The Influence of Tape Geometry on the Mechanical Performance of Bolted CFRTP-SMC Joints

No. 1246

(Composites Behaviour & Life Cycle Performance - Mechanics of composites)

X. Tong, L. Meng , Y. Wan and J. Takahashi

Department of Systems Innovation
The University of Tokyo, Japan

Content

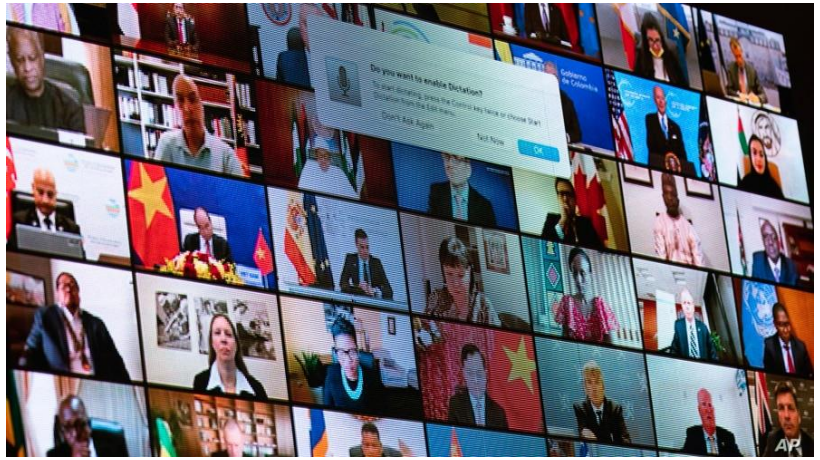
Introduction

Research content and experiments

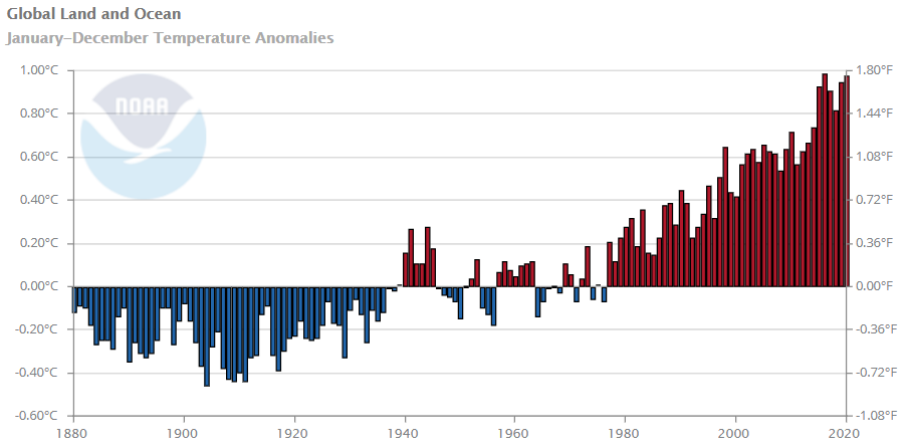
Results and analysis

