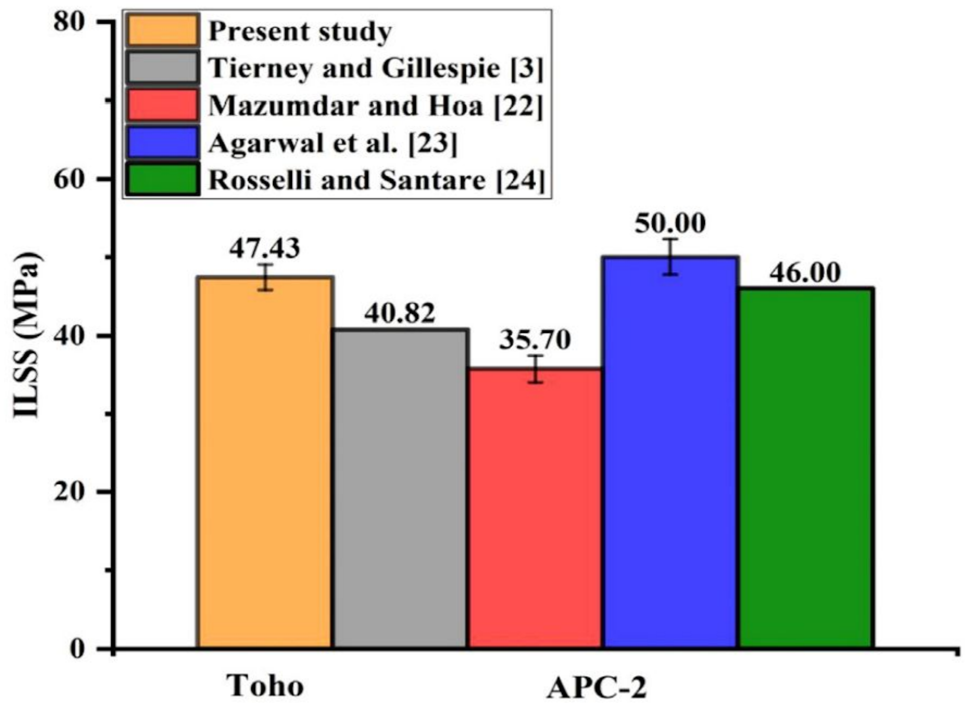
How to improve interlaminar strengths



Autoclave : 80 MPa

Reasons for low values:

