Manufacturing and Condition-based Structural Health Monitoring of CFRPs

Researcher: Hyung Doh Roh, Ph.D.
Department of Mechanical Engineering
Hanyang University ERICA

Present for: Anyone interested in composites
Updated on: July 18, 2025

Credentials

Job

Assistant Professor	September, 2023 – Current	**Department of Mechanical Engineering,** **Hanyang University ERICA**
Senior Researcher	July, 2021 – August, 2023	Department of Composite Materials Research, Korea Institute of Materials and Science (**KIMS**)

Education

Post-doc. Researcher	September, 2020 – July, 2021	Mechanical Engineering, UNIST (Composite rapid manufacturing and AI)
Master's and Ph.D.- Combined Degree	March, 2014 – August, 2020	Mechanical Engineering, UNIST (Composite manufacturing, AI, and self-sensing)
Bachelor's Degree	March, 2010 – February, 2014	Mechanical Engineering & Electrical and Electronic Engineering, UNIST

Thesis Title (Ph.D.)

Characterization and Optimization of Self-sensing Performance of CFRP
Using Electrical Resistance Analysis and Electrical Circuit Models

Scholarship

Tuition and Book Fees	2010 Spring – 2019 Fall	34,739,000 won for Undergraduate Course and 97,562,000 won for M.S.-Ph.D. Combined Program

Major Research Interests

Composite Manufacturing
(Rapid manufacturing, AI optimizing and digitalized real-time manufacturing monitoring)

Composite Joining
(Fastener-free joining of CFRTPs and self-assembly of sandwich composites)

Smart Structural Health Self-monitoring
(Structural health monitoring, prognostics and health management and non-destructive evaluation)

CFRP: Carbon Fiber Reinforced Plastic
AI: Artificial Intelligence

스마트 복합재료 연구실 (R Lab)

조교수 **노 형 도**

(rhd1213@hanyang.ac.kr)

한양대학교 기계공학과 조교수	2023 ~ 현재
한국재료연구원 선임연구원	2021 ~ 2023
울산과학기술원 박사후연구원	2020 ~ 2021

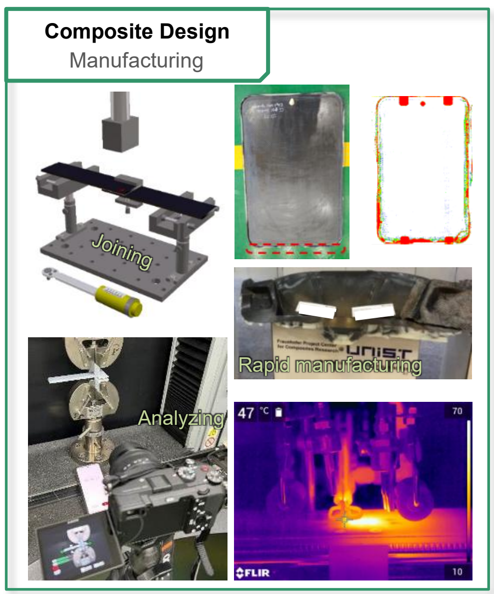
➢ 연구실 정보

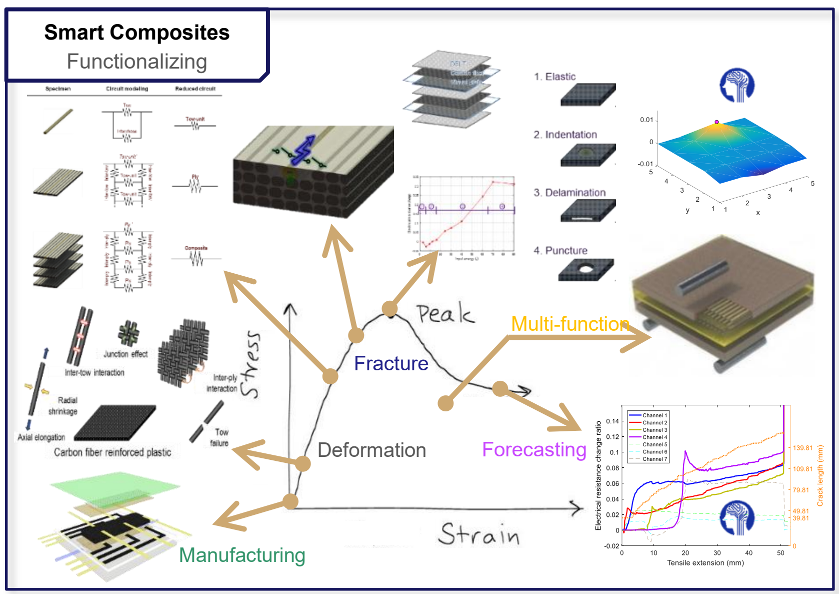
- 연구실 위치 : ERICA 제5공학관 228호
- 연구실 연락처 : 031-400-5246

➢ 기타 연구실 관련 정보

- 현재 구성원 : 석사과정 5명, 석박통합과정 1 명, 학부연구원 5명
- 연구실 홈페이지 : https://rhd1213.github.io/

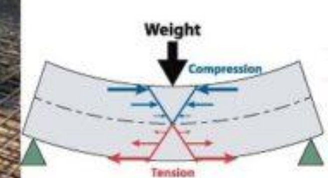
주요 연구 분야: **탄소섬유강화 플라스틱의 성형, 접합, 건전성 진단 및 수명 예측** with AI





Composite

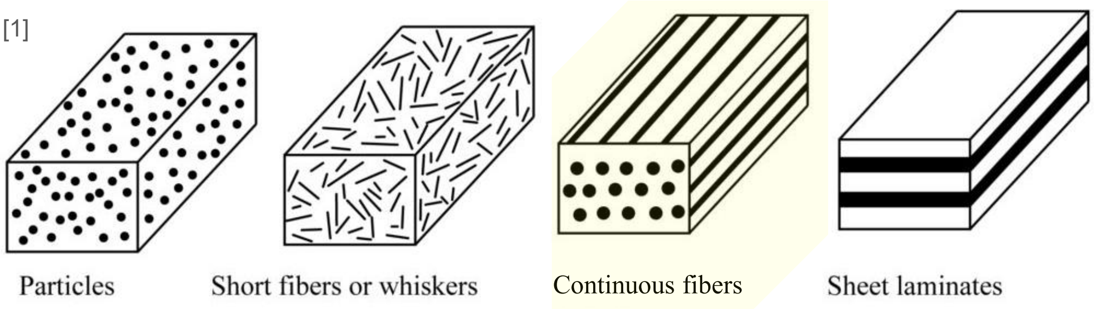
A composite material is a material which is produced from two or more constituent materials. (Wikipedia)



Introduction (Backgrounds)

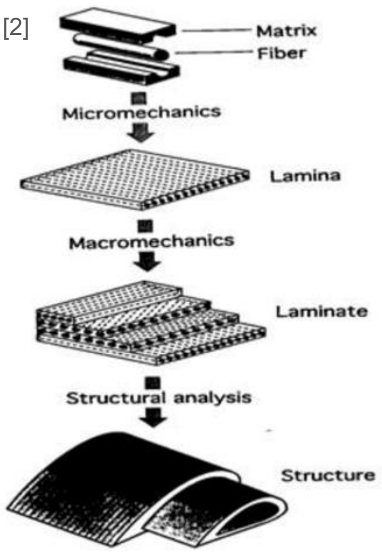
▶ Composites – CFRP – Manufacturing & Safety – AI

[1]



[6]

[2]



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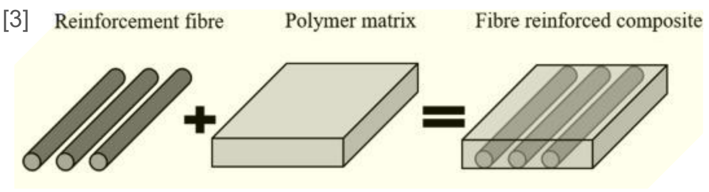

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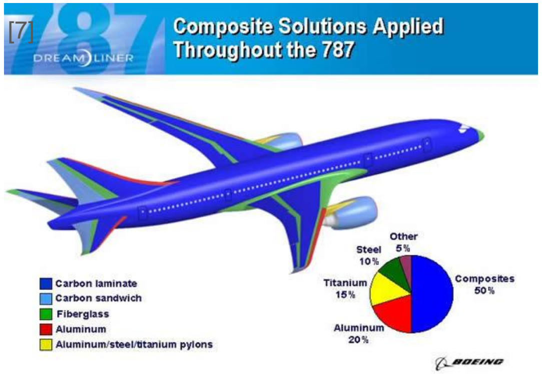

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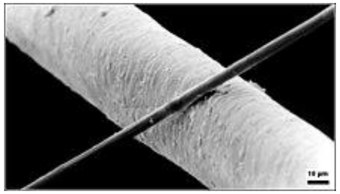

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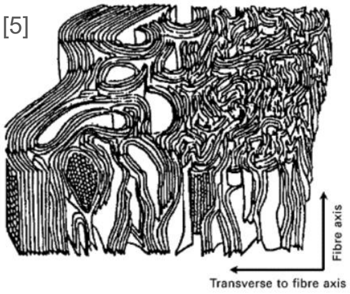
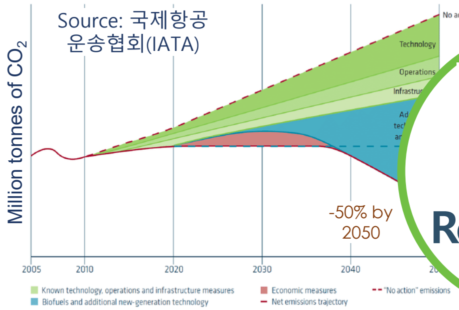


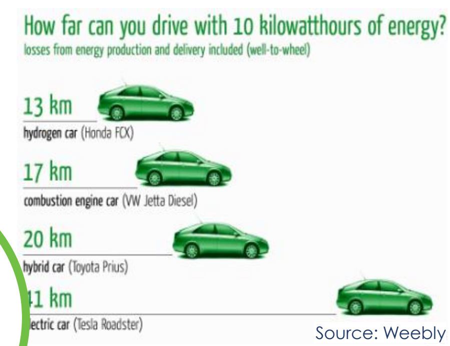
[8]

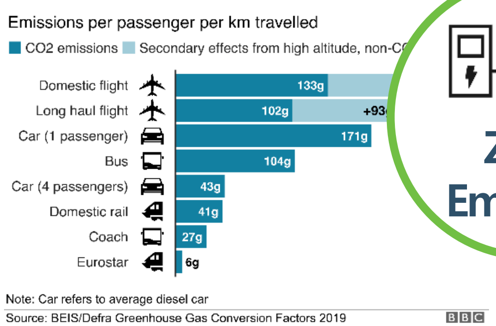
Source: [1] Bartleby, [2] Progressive failure analysis of composite materials using the Puck failure criteria, [3] Modeling of reinforcement fibers and textiles, [4] Composite material –Wiki, [5] S. C. Bennett and D. J. Johnston. (1978), [6] BMW i3, [7] Boeing 787, [8] Aloha airlines

CFRP: Carbon Fiber Reinforced Plastic
AI: Artificial Intelligence

Mega-trend of Future Mobility



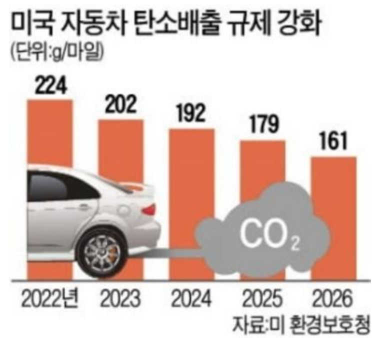


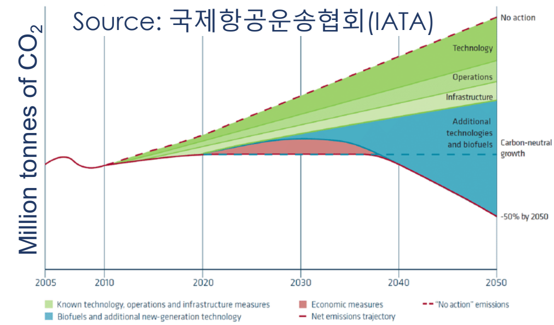


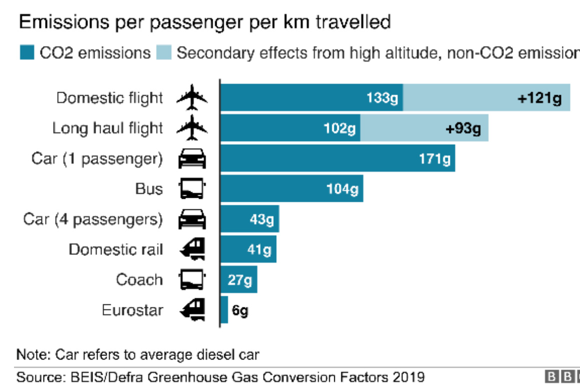
Global Environmental Regulation

Environmental
Social
Governance

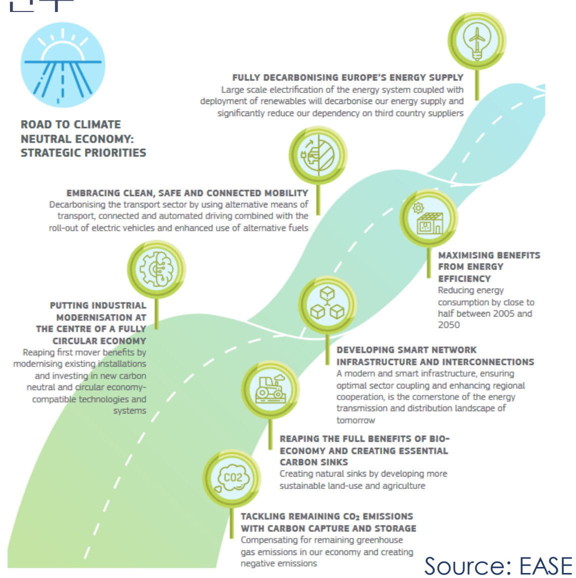
- Regulations and Strategies
  - **탄소중립**: 이산화탄소와 같은 탄화가스 규제
  - **기후중립**: 온실효과에 미치는 모든 가스 규제
  - 항공기와 자동차의 매연 저감이 급선무



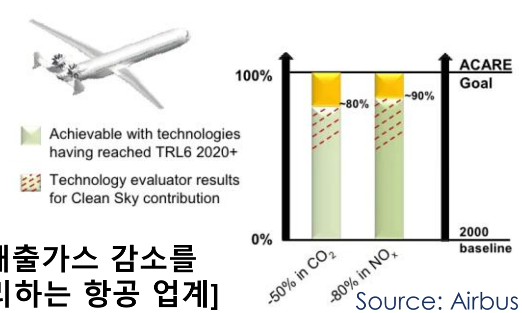




[탄소중립(Carbon-neutral) 추진 전략]



[기후중립(Climate-neutral) 추진 전략]



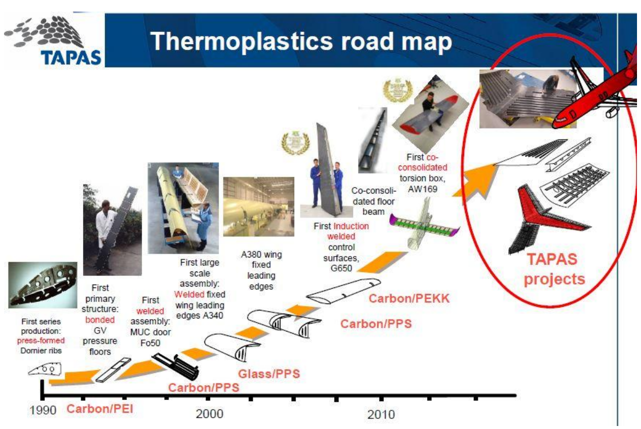
[배출가스 감소를 관리하는 항공 업계]

Lightweight with Composites

Lightweight for Energy efficiency

- Composites for structural lightweight
  - **New energy source and its efficiency**
  - **Maintenance of structures**

[경량화 진행 중인 Airbus 항공기]