Conclusions

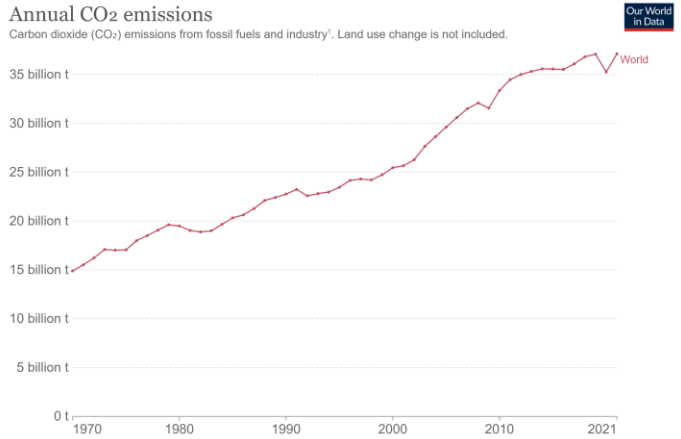
Background



Virtual climate summit 2021



History of global surface temperature



Global annual CO_2 emissions

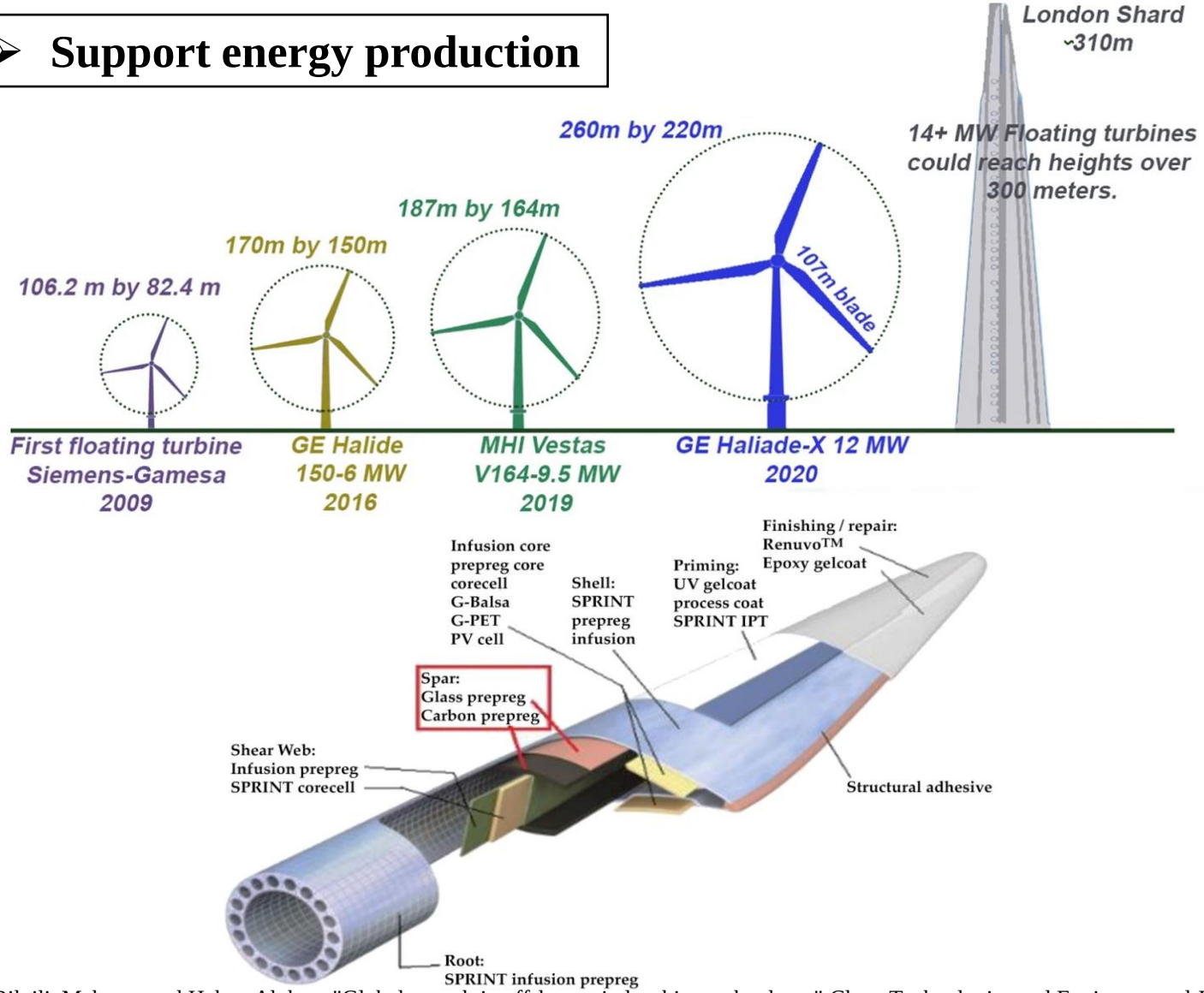
Mid to long-term targets for emission reduction

	2030 target	Time point for achieving carbon neutrality
U.S.A	50%-52% cut from 2005 level	2050
Japan	46% cut from 2013 level	2050
EU	55% cut from 1990 level	2050
U.K.	78% cut from 1990 level	2050