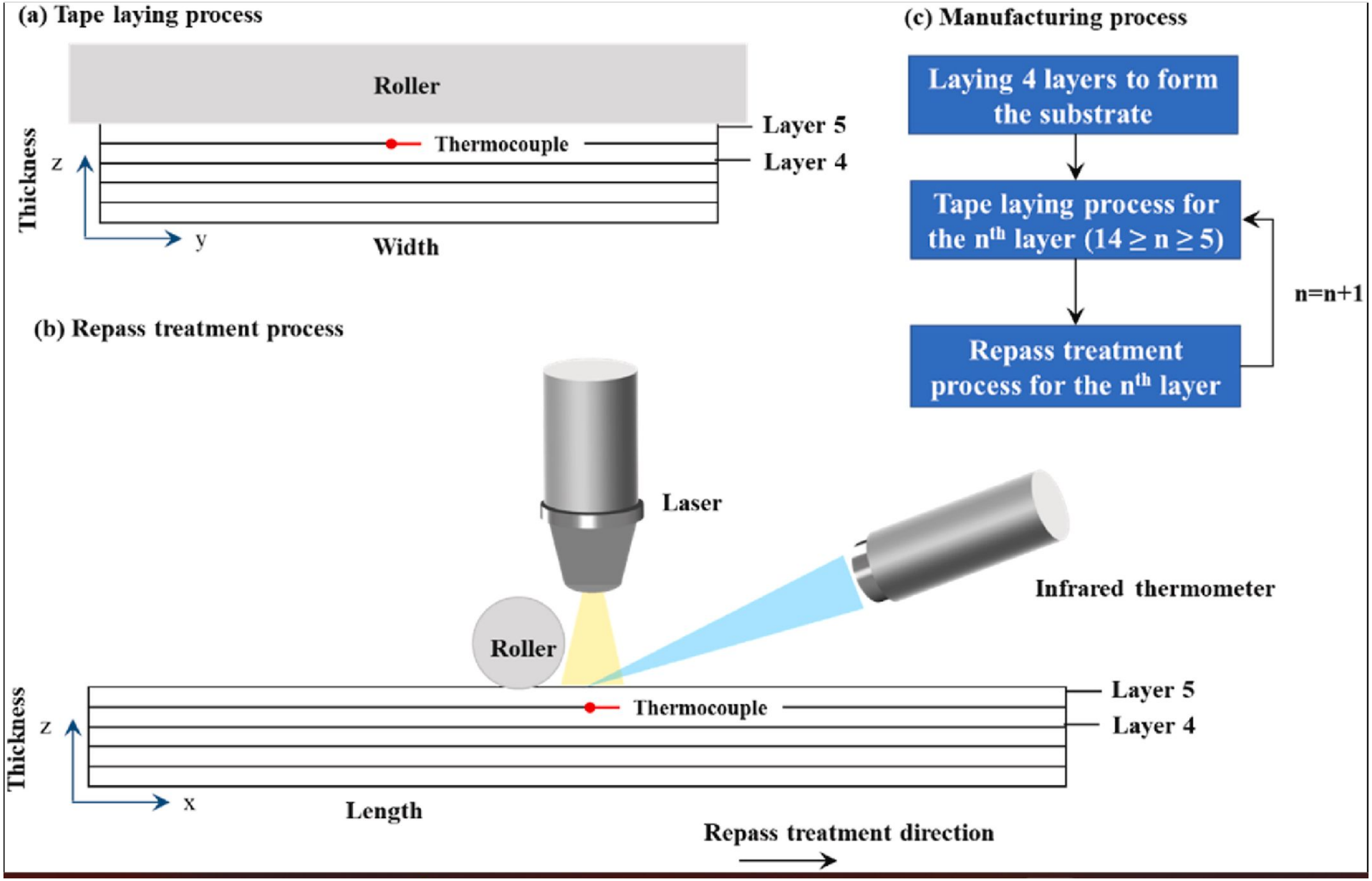
- **Contact time too short**
- **Possiblity of deconsolidation**