Introduction

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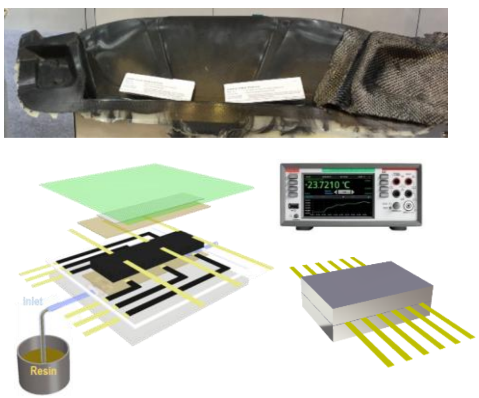
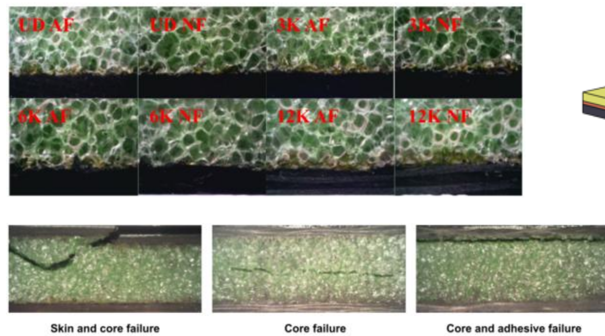
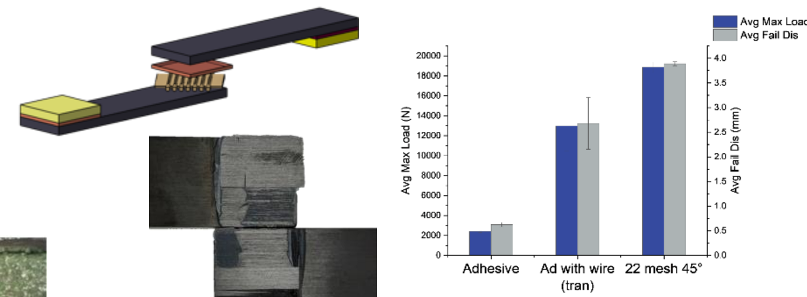
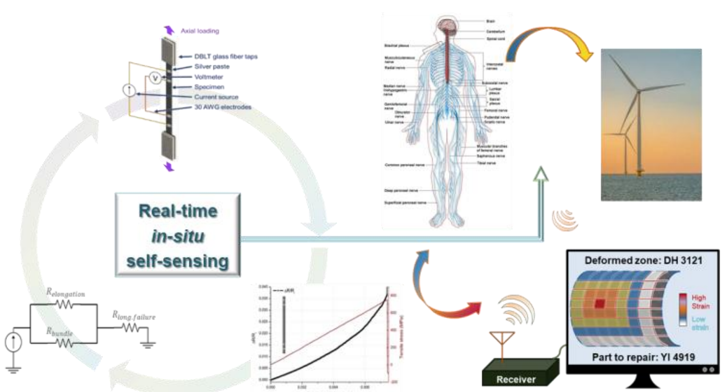
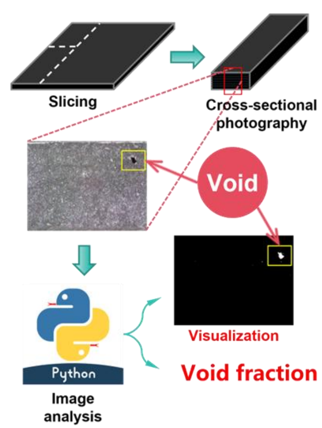
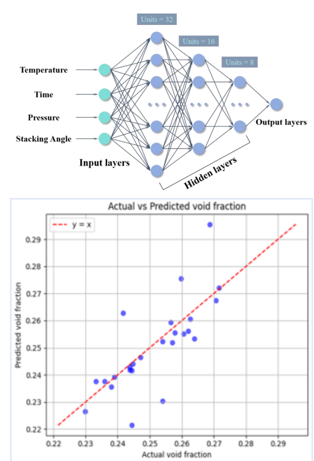


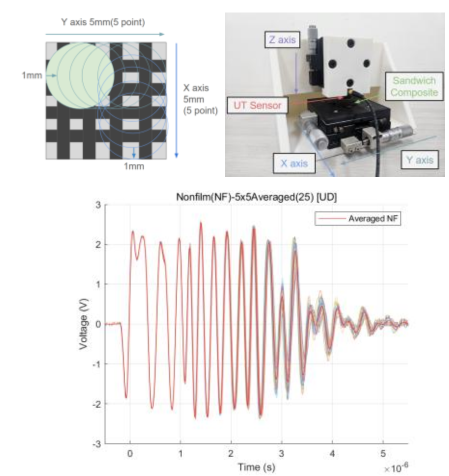












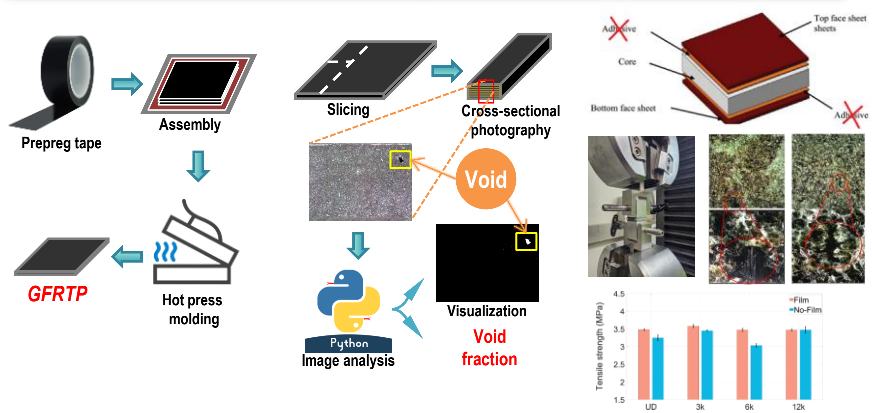
CFRP: Carbon Fiber Reinforced Plastic
AI: Artificial Intelligence

Contents

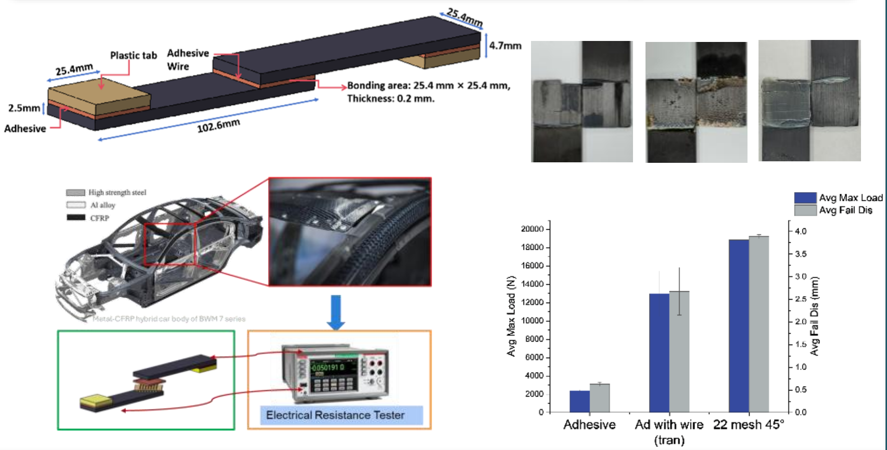
Research Achievements (Overview)

Composite Manufacturing
Optimizing & Joining

Manufacturing Optimization

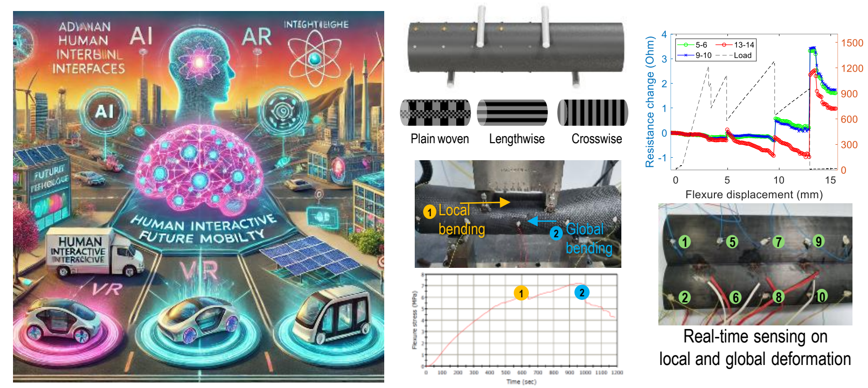


Fastener-free Joining

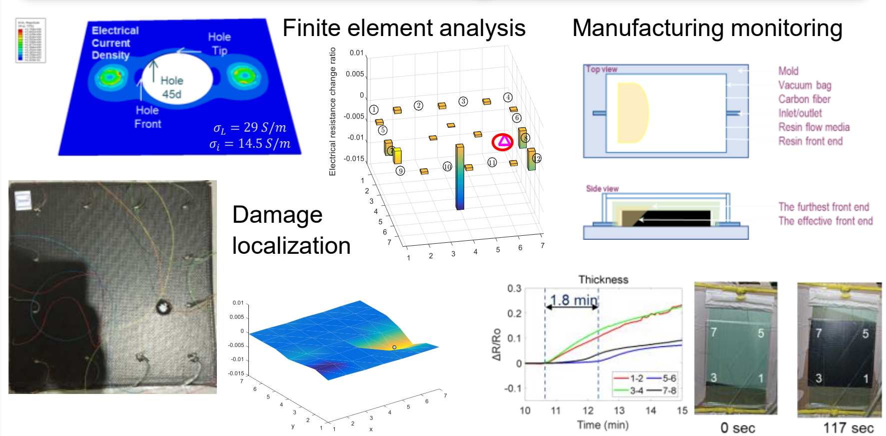


Smart Composites
Functionalizing

Functional Composites



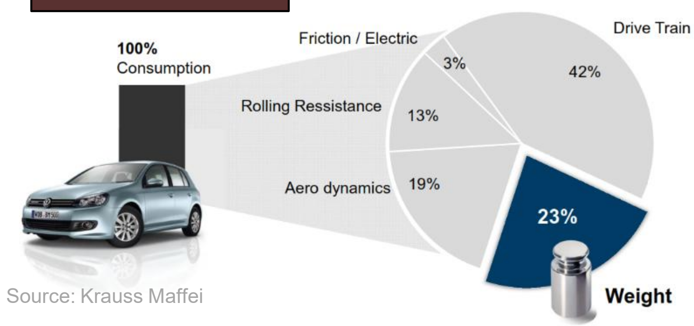
Self-monitoring of CFRPs



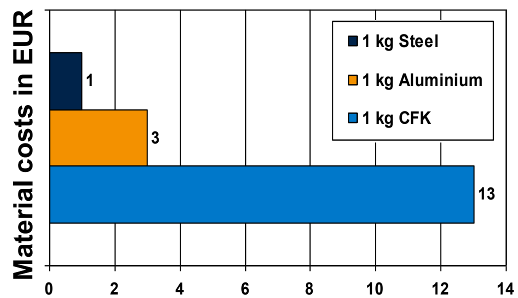
Research Achievements (Manufacturing)

Composite Manufacturing

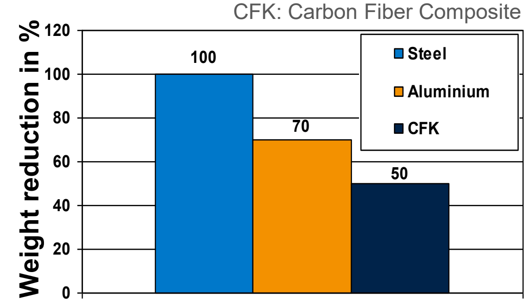
Motivation



Source: Krauss Maffei



CFK: Carbon Fiber Composite



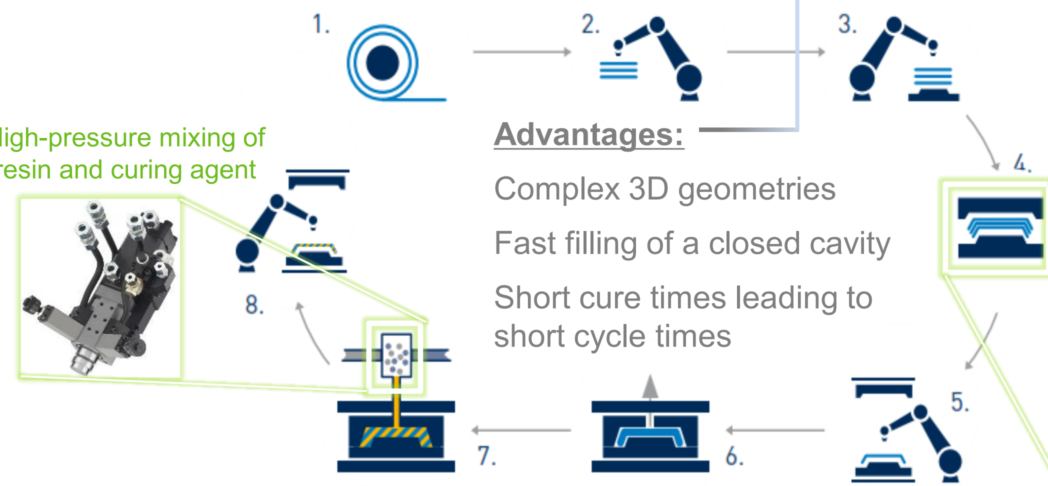
Source: Krauss Maffei

Needs for the lightweight material ↑

Needs for continuous carbon fiber composite ↑

Background

High-pressure mixing of resin and curing agent



Source: Krauss Maffei

Advantages:

Complex 3D geometries

Fast filling of a closed cavity

Short cure times leading to short cycle times

Ultimately, make CFRPs well

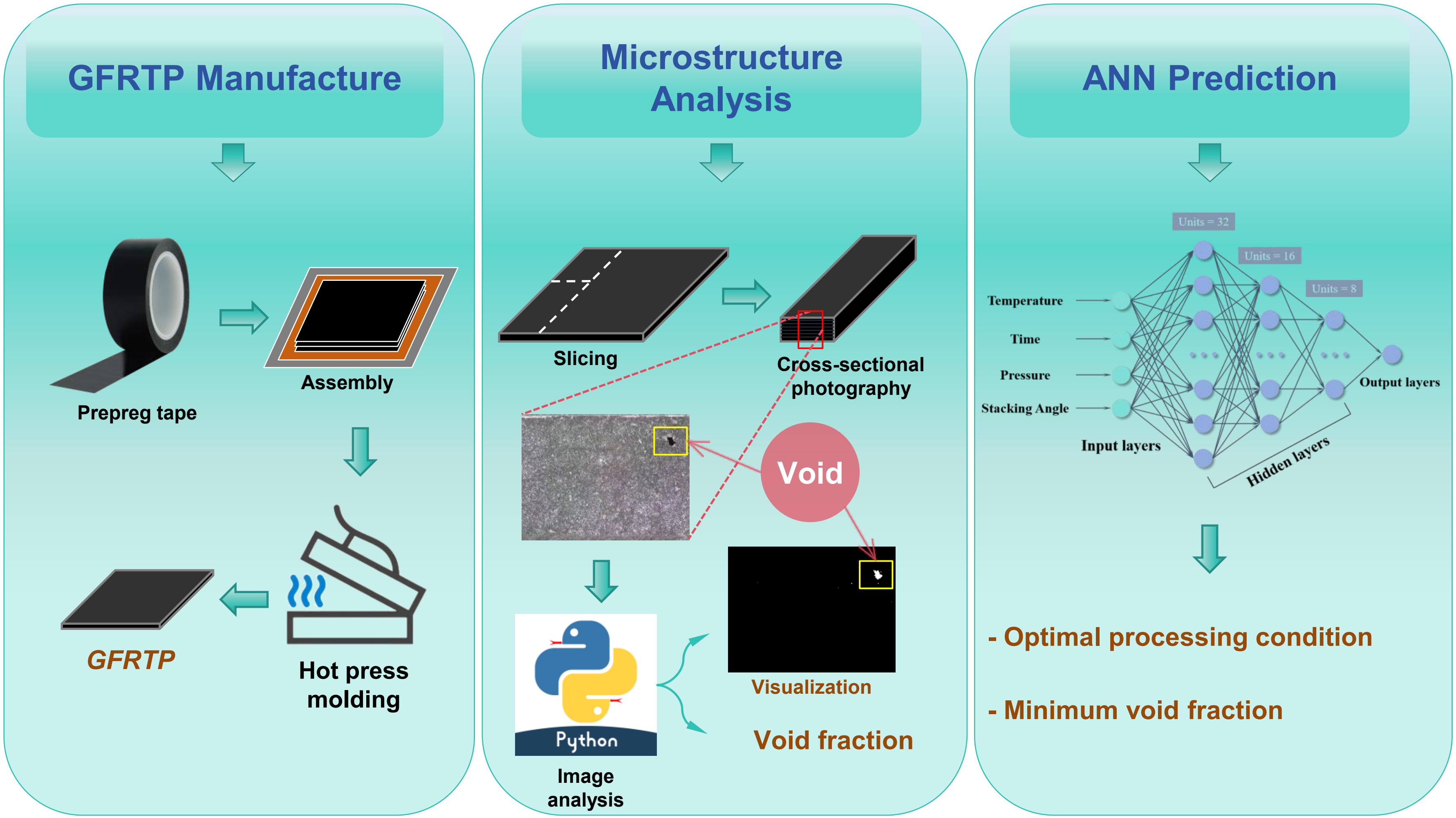

Source: Fraunhofer ICT

Preforming

Visiting researcher experience in Fraunhofer ICT, Germany

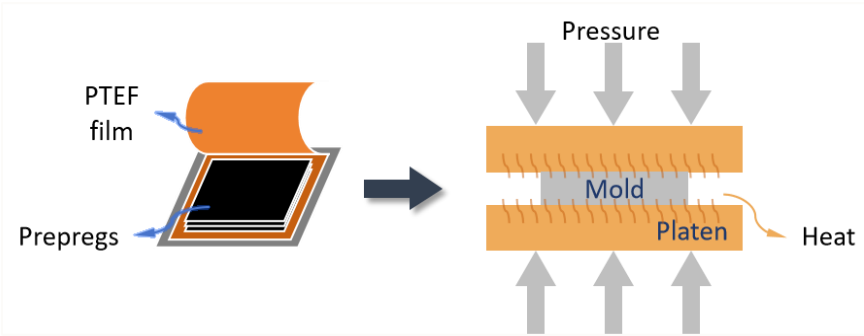
Research Achievements (AI for Optimization)