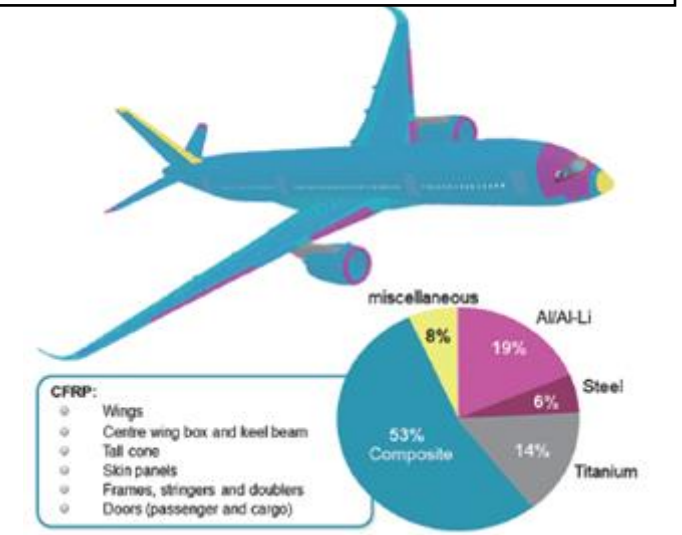
[1] https://www.voanews.com/science-health/biden-urges-world-leaders-keep-promises-climate-following-summit
[2] NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published June 2021, retrieved on June 28, 2021 from https://www.ncdc.noaa.gov/cag/
[3] Our World in Data based on Friedlingstein, etc.: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811-4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.
[4] https://asia.nikkei.com/Spotlight/Environment/Climate-Change/Japan-and-US-pledge-sharper-cuts-by-2030-at-Biden-climate-summit

The role CFRP material will play in emission reduction

➢ Support energy production



➢ Reduce energy consumption



[1] Bilgili, Mehmet, and Hakan Alphan. "Global growth in offshore wind turbine technology." Clean Technologies and Environmental Policy 24.7 (2022): 2215-2227.
[2] Steigmann, Rozina, et al. "Wind turbine blade composites assessment using non-contact ultrasound method." J. Clean Energy Technol 4 (2016): 440-443.
[3] Bachmann, Jens & Hidalgo, Carme & Bricout, Stéphanie. (2017). Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review. Science China Technological Sciences. 60. 10.1007/s11431-016-9094-y.
[4] https://www.compositesworld.com/articles/the-making-of-the-bmw-i3

The new requirements for CFRP

- From high-tech industry to civil industry
- From performance-oriented to cost-oriented
- From focusing on quality to focusing on production efficiency

Developing materials with lower cost
&
Finding more effective assembly method

[1] https://www.jaxa.jp/projects/sat/qzss/topics_j.html
[2] http://www.acv.co.jp/02_racing/active_handle_race.html
[3] https://tri-austin.com/portfolio-item/resins-for-missile-casing-projects/
[4] https://www.compositesworld.com/articles/safe-cycling-keys-to-composite-bike-design-integrity
[5] https://tri-austin.com/portfolio-item/efficient-on-aircraft-composite-repair/
[6] https://www.m-chemical.co.jp/news/2017/__icsFiles/afieldfile/2017/05/18/20170518.pdf

Lower cost material

Carbon fiber reinforced plastics (CFRP)

Carbon fiber reinforced thermoset plastics (CFRTS)

- More expensive resins
- Better processability
- Good temperature resistance
- Difficult to recycle and reprocess