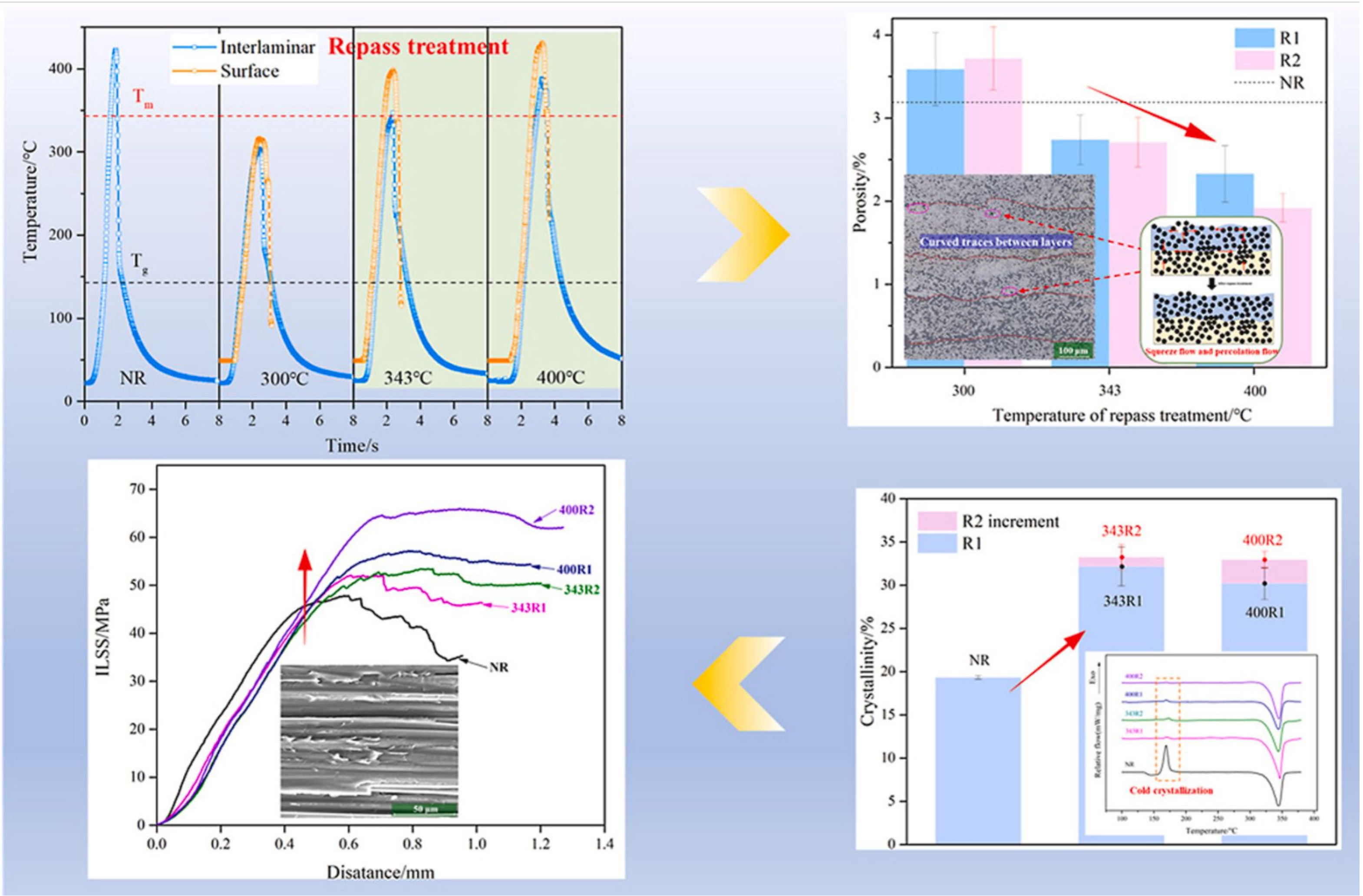
"Effect of voids and crystallinity on the interlaminar shear strength of in-situ manufactured CF-PEEK laminates using repass treatment", by Dongjiang Wu + 4 others, Composites Science and Technology, Vol. 224, June 16, 2022, 109448

Dalian University of Technology, China

Repass technique can be used to improve Interlayer strengths

Temperature at interlayer interface has to be more than T_m to be beneficial


(a) Tape laying process
Roller
Layer 5
Thermocouple
Layer 4
Thickness
z
y
Width
(c) Manufacturing process
Laying 4 layers to form the substrate
Tape laying process for the nth layer (14 ≥ n ≥ 5)
n=n+1
Repass treatment process for the nth layer
(b) Repass treatment process
Laser
Infrared thermometer
Roller
Layer 5
Thermocouple
Layer 4
Thickness
z
x
Length
Repass treatment direction


Interlaminar
Surface
Repass treatment
Temperature/°C
Time/s
NR
300°C
343°C
400°C
R1
R2
NR
Porosity/%
Temperature of repass treatment/°C
Curved traces between layers
Squeeze flow and percolation flow
ILSS/MPa
Disatance/mm
400R2
400R1
343R2
343R1
R2 increment
Crystallinity/%
Cold crystallization

How to reduce distortion in structures with free edges?