Prediction of Void Fraction and Optimization of GFRTP Thermoforming Conditions Using ANN



Research Achievements (AI for Optimization)

Prediction of Void Fraction and Optimization of GFRTP Thermoforming Conditions Using ANN



Materials

UD Tape (439 gsm): 70 vol.% E-glass fiber, Celanese

Resin: PP (Polypropylene)

Geometry: L 150 mm * W 150 mm * t 0.25 mm

Characterization

Cross-section Analysis

→ Cut the test piece with Rotating wheel
→ Semi-auto polishing
→ Shoot cross-section by Digital Optical Microscope
→ Analyze the stacking status and presence of voids
→ Analyzing porosity by Python

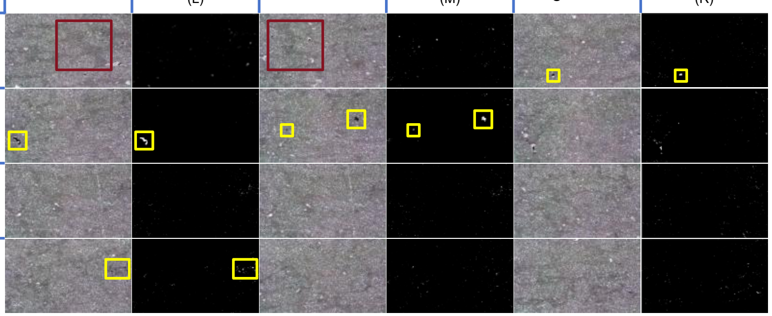
ANN Prediction

→ Import Temperature, Pressure, Stacking angle and Heating time as inputs into the ANN model.
→ Output minimum void fraction and optimal production conditions.

➢ *Cross-sectional Image Analysis*

□: Void
□: Resin rich area

Pressure	void fraction (%)	Left area	Void visualization (L)	Middle area	Void visualization (M)	Right area	Void visualization (R)
30 bar	0.22982						
40 bar	0.21530						
50 bar	0.25396						
60 bar	0.25648						



Research Achievements (AI for Optimization)

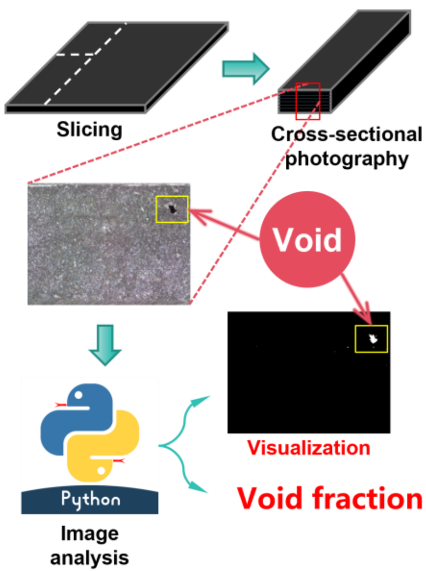
Prediction of Void Fraction and Optimization of GFRTP Thermoforming Conditions Using ANN

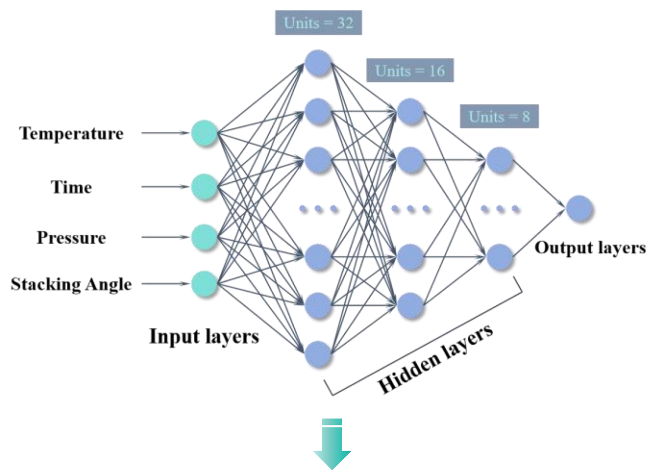
Novelties

- Emphasis on microstructure analysis.
- ANN-aided optimization.
- Time, cost, and labor minimization
- Process optimization

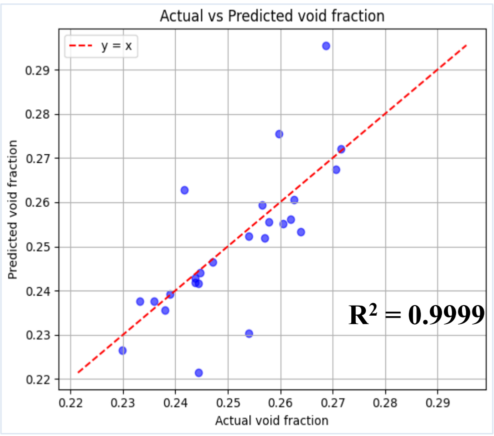
Improved

Predicting the optimal process parameters through ANN,
- Improve molding quality;
- Reduce void fraction;
- Enhance product consistency.





- Optimal processing condition
- Minimum void fraction



▶ **The proposed ANN models are effective in optimizing GFRTP manufacturing parameters.**

Research Achievements (Sandwich Composite)

One-shot Sandwich Composite Co-curing

Co-curing manufacturing

Face Sheet Lay-up → Face Sheet Curing → Bonding of Face Sheet and Core → Curing → Post-processing

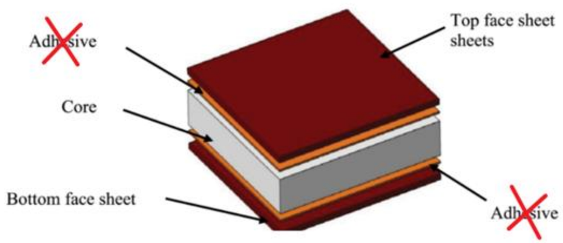
Simultaneous Lay-up of Face Sheet and Core → Co-Curing → Post-processing

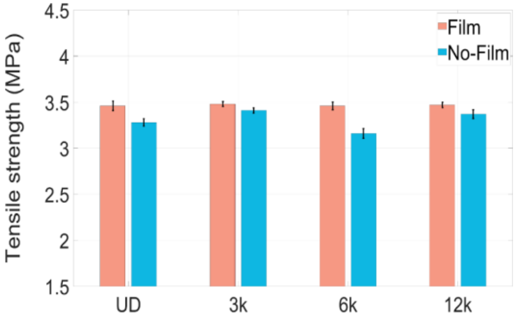
Reduction in process time by eliminating the bonding process

Objectives

1. Process time reduction
2. Manufacturing cost reduction
3. Weight reduction

Adhesive film removal / testing



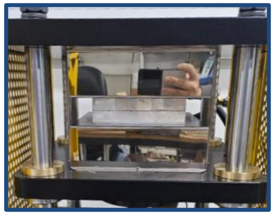


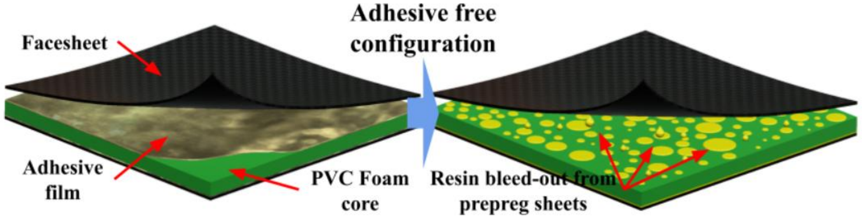
Maintaining proper bonding strength even after removing the adhesive film

Research Achievements (Sandwich Composite)

One-shot Sandwich Composite Co-curing

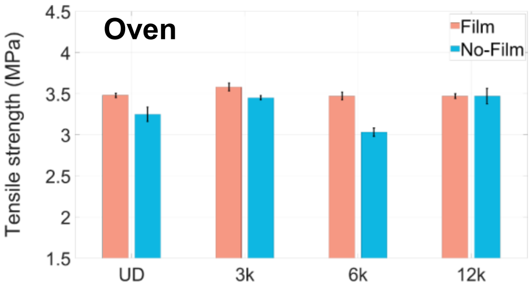
Proposed Method

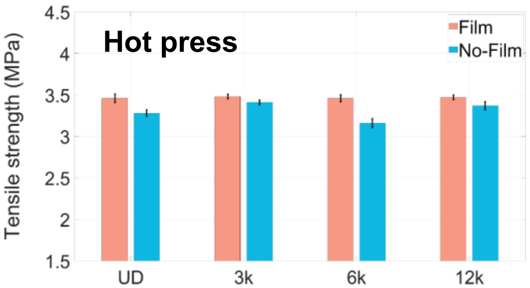




Testing and Results

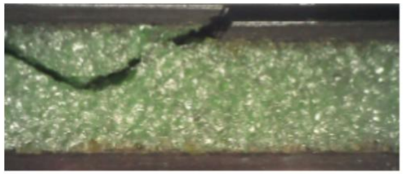
▶ **The proposed co-curing method successfully manufactured sandwich composites.**



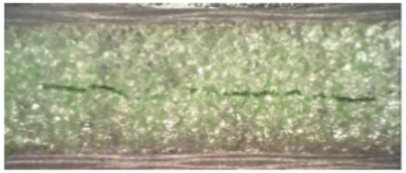


Specimen	OVEN	
	Film usage	Failure Mode
UD	X	Skin failure and core failure (2) Core failure and adhesive failure (3)
3K	X	Core failure (5)
6K	X	Core failure and adhesive failure (5)
12K	X	Core failure (5)
UD	O	Core failure (5)
3K	O	Core failure (5)
6K	O	Core failure (5)
12K	O	Core failure (5)

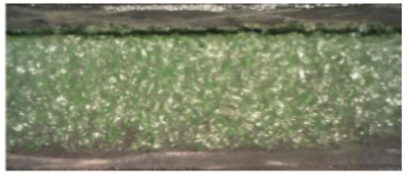
Specimen	Hot - press	
	Film usage	Failure Mode
UD	X	Skin failure and core failure (1) Core failure and adhesive failure (4)
3K	X	Core failure (5)
6K	X	Core failure and adhesive failure (5)
12K	X	Core failure (5)
UD	O	Core failure (5)
3K	O	Core failure (5)
6K	O	Core failure (5)
12K	O	Core failure (5)



Skin and core failure



Core failure

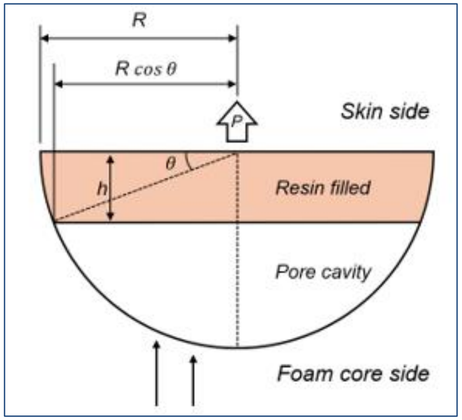


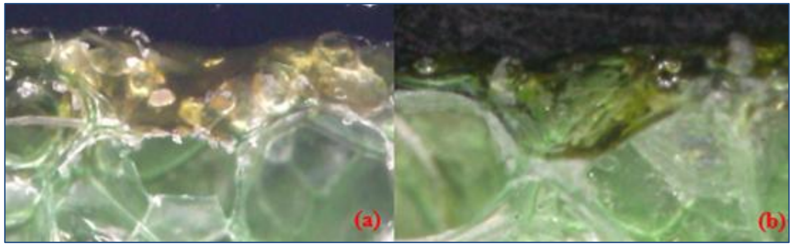
Core and adhesive failure

Research Achievements (Sandwich Composite)

One-shot Sandwich Composite Co-curing

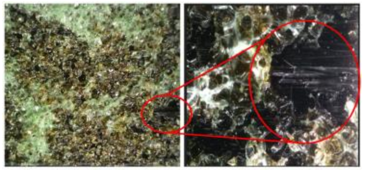
Key Technology



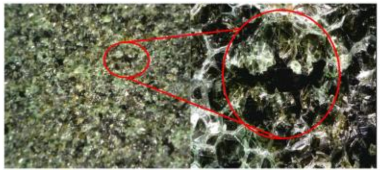


Left : Hemispherical-pore infiltration model for pressure-driven resin flow.

Right : Optical comparison of NF specimens: (a) well-filled, (b) poorly filled.



UD



6K

- **Understanding the resin flow into the core is the key feature to optimize the manufacturing process.**
- The amount of resin impregnation to the foam core is directly related to the joining strength betwee the skin and the core.

Impregnated depth: $h = R \sin\theta$

Efficient area for bonding: $A_{efficient} = \pi\,\{R^2 - (R\cos\theta)^2\} = \pi\,h^2$

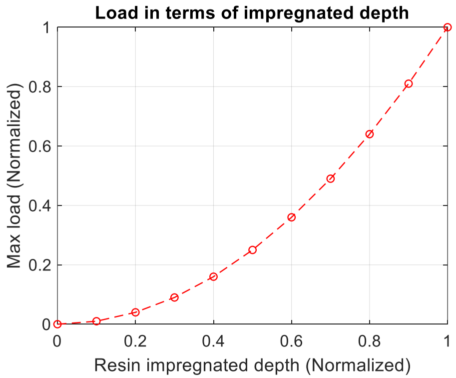
Normal joining strength of the adhesive: $\sigma_{joining} = \frac{P}{A_{efficient}}$

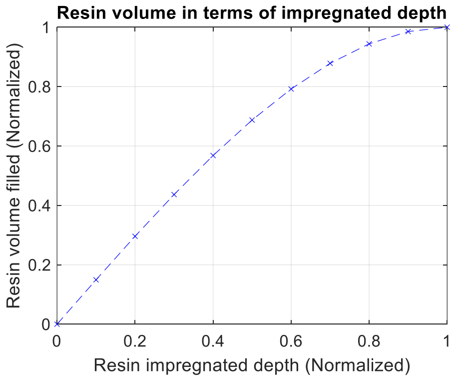
Maximum load: $P = \sigma_{joining} \times A_{efficient}$

Pore cavity volume: $V_{Pore} = \frac{\pi}{3}\,\{(R-h)2 \times (3R - (R-h))\}$

Volume filled: $V_{Filled} = \frac{2\pi}{3}\,R^3 - V_{Pore}$

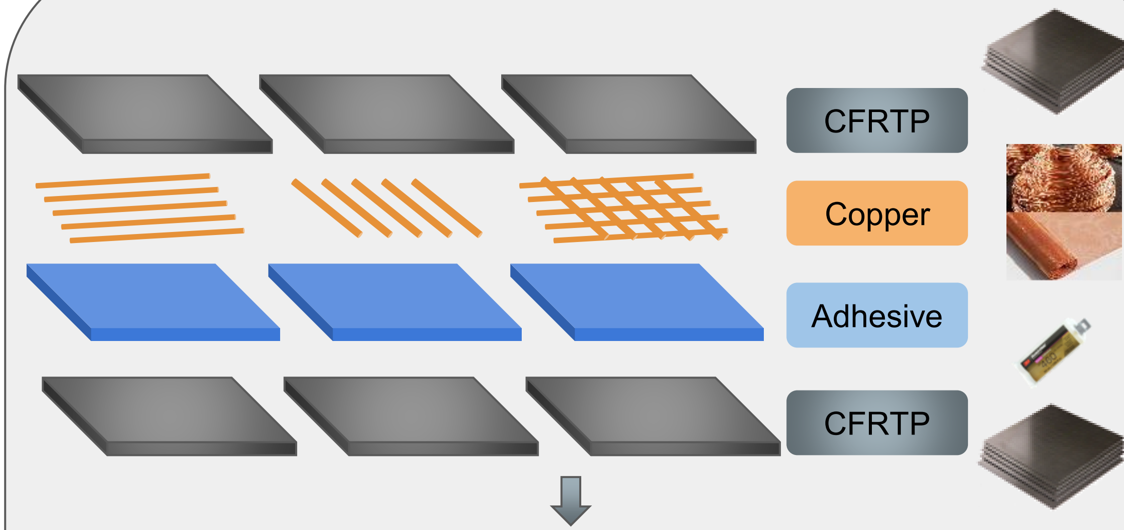
Viscosity and velocity: $\tau_{yx} = \mu \cdot \frac{du}{dy}$ (Newton's law of viscosity)



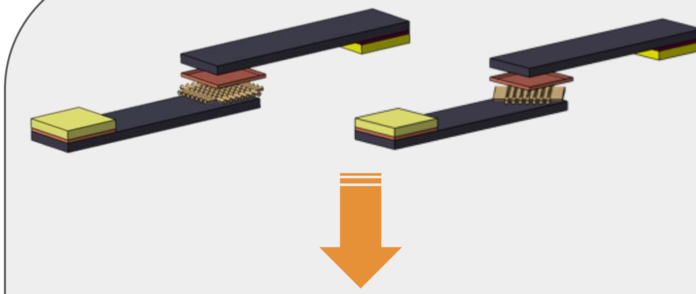


Research Achievements (Joining)

Fastener-free Joining



- The CFRTP is polished with sandpaper.
- The polished surface is cleansed with acetone.
- The cleansed CFRP is cured in high-temperature vacuum environment.