Widely used in aviation, aerospace and military industries

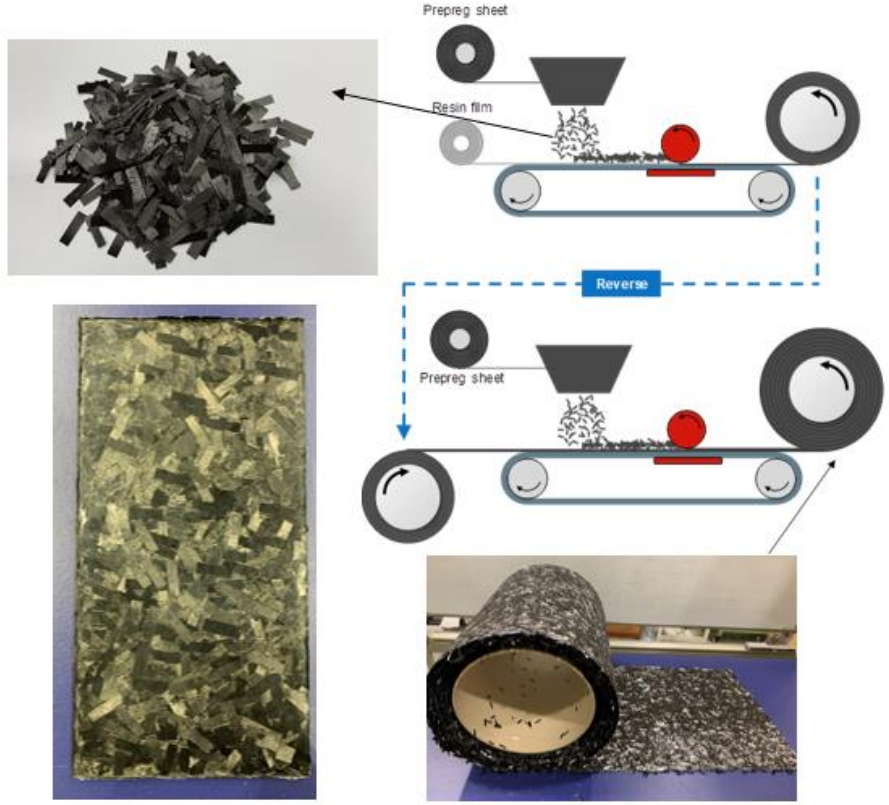
Carbon fiber reinforced thermoplastics (CFRTP)

- Lower cost resins (PA,PP)
- Good impact resistance
- High process cycle efficiency
- Able for secondary treatment and recycling

Promising material for mass production

CFRTP-SMC

(Carbon fiber reinforced thermoplastics sheet molding compound)

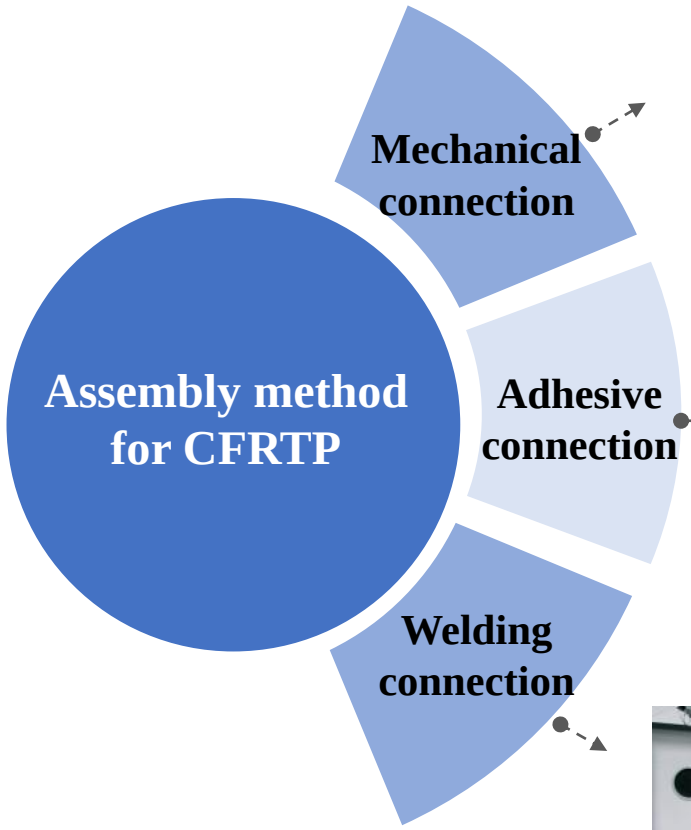


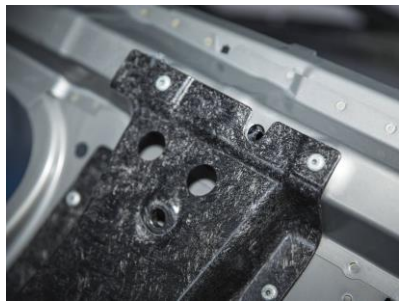
- Randomly oriented strands material
- Chopped tapes of carbon fiber and PA6 prepreg

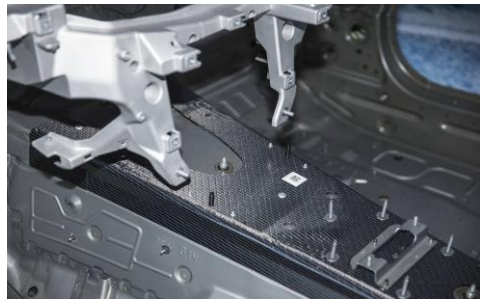
Good mechanical properties and affordable price

[1] Nakashima Y. Relationship between internal geometry changes during compression molding and mechanical behavior of chopped carbon fibre tape reinforced thermoplastics. The University of Tokyo, 2018.