- Use a hot mandrel
- Annealing after manufacture

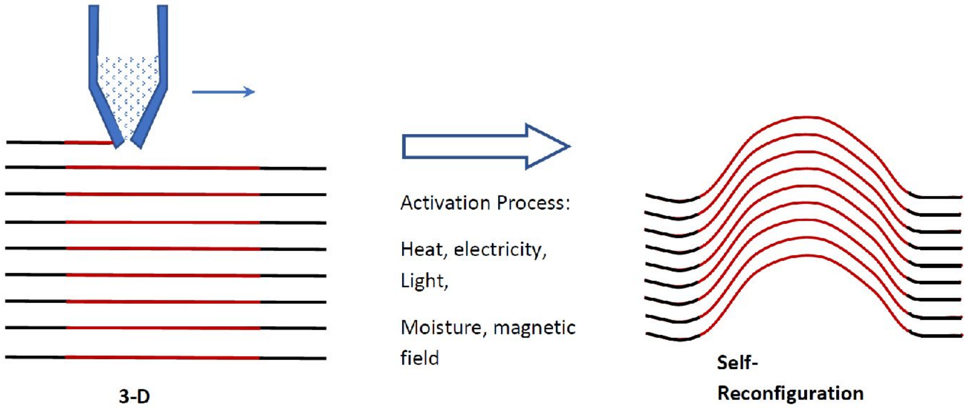
4D Printing of composites (4DPC) (Mouldless manufacturing of composites)

Regular 4D printing and 4D printing of composites

3D printing

Regular 4D printing of materials: Soft plastics- Low stiffness & strength

4D printing of composites: continuous carbon/epoxy – high stiffness/strength



4D printing of composites: 4DPC- Using long continuous fiber composites- High stiffness and strength

3D printer versus automated fiber placement machine (AFP)

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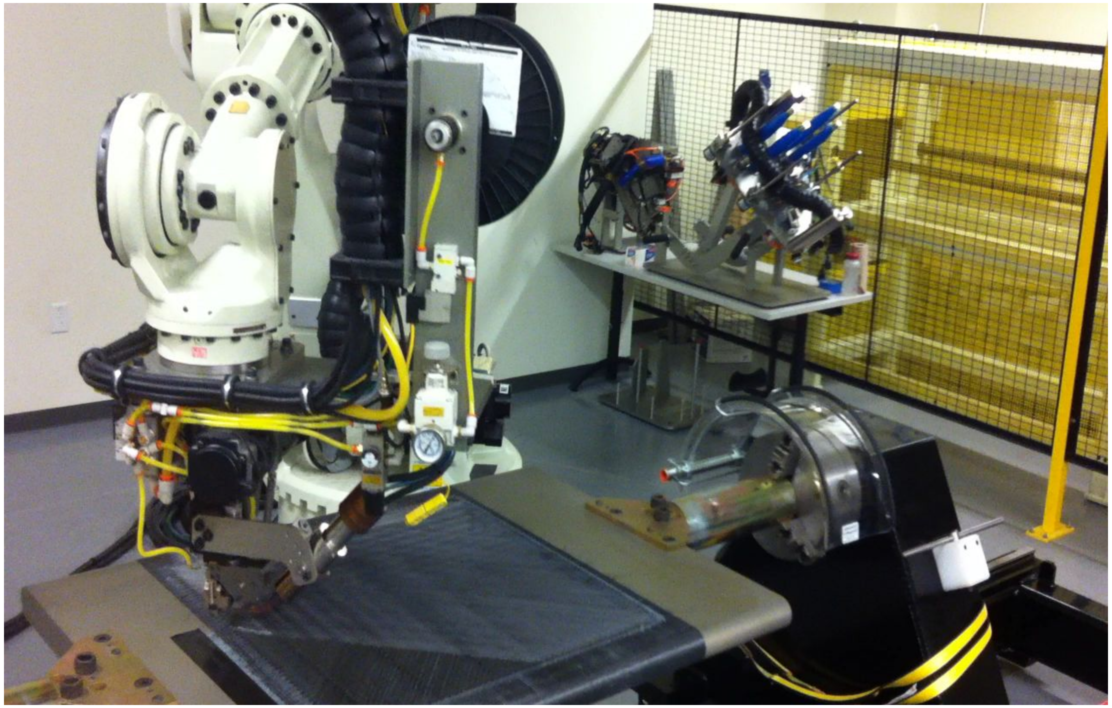