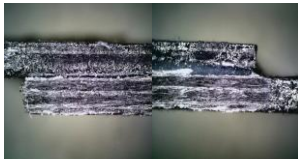


Research Features:

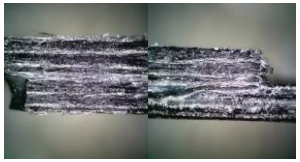
- High strength
- High conductivity
- Lightweight

Key Improvements:

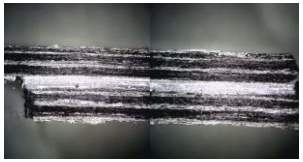
- Copper mesh reinforces joining
- Lightweightness with functional and structural components



Adhesive



Adhesive & oven



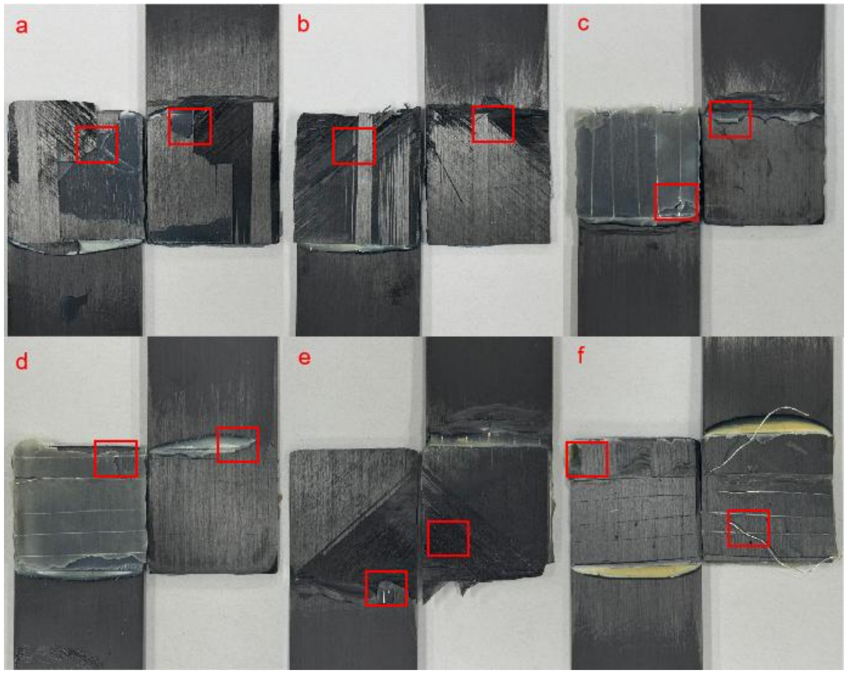
Adhesive wire & oven (long)

- **CFRTPs were joined with copper wire** (or mesh) **and adhesive.**
- The copper material reinforced the joining strengths between CFRTPs.

Research Achievements (Joining)

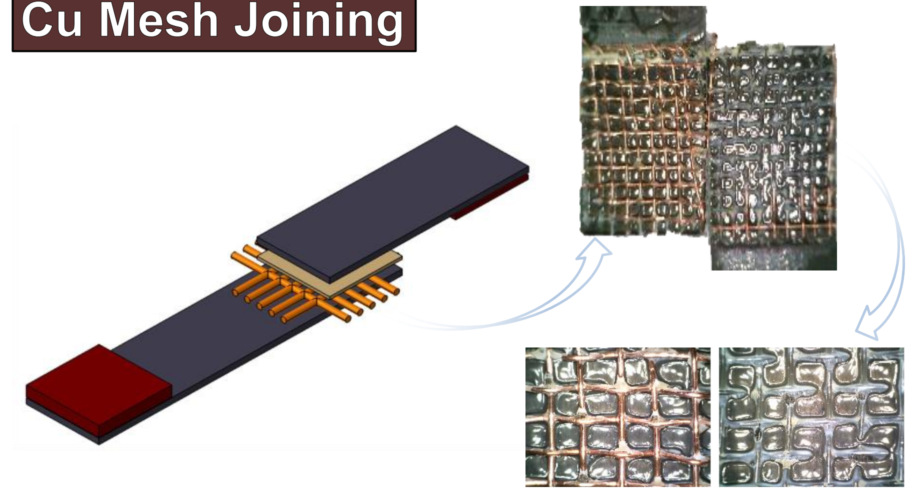
Fastener-free Joining

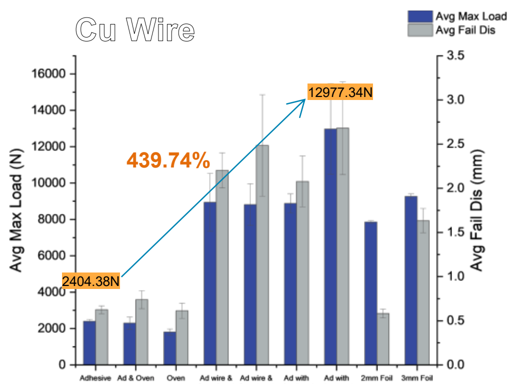
Cu Wire Joining

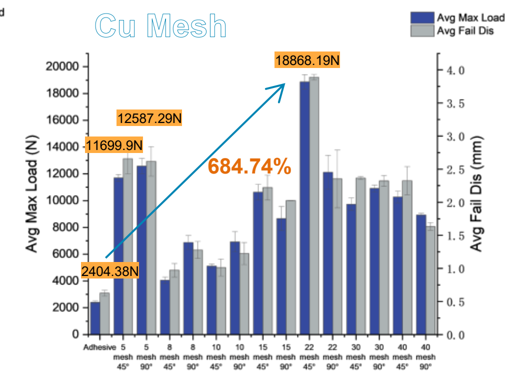


a. Cohesive failure b. Substrate failure c. Adhesive failure
d. Mixed failure e. Delamination f. Mixed failure

Cu Mesh Joining





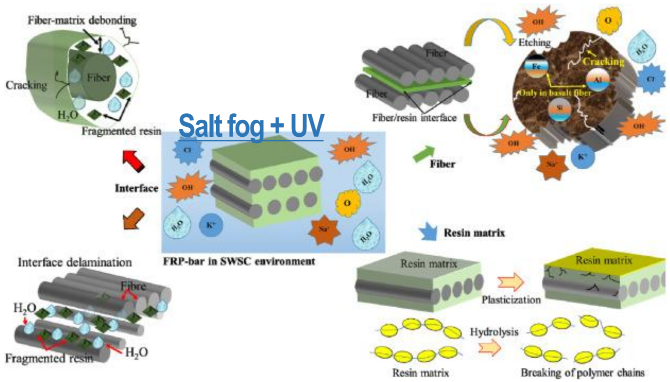


- The proposed copper aided joining showed superior joining strengths.
- The copper materials sustained the structural loads at the joining interface.
- **The proposed joining method represented 684.74% higher joining strength.**

Research Achievements (Non-destructive Evaluation)

Ultrasonic Non-destructive Testing

Durability of C/GFRPs

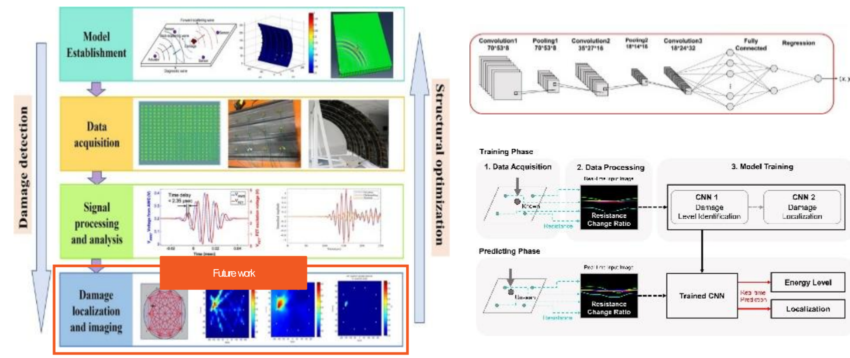


- FRP degratation mechanism diagram in sea water

UT (MHz) Active system (Pulse)	Monitoring failures
AE (kHz) Passive system (Event)	Requires external loading

Frequency

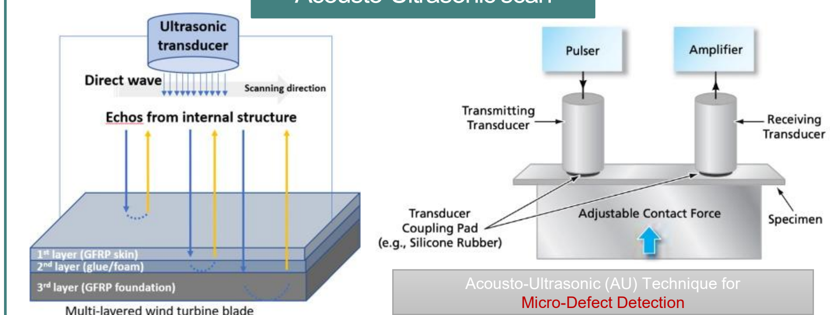
Evaluate / Model / Estimate the Structural Endurance



- Real time FFT signal processing using Simulink
- Modeling for remaining useful lifetime using CNN
- Optimized image processing for NDE systems

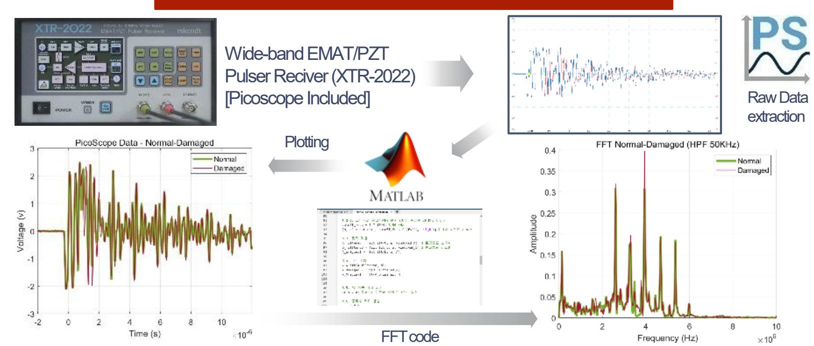
Scan and Analysis

Acousto-Ultrasonic scan



- Synergistic combination of AE and UT in non-destructive evaluation

Analysis



Research Achievements (Non-destructive Evaluation)

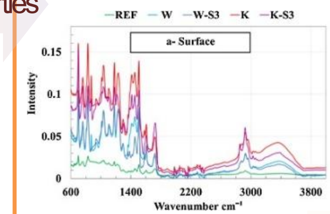
Ultrasonic Non-destructive Testing

Original C matrix (by TDS)

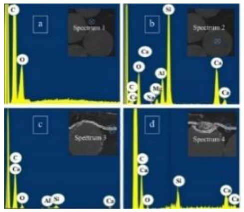
$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

Properties

Chemical feature



FTIR



SEM/EDX

Compare with

Compare with

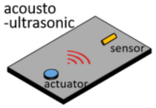
Inverse C matrix calculation (by wave velocity)

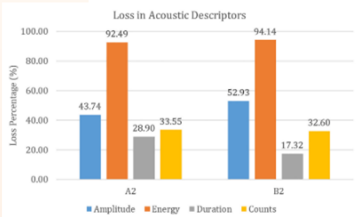
Component	Velocity type	Direction	
E_1	V_{S0}^{grp}	0°	In plane
E_2	V_{S0}^{grp}	90°	
E_3	V_L^{bulk}	z	Out of plane
G_{12}	V_{ASH1}^{grp}	in-plane 45°	
G_{13}	$V_{45,1-3}$ (SSH1/bulk)	0°–z	*Angular Incidence (mode selection)
G_{23}	$V_{45,2-3}$ (SSH1/bulk)	90°–z	

Data

Signal

Acousto - Ultrasonic Feature





Amplitude, Energy, Duration, Count

Degraded C matrix (by aging)

Molecular mechanics

Degrading coefficients

Finite Element Method
with updated C matrices

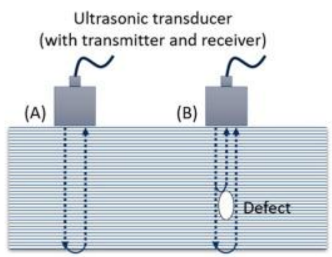
Advanced
Remaining Useful Lifetime

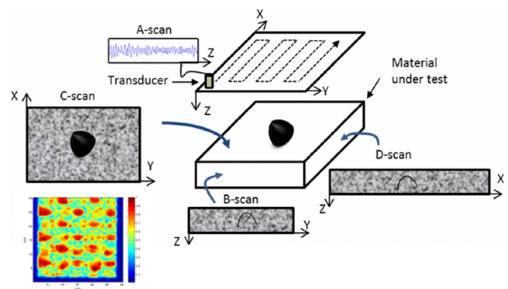
Research Achievements (Non-destructive Evaluation)

Ultrasonic Non-destructive Testing

Ultrasonic testing (Sole probe)

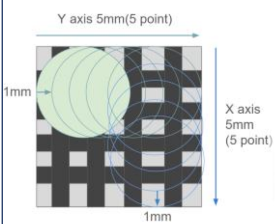
- Identifies defects by analyzing reflected echo signals
- Low resolution and easy to analyze
- Good for crack detection and imaging





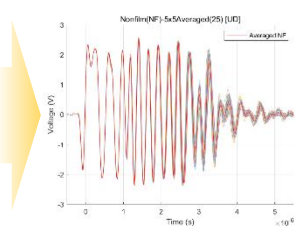
Normalizing A-scan signal

- 5x5(25) point array inspection

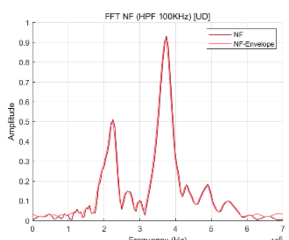


$$x_{\text{avg}}(t) = \frac{1}{N}\sum_{i=1}^{N} x_i(t)$$

N: The number of signal



Averaged waveform



FFT with RMS Envelope

Acousto-Ultrasonic testing (Paired probes)

- Detects internal micro-damage through stress wave energy
- High resolution, Hard to analyze
- Optimized for evaluating mechanical properties of materials

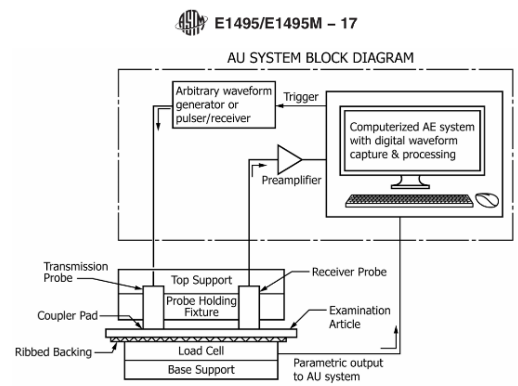
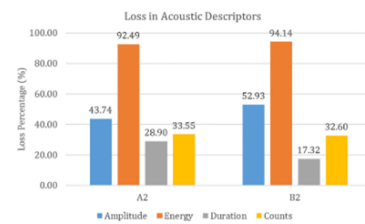


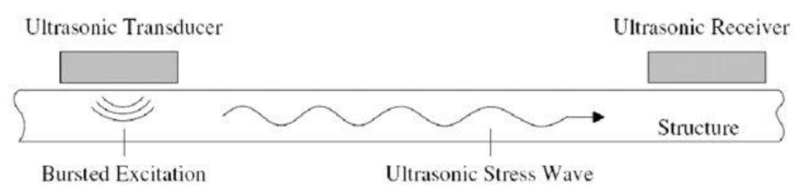
FIG. 2 Diagram of Apparatus and Instrumentation Used for Laboratory Application of AU