http://concom.encs.concordia.ca

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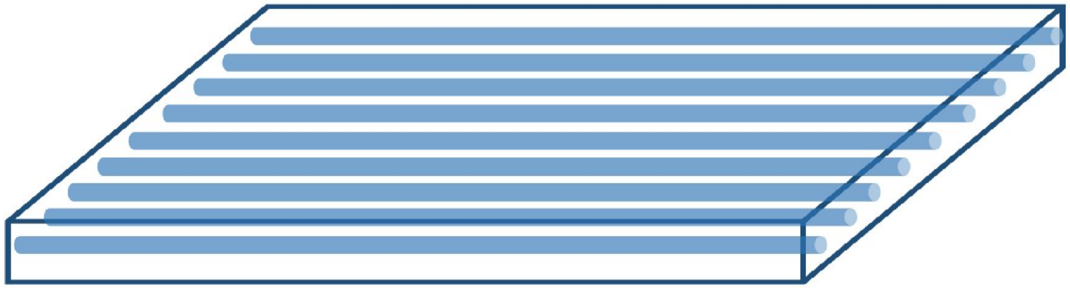
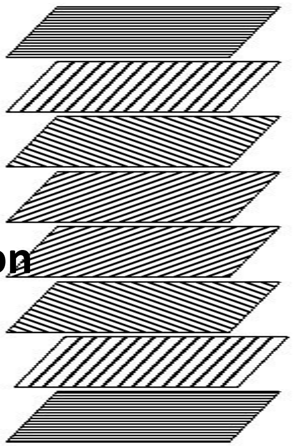
Anisotropic behavior



t = 0.13mm
E = 155 Gpa
S = 1500 MPa

Fibers and resin
0° direction: Shrink less
90° direction: Shrink more

Stack of layers at:
- **0° orientation**
- **90° orientation**
- **45/-45 orienation**



Stay flat

Becomes curved

[0/90] laminate

Unsymmetric----Symmetric

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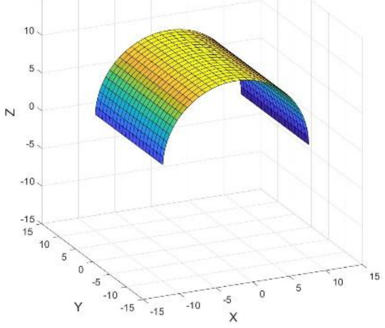
Effect of lay-up sequence

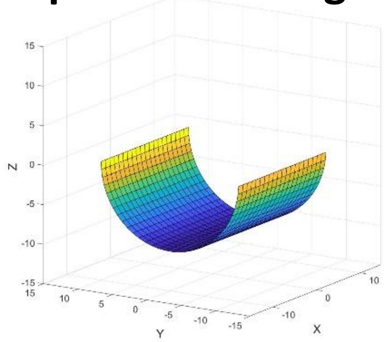
[90/0]

Downward bending



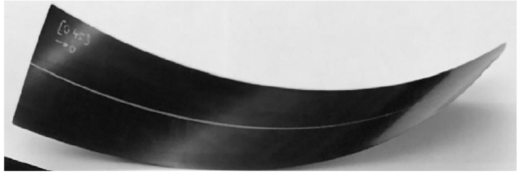
[0/90]

Upward bending



[0/45]

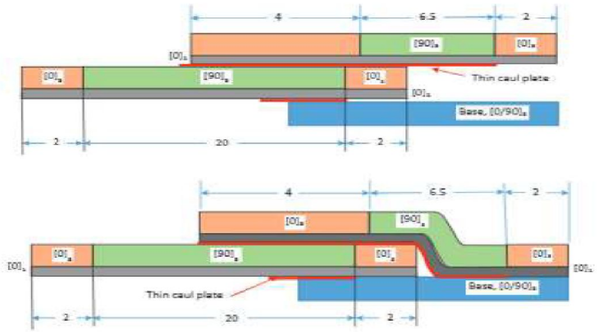
Bending and twisting



Two example pieces

1. **CONCORDIA**
2. **Composite leaf springs**

The letters: C , O, N, C, O, R, D, I, A



Suong V. Hoa and Daniel Rosca, "Formation of letters in the alphabet using 4D printing of composites", Materials Today Communications, 25, 2020, pp. 101115.