AU SWF
(Stress Wave Factor)

$$\text{Weighted ringdown} = \sum_i^p V_i(C_i - C_{i+1})$$

$$\text{Energy integral} = \int_{t_1}^{t_2} [v(t)]^2 dt$$

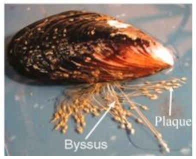




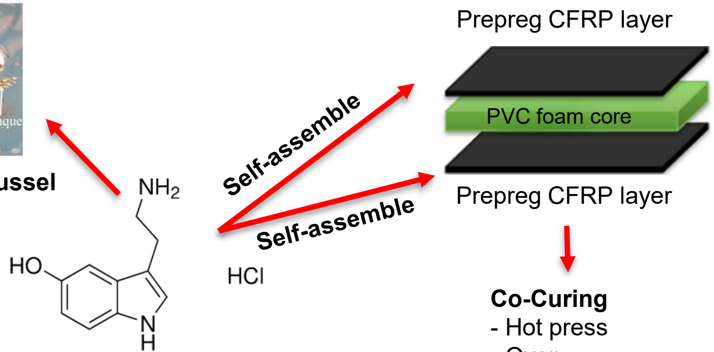
Research Achievements (Skin-Foamcore Self-assembly)

Polydopamine based Skin-Foamcore Joining

Introduction



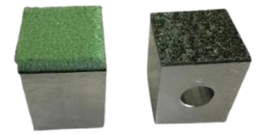
Discovered in **mussel**



Co-Curing
- Hot press
- Oven

Dopamine hydrochloride

Results



Delamination

Reason
- The epoxy dissolves in acid
- The epoxy absorbed moisture, reducing adhesion
- The immersed CFRP was dried at 60°C, and partial curing proceeded, resulting in lower adhesion

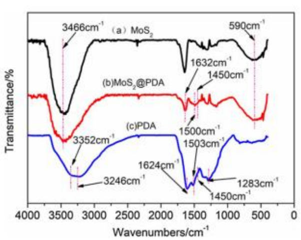
Plan

- Dry CFRP completely at room temperature
- Experiment with various conditions

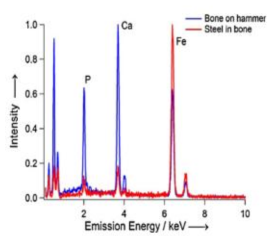
Analysis Method

Chemical reaction

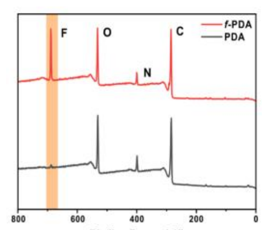
FTIR



SEM–EDX

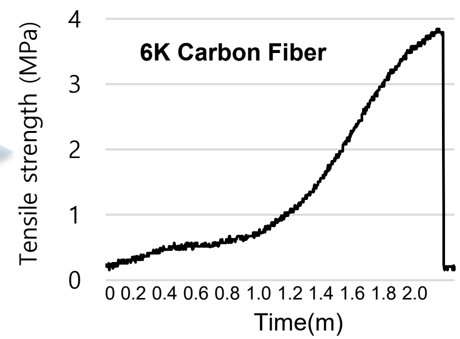


XPS



Tensile strength

Tensile testing(Z-dir)



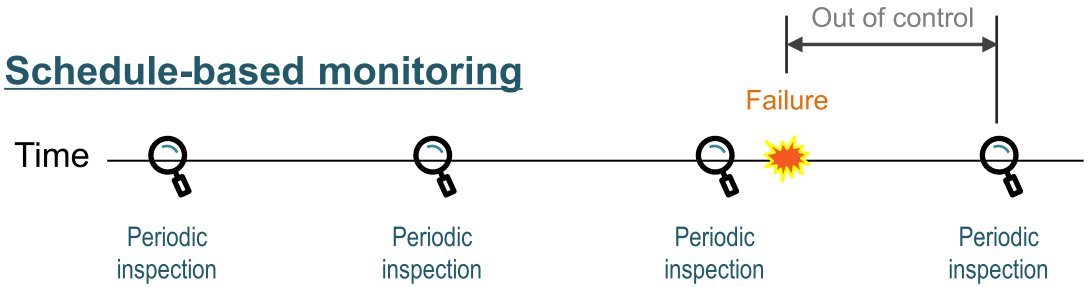
Structural Duty and Safety

- Structural Health Monitoring
  - **Safety, cost, and operating efficiency**
  - **Sensing element, method, and cost**
- Condition-based Monitoring
  - **Real-time, low cost, and easy installment**
  - **Inspection under in-service**

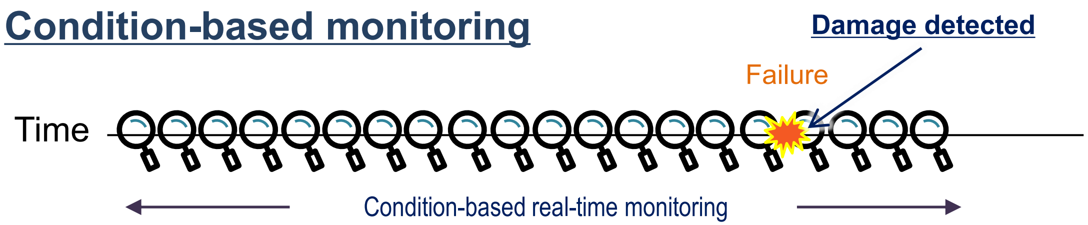
Aloha airlines aircraft failure (1988)

35W bridge collapse (2007)

Schedule-based monitoring

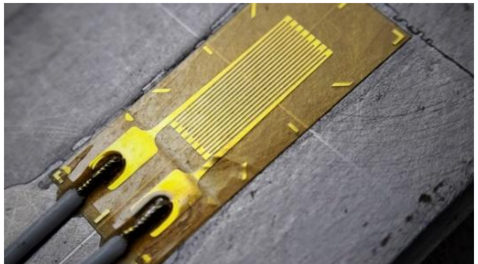


Condition-based monitoring

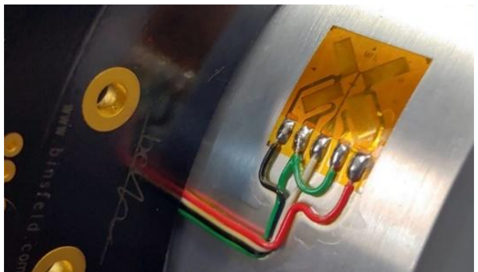


Structural Health Monitoring

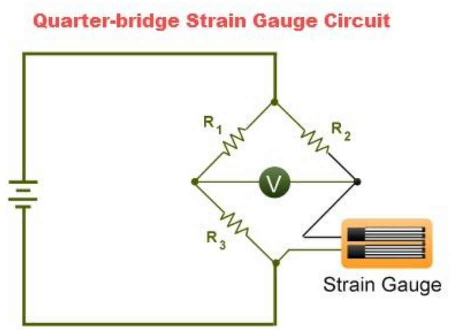
Strain gauge



Source: Michigan Scientific Corp.

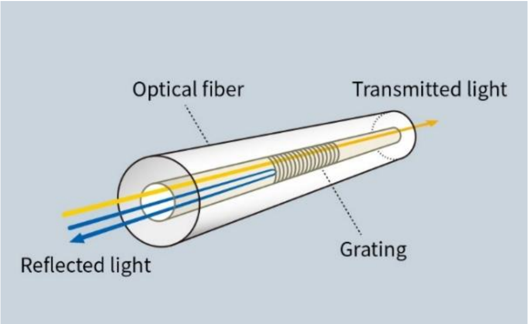


Source: Binsfeld

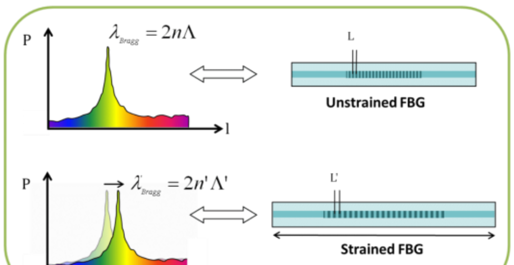


Fiber Bragg grating

Source: Fiber Transceiver Solution Corp.

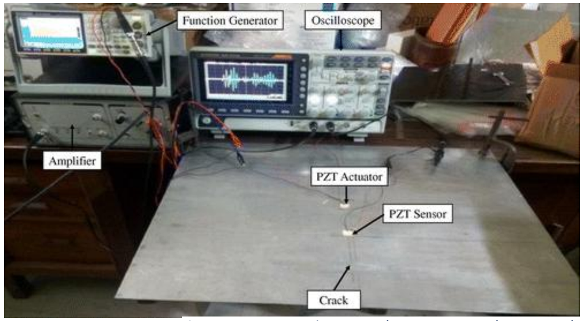


Source: Tatsuta Corp.

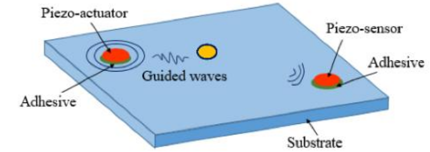


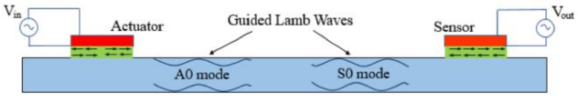
Source: FBG 센서의 기초, Naver blog

Lamb wave

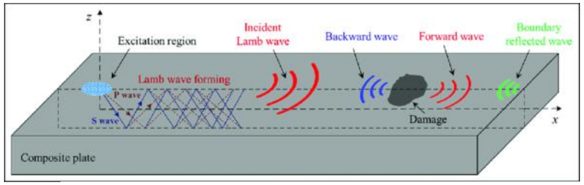


Source: Data-Driven Lamb-Wave-Based Approach to Detect Multiple Structural Damages, 2021





Source: Hole-Edge Corrosion Expansion Monitoring Based on Lamb Wave, 2020



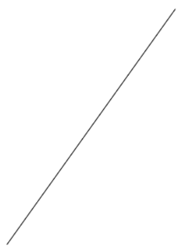
Source: Barely visible impact damage imaging using non-contact air-coupled transducer/laser Doppler vibrometer system, 2016

Research Achievements (Smart composites for SHM)

Electromechanical Analysis of CFRPs

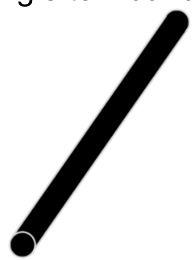
Overview

Ø 8 μm Carbon fiber monofilament



Gather 3000 filaments

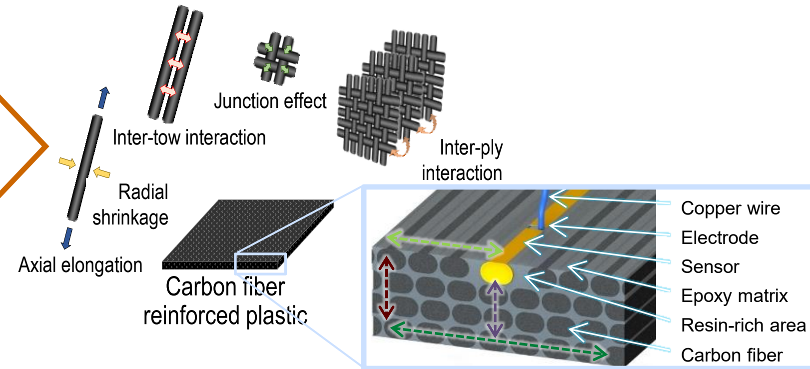
3K carbon fiber single tow bundle



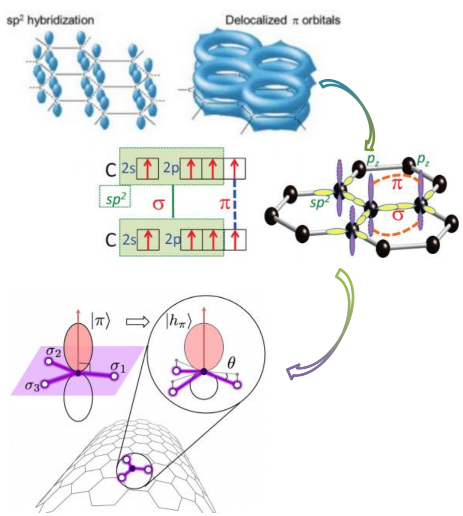
Composite

VARTM or hot-pressing

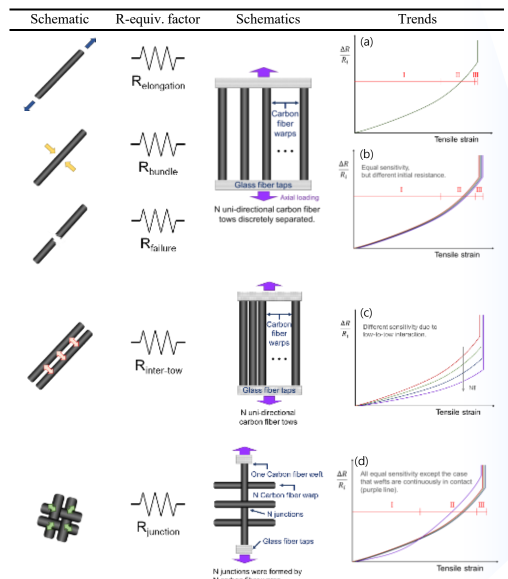
Composite with various electromechanical parameters

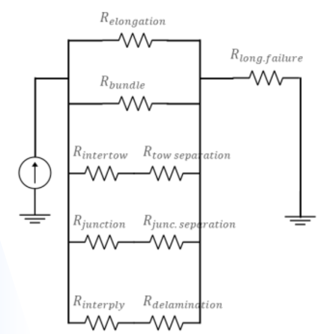


Change in π orbitals and electrical networks



Multi-scale treatment and electrically equivalent circuit modeling





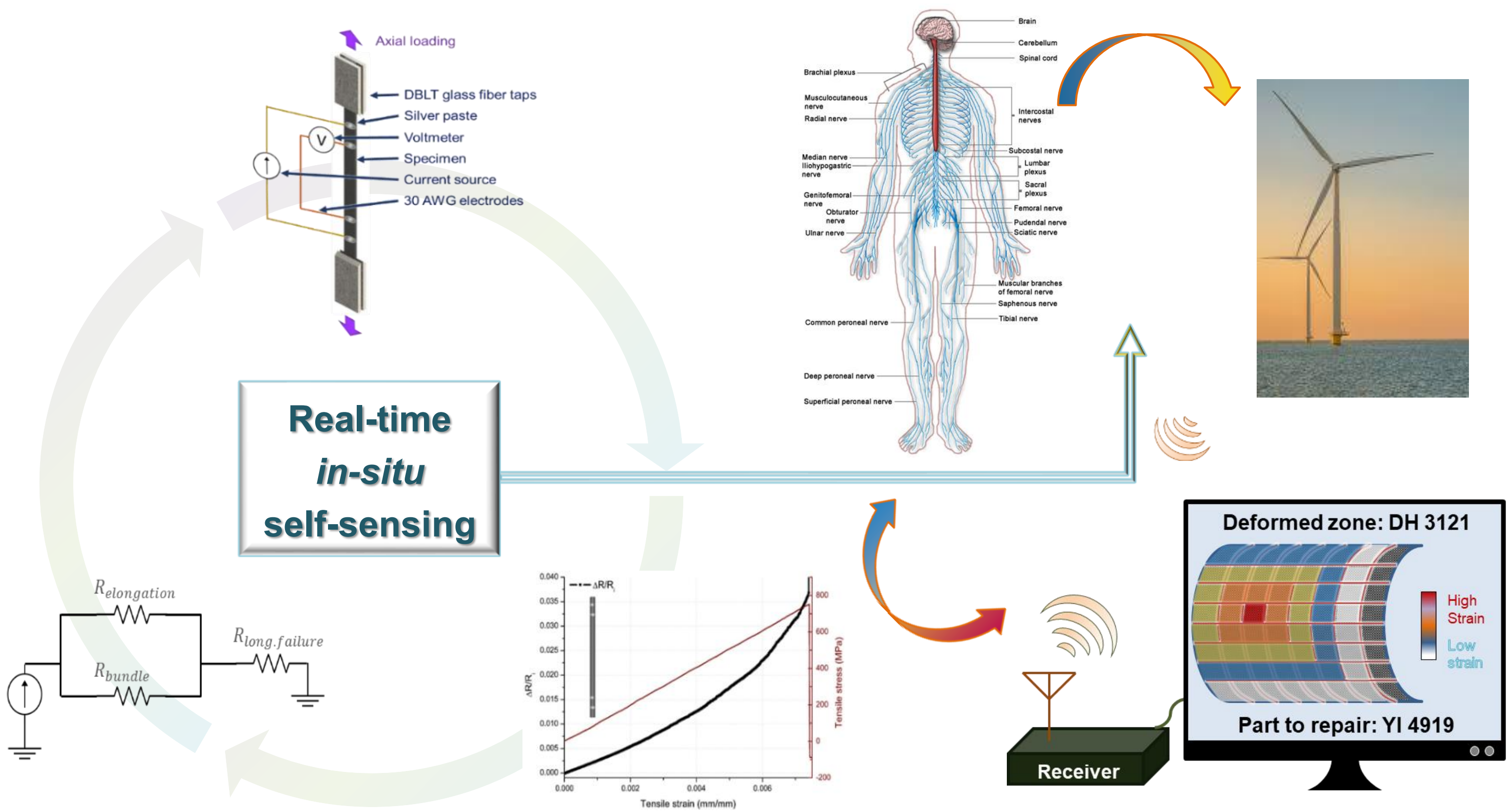
▶ **Elastic deformation**

↔ **Electrical resistance**

SHM: Structural Health Monitoring
VARTM: Vacuum Assisted Resin Transfer Molding

Research Achievements (Smart composites for SHM)

Research Objectives



- **Electromechanical behavior of CFRP enables self-sensing.**
- **<u>Smart CFRP is reliable with real-time self-sensing system.</u>**

M. McGugan and L. Mishnaevsky Jr., Coatings, 10 (2020) 1223

Research Achievements (Manufacturing monitoring)

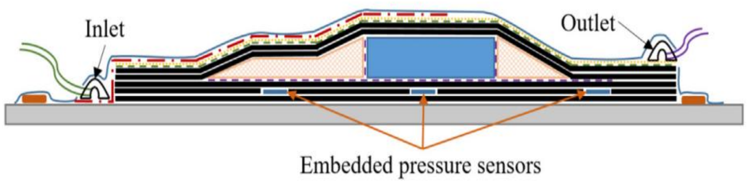
Monitoring CFRP Manufacturing

Motivation ▶ **CFRP manufacturing is high-cost, labor-intensive, and time-consuming.**

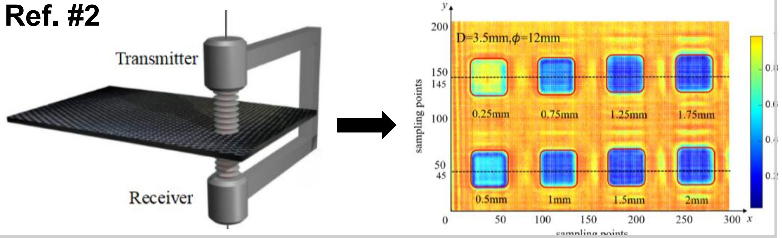
Limitations from the Literatures

1. **Embedded Sensor**
   - **Expensive, Possible of damage,**
   - **Cause of stress concentration.**
2. ***A posteriori* inspection system**
   - **Absence of real-time monitoring.**

Ref. #1

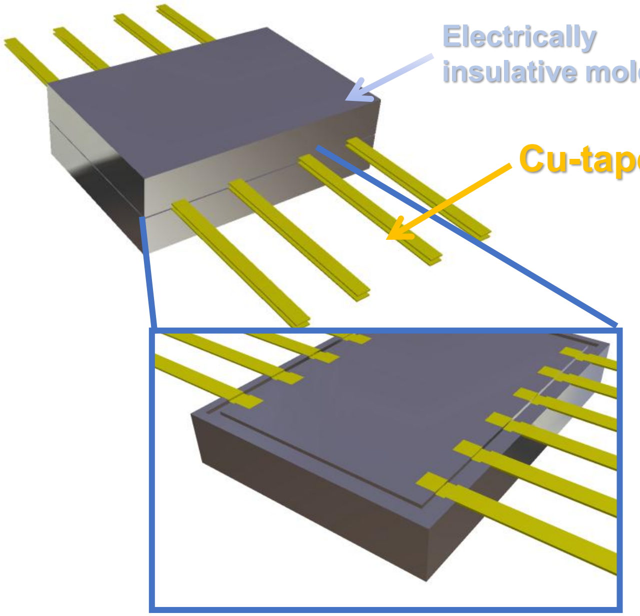


Ref. #2



Novelty and Originality

1. **Low cost**
2. **Simple installation**
3. **Real-time**



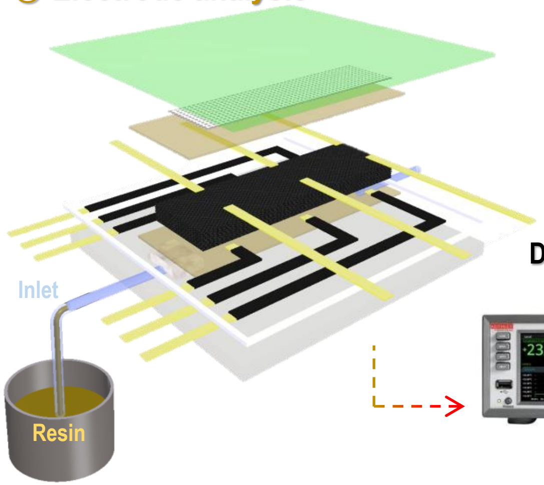
#1. A. Dimassi, *Materials Today : Proceedings*, (2021),140-8
#2. Chenchen Zhang et al., Ultrasonics, (2023), 106884

Research Achievements (Manufacturing monitoring)

Monitoring CFRP Manufacturing

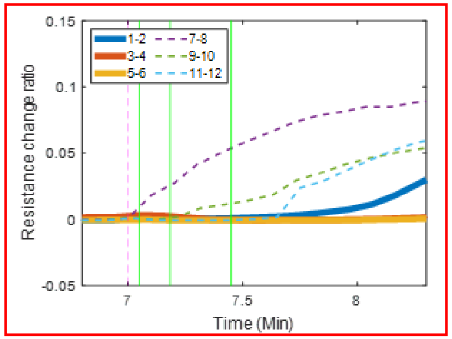
Overview

① Electrode analysis

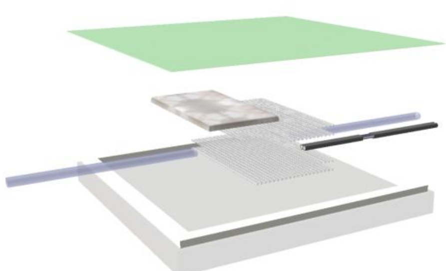


② Resin flow monitoring

DAQ 6510
(Multimeter)

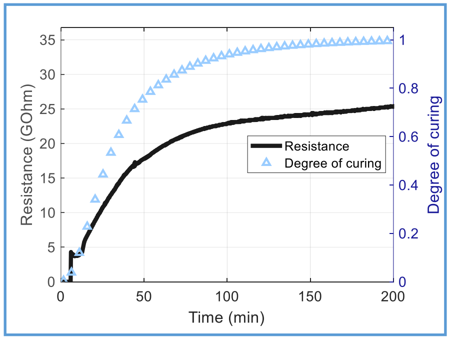


③ Resin curing



④ Resin curing monitoring

DAQ 6517B
(High-resistance multimeter)



① Electrode analysis

Electrode material:
Silver paste vs. Cu-tape

Pressure and contact resistance

② Resin flow monitoring

Electrical resistance changes

Resin front detection

Degree of impregnation (thickness)

③ Resin curing

In-mold resin reservoir system

Customized electrical probe

④ Resin curing monitoring

Differential scanning calorimetry (DSC)

Polymer crosslinking and electrical conductivity changes

Ultimately,

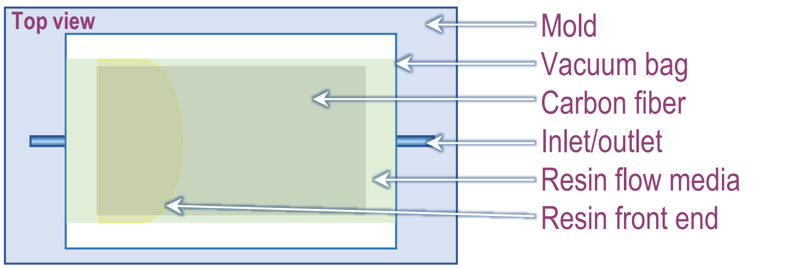
Real-time composite-manufacturing monitoring mold

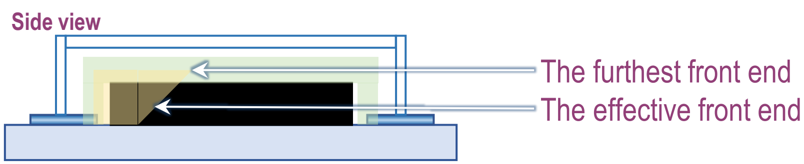
Detect resin impregnation and curing using electrical resistance

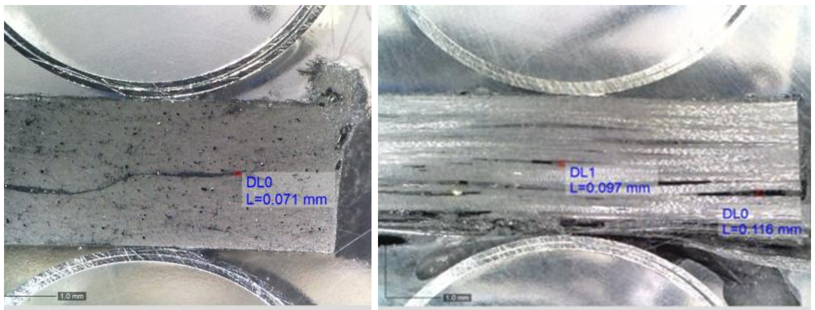
Research Achievements (Manufacturing monitoring)

Monitoring CFRP Manufacturing

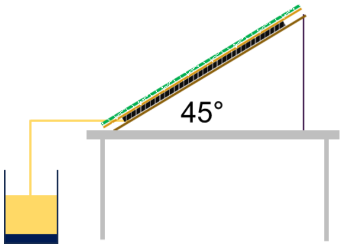
Experimental Analyses



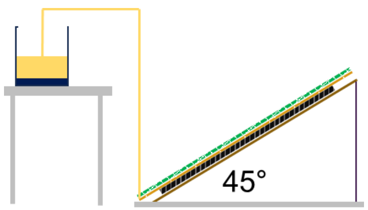


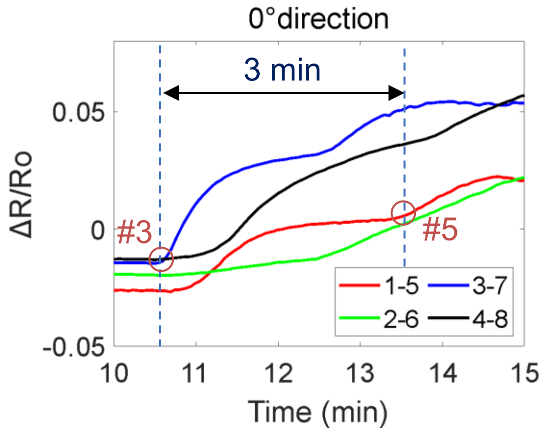


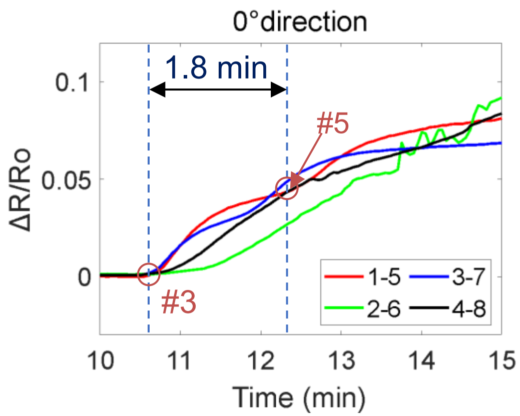
Poorly impregnated | Well impregnated



$$\frac{v^2}{2} + gz + \frac{p}{\rho} = \text{constant}$$





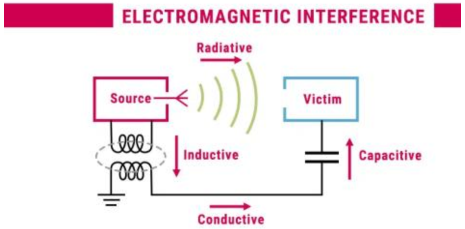


▶ **CFRP manufacturing considering Bernoulli's equation and void contents was investigated to improve the composite quality**: Time and void.

Thermal and Electromagnetic Effectiveness

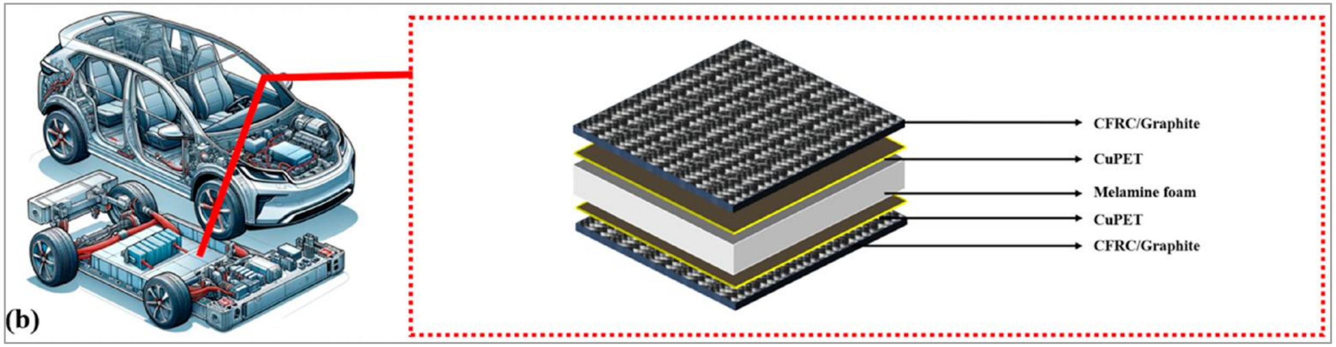
Electric Vehicle Communication Controller (EVCC)

EVCC is a device that communicates with charging stations on rechargeable electric vehicles.



➢ Key Functions of an EVCC

- **Communication Management**
  - The EVCC acts as a bridge, enabling seamless communication between the vehicle and the charging station.
- **Power Control**
  - It manages the flow of electricity, controlling voltage and current levels to ensure optimal and safe charging.
- **Charging Management**
  - The EVCC handles the overall charging process, including starting and stopping charging, and monitoring charging parameters.



Hu, Shi, et al. (2024). Electromagnetic interference (EMI) shielding and thermal management of sandwich-structured carbon fiber-reinforced composite (CFRC) for electric vehicle battery casings. Polymers, 16(16), 2291.

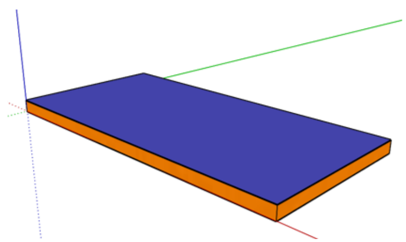
EVCC: Electric Vehicle Communication Controller

Research Achievements (Electromagnetic Interference)

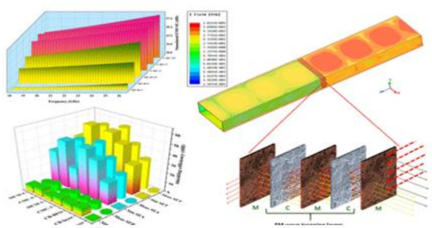
Thermal and Electromagnetic Effectiveness

[As-is]

Electromagnetic shielding performance verification



- Electromagnetic shieling performance according to the difference in thickness of the conductive layer

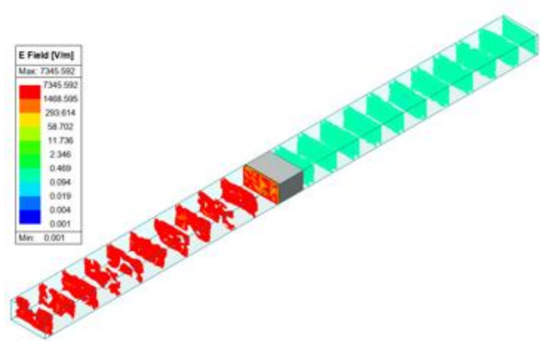


- Application of MG model to electromagnetic wave analysis of composite materials
- Shielding/absorption analysis

[Break-though]

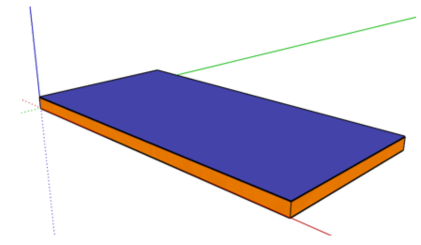
$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

- Analysis of electromagnetic shielding through extension of CLPT theory
- Developing an automated electromagnetic shielding analysis tool



- Electromagentic shielding analysis using Ansys HFSS, Twin Builder / Circuit Simulator, SIwave, CST studio

[To-be]