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Composite leaf springs

Table 1
Typical dimensions of composite leaf springs for automotive applications.

Items	Typical dimensions
Total length (mm)	1000
Width (mm)	50
Arc height (mm)	188
Radius of curvature (mm)	950
Thickness of leaf (mm)	10
Spring constant (N/cm)	400

Table 3
Radii of curvatures, and included angles for laminates with different stacking sequences.

Laminate	# layers	Thickness (mm)	Radius of curvature R (cm)	Radius of curvature (exp) (cm)	Included angle $2\theta_o$ radian (°) (G = 30.48 cm)
0/90	2	0.250	6.3	5.6–7.2.	4.87 (279)
$0/90_2$	3	0.375	6.1	5.6–6.2	5.00 (286)
$0/90_3$	4	0.500	7.6	6.3–7.0	4.01 (230)
$0/90_4$	5	0.625	9.5		3.22 (184)
$0/90_5$	6	0.750	11.5		2.65 (152)
$0/90_6$	7	0.875	13.7		2.22 (127)
$0/90_7$	8	1.000	15.9	14.6–15.9	1.92 (110)
$0/90_8$	9	1.125	18.4		1.66 (95)
$0/90_9$	10	1.250	20.8		1.47 (84)
$0/90_{10}$	11	1.375	23.4		1.30 (75)
$0_2/90$	3	0.375	20.1		1.52 (87)
$0_2/90_2$	4	0.500	12.5	13.3	2.43 (139)
$0_2/90_3$	5	0.625	11.6	13.8	2.63 (151)
$0_2/90_4$	6	0.750	12.3		2.48 (142)
$0_2/90_5$	7	0.875	13.6		2.25 (129)
$0_2/90_6$	8	1.000	15.2		2.01 (115)
$0_2/90_7$	9	1.125	17.0		1.79 (103)
$0_2/90_8$	10	1.250	18.9		1.61 (92)
$0_2/90_9$	11	1.375	21.0		1.45 (83)
$0_2/90_{10}$	12	1.500	23.1		1.32 (76)
$0_8/90_{12}$	20	2.500	46.4	60	0.65 (38)
$0_{16}/90_{24}$	40	5.000	93	105	0.33 (19)
$0_{24}/90_{36}$	60	7.500	139		0.22 (13)

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Composite leaf spring

$90_{36}/0_{24}$

Stiffness constant equivalent to metallic lead springs used in automobiles

Hoa Suong Van "Development of composite springs usin 4D printing method", Composite structures, 2020, 219, 869-876.

486 N/cm.

Lasts more than 1 million cycles from flat to curved in flexural fatigue.