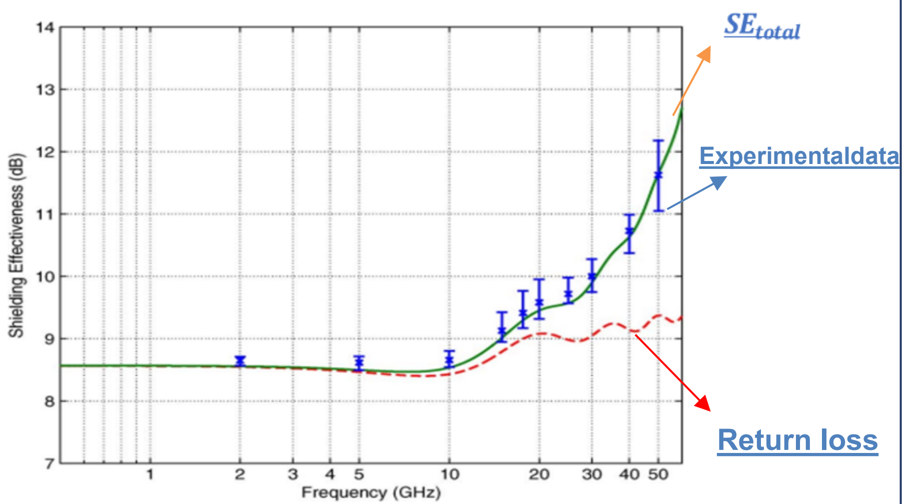
- Conductive layer with appropriate thickness
- Conductive layer material with high electromagnetic shielding performance efficiency
- Equivalent model for thermal and electromagnetic analysis with finite element analysis

EVCC: Electric Vehicle Communication Controller

Research Achievements (Electromagnetic Interference)

Thermal and Electromagnetic Effectiveness

Current method



- Results of measuring/simulating actual S-parameters

Theory

$$SE_{\text{total}}(f) = R(f) + A(f)$$

- **Return loss**

$$R(f) = 20\log_{10}\left|\Gamma(f)\right|, \quad \Gamma(f) = \frac{Z_{\text{mat}}(f) - Z_0}{Z_{\text{mat}}(f) + Z_0}$$

$$Z_{\text{mat}}(f) = \sqrt{\frac{\mu_0}{\varepsilon_0\,\varepsilon_{\text{eff}}(f)}}, \quad Z_0 \approx 377\ \Omega$$

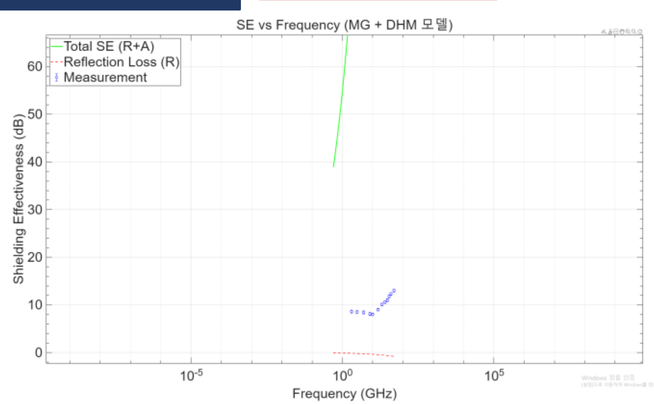
- **Absorption loss**

$$A(f) = 8.686\,\alpha(f)\,d, \quad \alpha(f) = \Re\{\gamma(f)\},$$

$$\gamma(f) = j\omega\sqrt{\mu_0\,\varepsilon_0\,\varepsilon_{\text{eff}}(f)}$$

MG + DHM model

Our achievement



$$\varepsilon_{\text{eff}} = \varepsilon_m \cdot \left(\frac{\varepsilon_f + 2\varepsilon_m + 2f(\varepsilon_f - \varepsilon_m)}{\varepsilon_f + 2\varepsilon_m - f(\varepsilon_f - \varepsilon_m)}\right)$$

- MG + DHM: Multiple reflections, phase delays, and wave guide modes are not considered
  - ➢ **Absorption loss increases explosively**
- S-parameters: Experimental errors, antenna beam patterns, and other real-world effects
  - ➢ **Slow changes between 8-13 dB**

EVCC: Electric Vehicle Communication Controller

Contents

Future Plan (Long term)

Composite Manufacturing

Smart optimization

GFRTP Manufacture

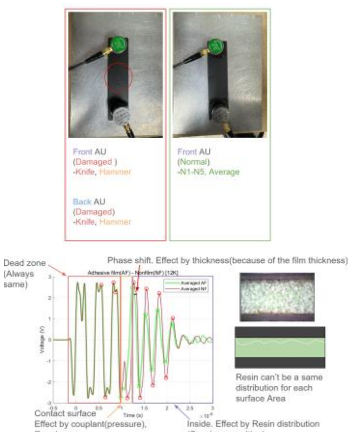
Comparative analysis of GFRTP manufacturing under different temperature, pressure, time, stacking angle, and vacuum conditions.

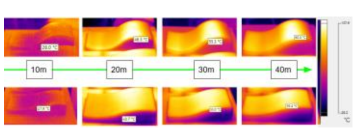
Microstructure Analysis

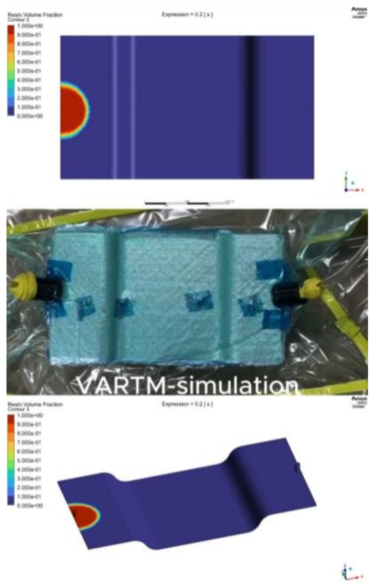
Cross-sectional analysis of the GFRTPs using Python.

ANN Prediction

To develop ANN to predict the optimal conditions of GFRTP manufacturing.

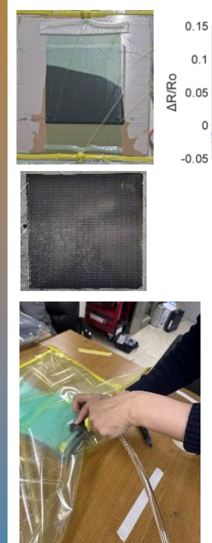


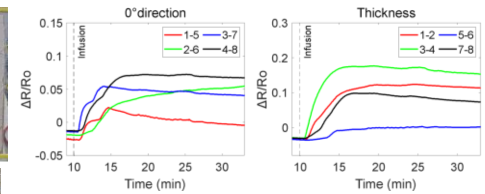




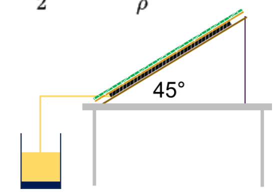
Smart Composites

Functionalization

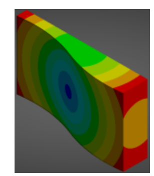




$$\frac{v^2}{2} + gz + \frac{p}{\rho} = \text{constant}$$



$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x - \alpha_x \Delta T \\ \epsilon_y - \alpha_y \Delta T \\ \gamma_{xy} - \alpha_{xy} \Delta T \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

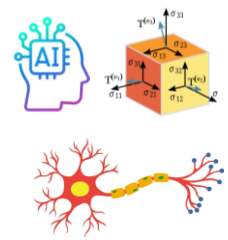


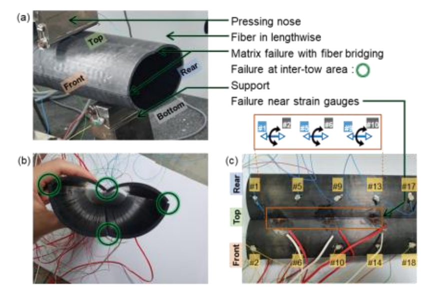
$$\epsilon = \frac{L_T - L_0}{L_0} \rightarrow \alpha_i = \frac{\epsilon_i}{\Delta T} = \frac{\frac{\Delta L_i}{L_{0,i}}}{\Delta T} \rightarrow \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \end{bmatrix} = \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} \Delta T$$

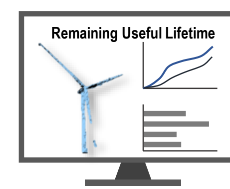
: 변형률 측정 / :열팽창 계수 정의 / : 열팽창 Tensor 정의

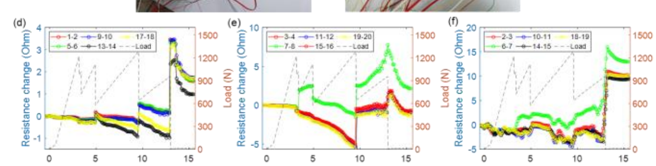
$$\{\varepsilon\} = \{\varepsilon^0\} + z \cdot \{\kappa\} \rightarrow \{\varepsilon\} = \{\varepsilon_T\} = \boldsymbol{\alpha} \cdot \Delta T$$

: CLPT 복합재 적층된 변형률 / : 열팽창만 있는 경우 (가정)









Make Smart Composites, Intelligently

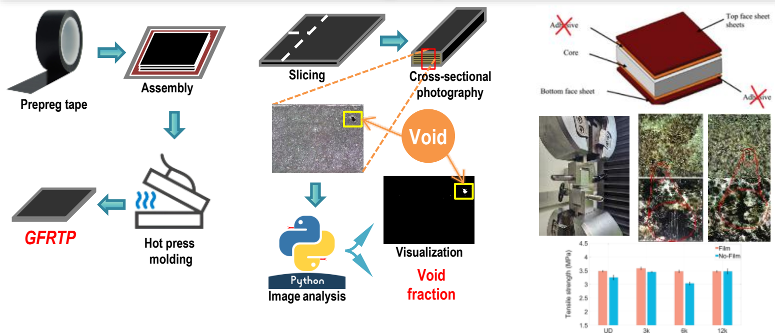
Contents

Summary

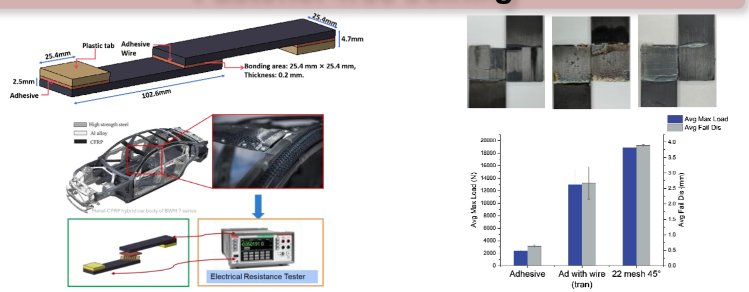
Manufacturing and Condition-based Structural Health Monitoring of CFRPs

Composite Manufacturing
Optimizing & Joining

Manufacturing Optimization

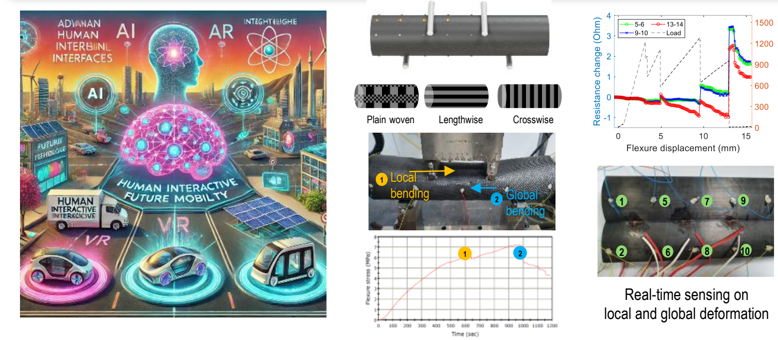


Fastener-free Joining

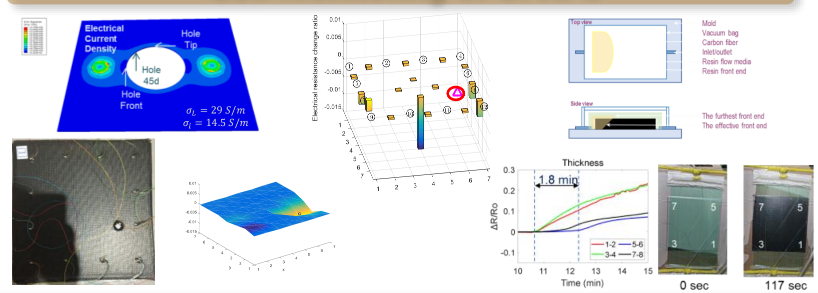


Smart Composites
Functionalizing

Functional Composites



Self-monitoring of CFRPs



Make Smart Composites, Intelligently

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Thank you for listening

Make Smart Composites, Intelligently

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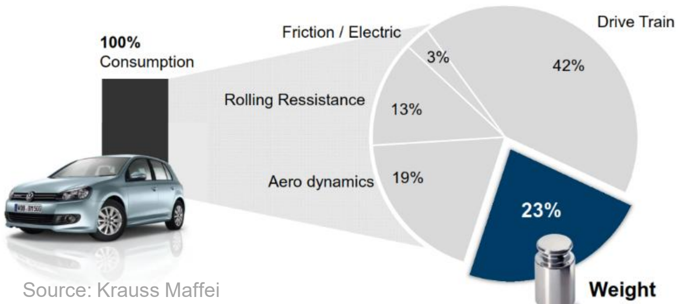
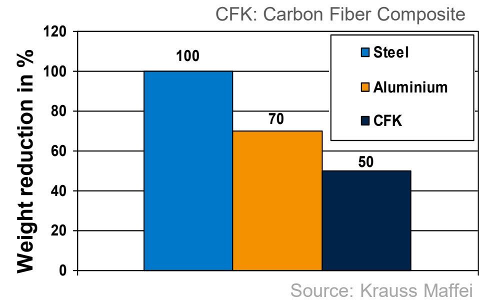
Contents

BeSTIS: Be Smart, Then It's Safe

Trend





환경, 에너지 효율 기반 경량화 ↑ 탄소섬유 복합재에 대한 수요 ↑ 고비용 복합재

Social Needs

복합재 채택 불가피

고비용 복합재 구조물의 구조 건전성 평가 필요

복합재 유지 및 보수 기술 필요

복합재 End-product 의 임무 수행 평가 필요

BeSTIS (베스티스)

Be Smart, Then It's Safe

Founder's Motto

이 세상을 이롭게 하자

편하게 살자

행복하게 살자

안전 돈 시간

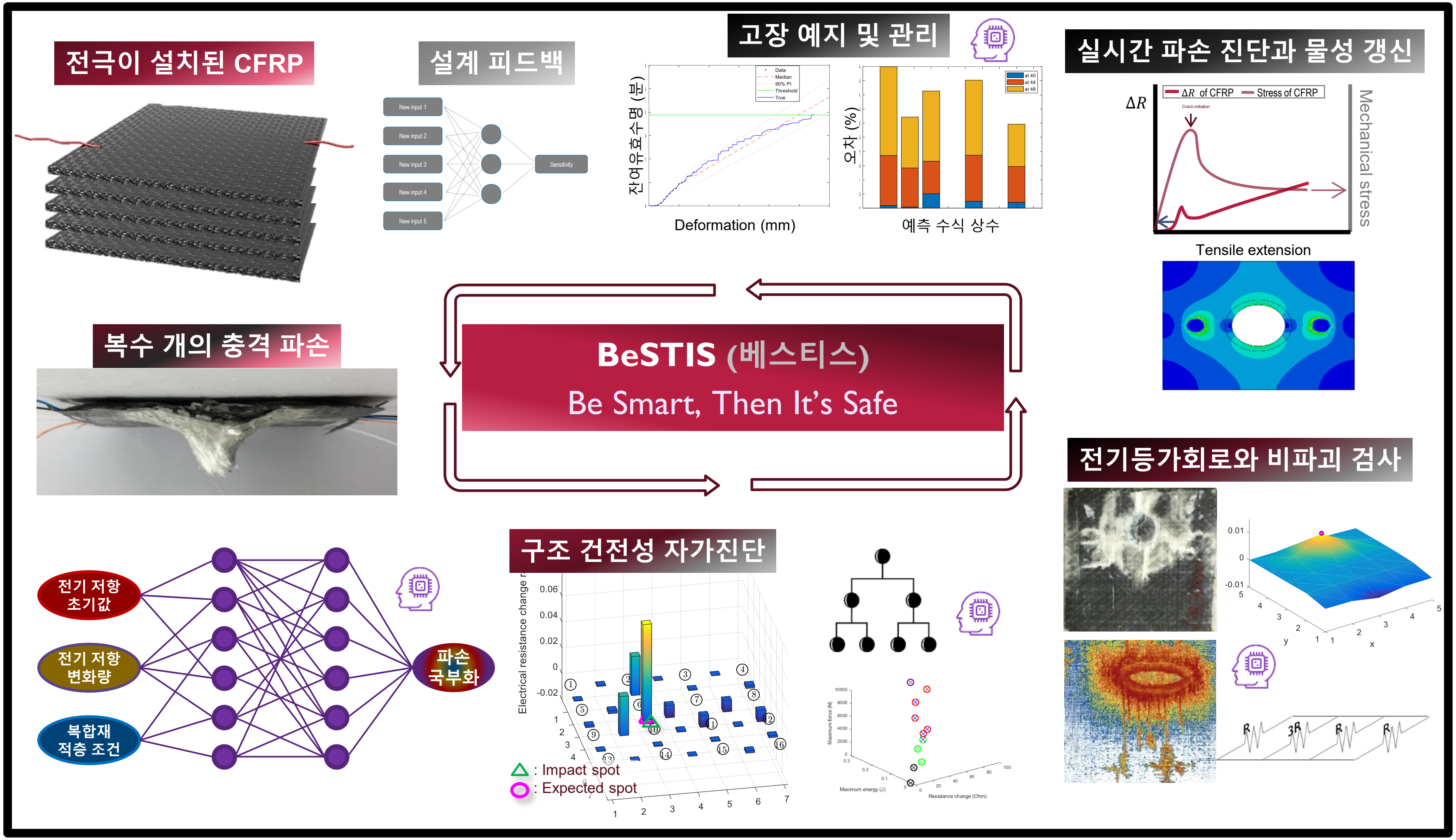
탄소섬유강화 플라스틱

(Carbon fiber reinforced plastic)

Composite

BeSTIS: Be Smart, Then It's Safe

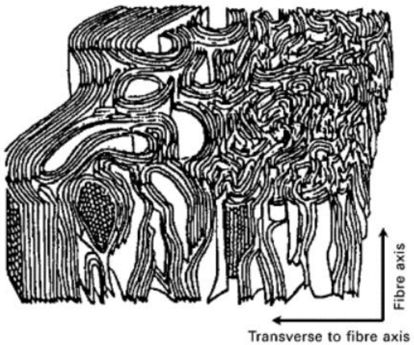
탄소섬유 복합재의 구조 건전성 진단, 고장 예지 및 관리, 설계 → 종합 솔루션 제공



Literature Review (Self-sensing)

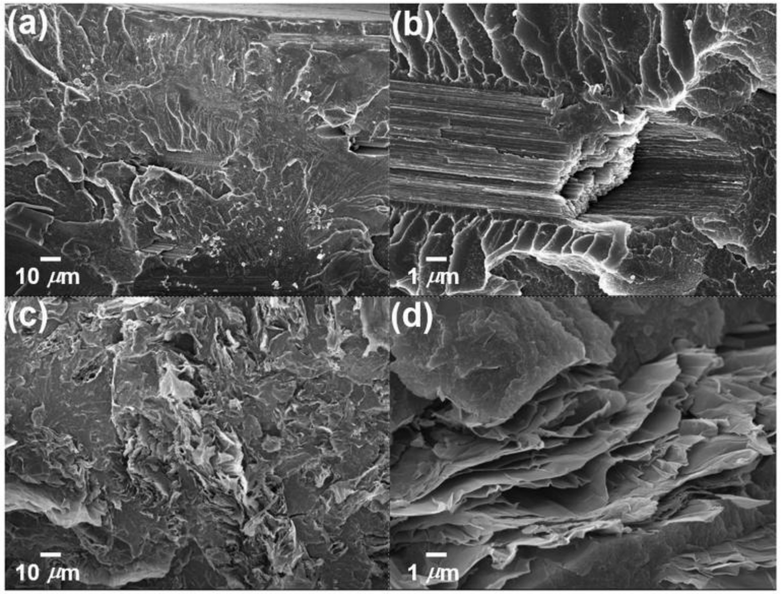
Carbon Fiber

Ref. #1

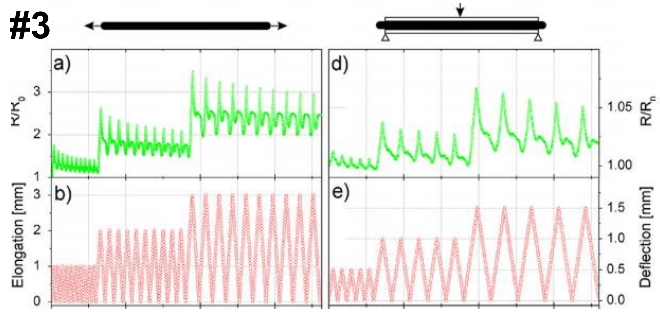


Carbon fiber = Graphite layers

Ref. #2

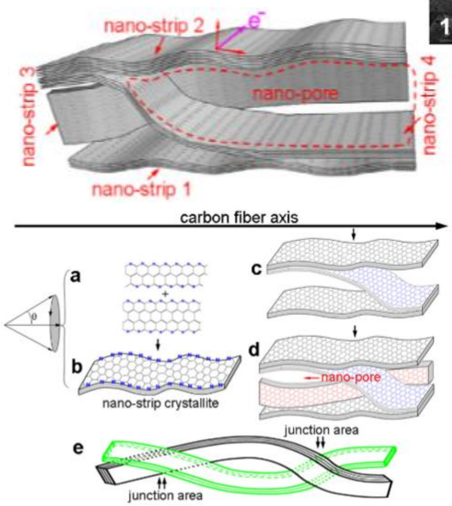


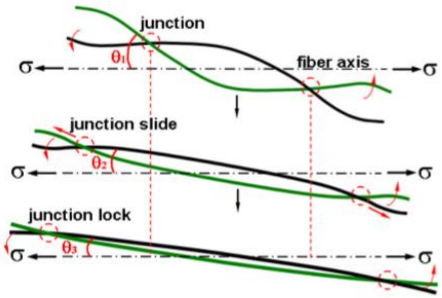
Ref. #3



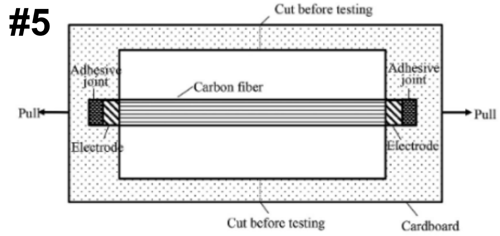
Change in a graphite crystallite due to mechanical loading changes electrical resistance

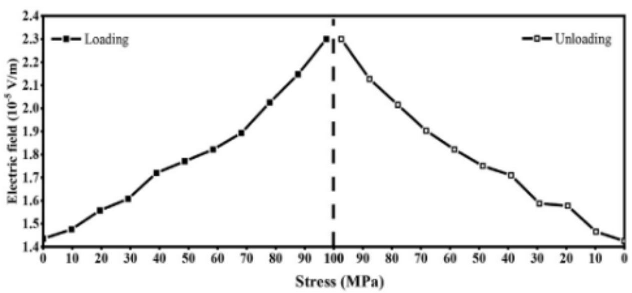
Ref. #4





Ref. #5





#1. S. C. Bennett and D. J. Johnston. Proceed. 5th London Carbon and Graphite Confer. 1 (1978) 377-86
#2. M. Lee *et al*. Scientific Reports. 5 (2015)11707
#3. S. Cravanzola et al. Carbon 62 (2013) 270-77
#4. G. Zhou, J. -H. Byun *et al.* Carbon. 76 (2014) 232-39
#5. X. Xi and D. D. L. Chung. Carbon. 145 (2019) 452-61

Machine Learning

Machine Learning for Self-sensing

$$f_X(x|Y=y) \sim N(\mu,\sigma^2) = \frac{1}{\sqrt{2\pi}\sigma} exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

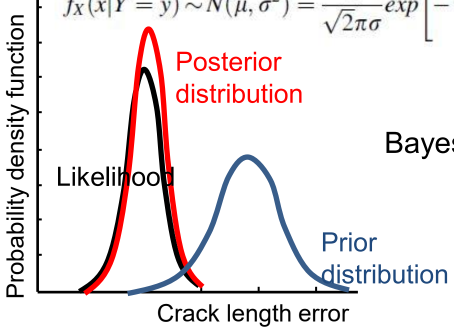
X : Uncertainty variable

Y : Measured data

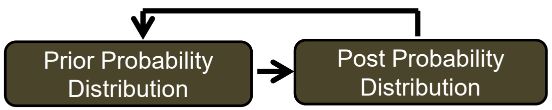
$$f_X(x|Y=y) = \frac{f_Y(y|X=x)f_X(x)}{f_Y(y)}$$

$$f_Y(y|X=x) = N(y,\sigma_y^2)$$

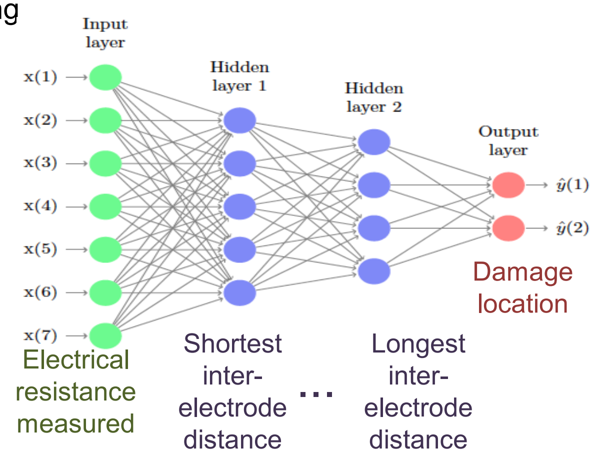
$$f_X(x) = N(\mu_0,\sigma_0^2)$$

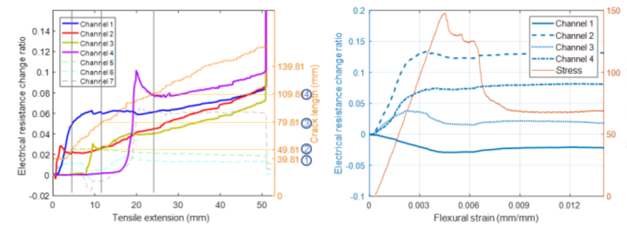


Bayesian learning



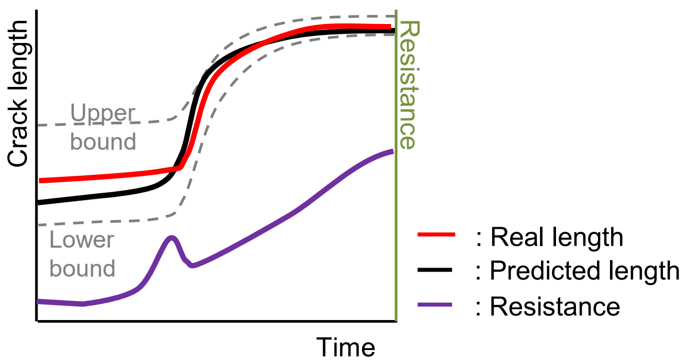
$$p(\mathbf{D}|\mathbf{w}) = \prod_{i=1}^{N} p(y_i|\mathbf{x},\mathbf{w}) = \prod_{i=1}^{N}(2\pi/b)^{-\frac{1}{2}}\exp\left[-\frac{b}{2}\{y_i - f(x_i,\mathbf{w})\}^2\right]$$

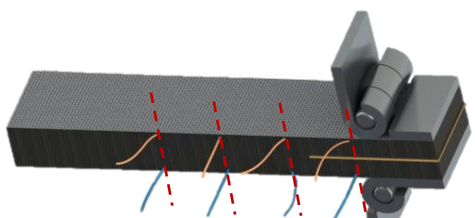




Training data

Guideline for iteration





Calibration at each electrode set

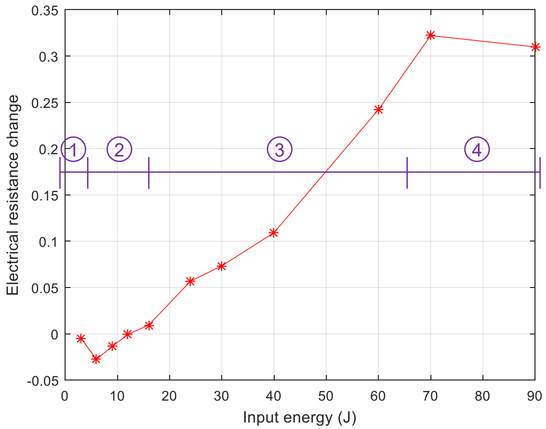
$$C(w,b) \equiv \frac{1}{2n}\sum_x \|y(x) - a\|^2$$

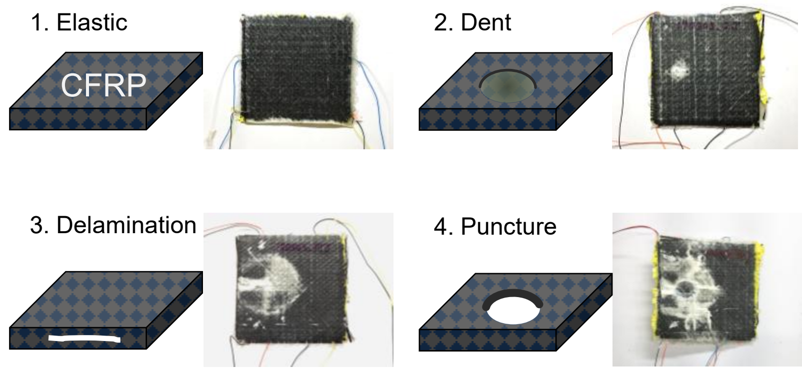
Cost function in backpropagation

AI (Artificial Intelligence) can simplify the self-sensing algorithm.

AI: Artificial intelligence

Machine Learning

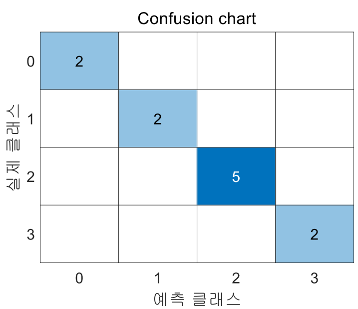




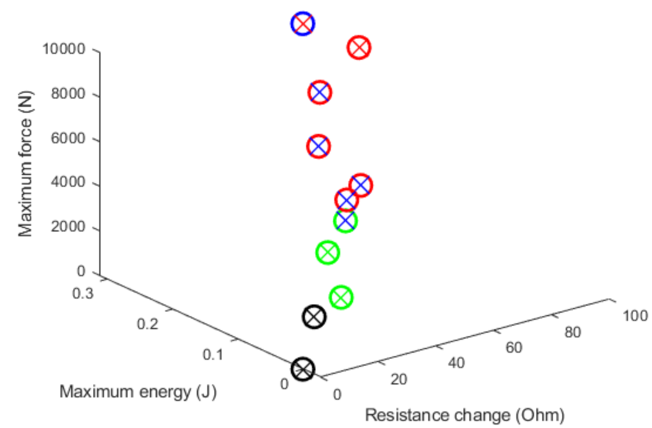
Damage Severity Analysis by Classification

CFRP: Carbon Fiber Reinforced Plastic
ML: Machine Learning
R: Electrical Resistance
E: Energy
F: Force

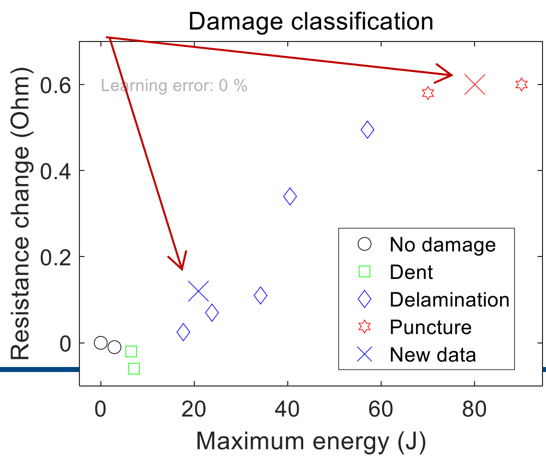
Actual data: Damage severity analysis of CFRPs

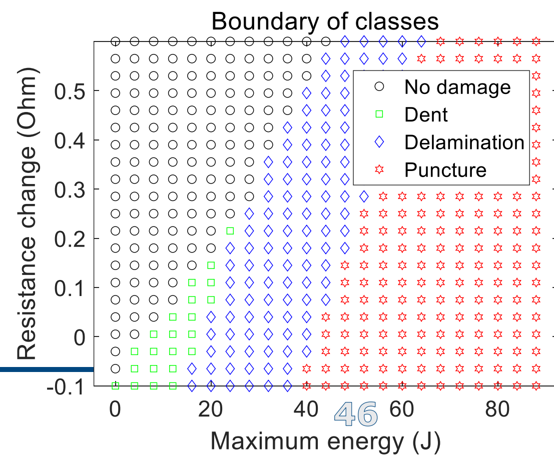


Input: Experimental data (R and E)
Tool: Classification by MATLAB
Output: Discriminate classes



ML: Classification of damage severity





Advanced ML: Fuzzy Clustering Method (FCM)

Input: Experimental data (R, E, F)
Tool: FCM by MATLAB
Output: Discriminate classes