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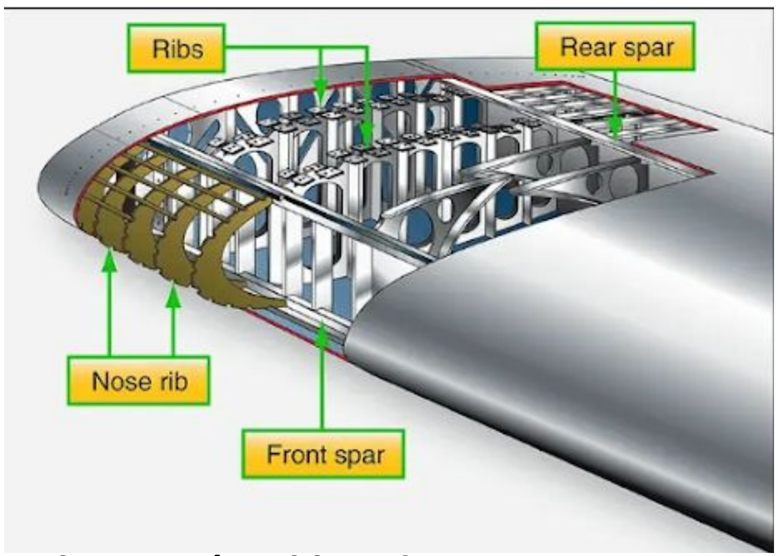
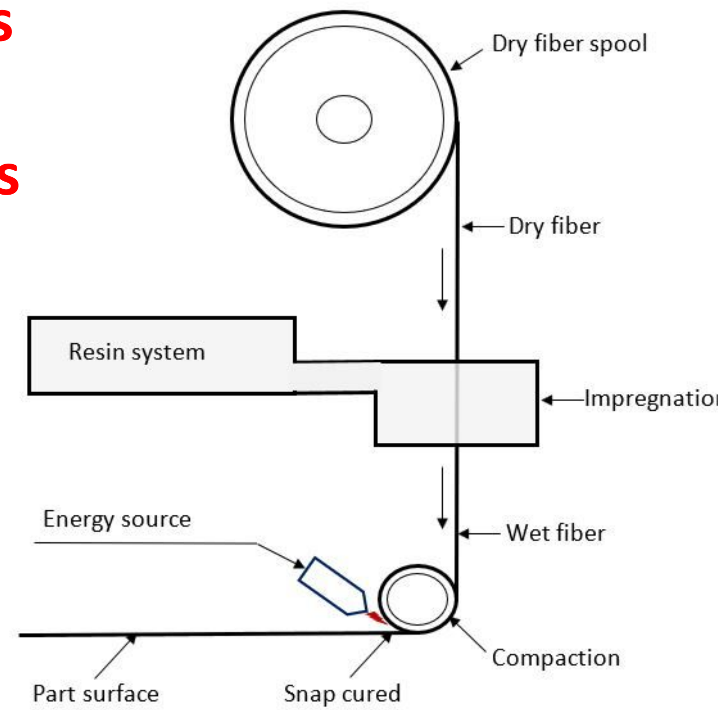
Future outlook- Continuous fiber 3D printing

Proposed to make not only skins, but airframes out of continuous fibre composites



Bob Koon (Lockheed Martin Aeronautics) and Nanthan Stranberg (Continuous Composites): SAMPE Journal, November-December 2021.



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Sixth International symposium on Automated Composites Manufactring (ACM6)

March 4-8, 2024 at the University of South Carolina, Columbia, South Carolina, USA.

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- **Key note speakers from Boeing, NASA, NIAR , Spirit Systems**
- **March 4- Cultural tour of USC campus-Reception at McNair**
- **March 8- Trip to Charleston-Tour of Boeing.**
- **Papers featured in Manufacturing Letters**

ADVANCED COMPOSITE MANUFACTURING CONFERENCE

Hosted by the University of South Carolina

Columbia , SC
March 4-8 2024

We are excited and honored to be hosting the 2024 ACM Conference at the University of South Carolina. You will not want to miss the exciting events we have planned, including keynote presentations, papers, poster sessions, and on site visits. Come and explore what makes the state of South Carolina a manufacturer's paradise.

Explore and Discuss Topics Including...

- Composites Design for Manufacturing
- Process Planning
- Virtual Manufacturing Environments & Digital Technologies
- Automated Composites Manufacturing Equipment
- Inspection and Quality Assurance
- Curing Advancements
- Workforce Development and Training

Featured Keynotes

Dawn C. Jegley
NASA ISAAC Lead

Dr. Sayata Ghose
Technical Fellow,
The Boeing Company

Dr. Waruna Seneviratne
Director of
NIAR ATLAS

Dr. Sean Black
Senior Vice President
at Spirit Aerosystems

Important Deadlines

Full Paper Submission
October 1, 2023

Acceptance Notification
December 1, 2023

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