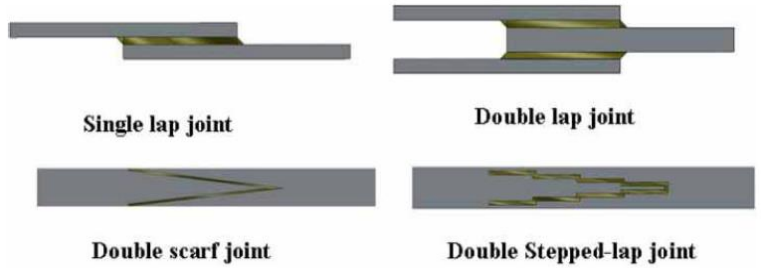
Assembly method







- ✓ Low cost
- ✓ Large size structure
- ✓ Reassemble
- ☐ Stress concentration
- ☐ Creep



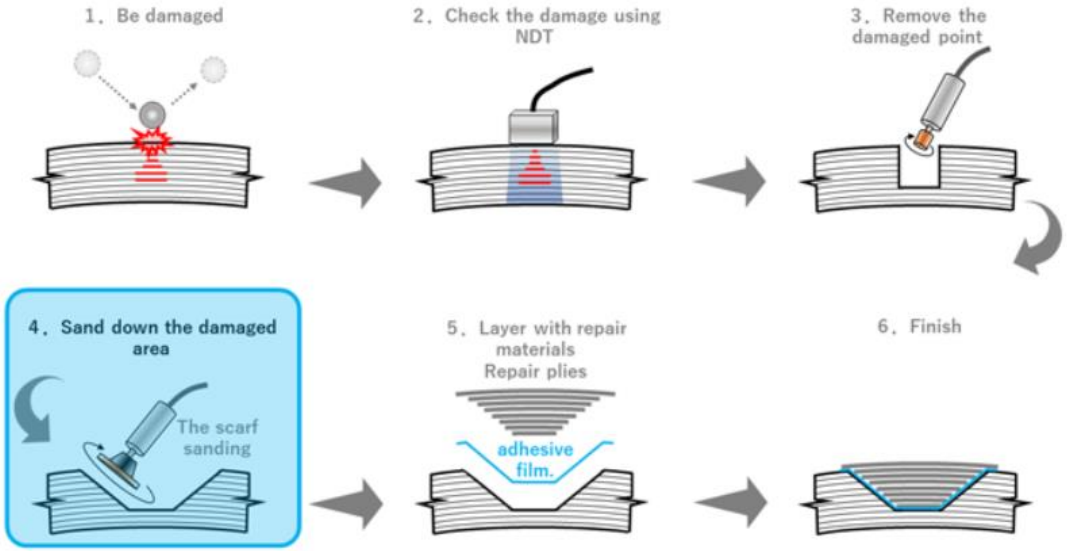
- ✓ Large size structure
- ✓ Stable performance
- ☐ Slow curing
- ☐ Surface treatment

- ✓ High performance
- ☐ Immature technology
- ☐ High cost

[1] https://www.autoweek.com/news/a1868071/carbon-core-2016-bmw-7-series-gets-carbon-fiber-implants/
[2] Banea, Mariana D., and Lucas FM da Silva. "Adhesively bonded joints in composite materials: an overview." Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 223.1 (2009): 1-18.
[3] Meer, Thomas, and Matthias Geistbeck. "Automated welding of thermoplastic joining element on CFRP." Lightweight Design worldwide 10.4 (2017): 34-39.

The prospect of mechanical connection

Broken CFRP parts



CFRP repairing process

	Mechanical connection	Adhesive connection	Welding connection
Fundamental joining force	Strictly mechanical forces	Atomic-level bonding forces based on chemical adhesive	Intermolecular forces based on molecular diffusion
Connection Type	Non-permanent connection	Permanent connection	

- For CFRP, there is still a lack of low-cost repairing methods
- Replacement of damaged parts is still one of the mainstream maintenance methods

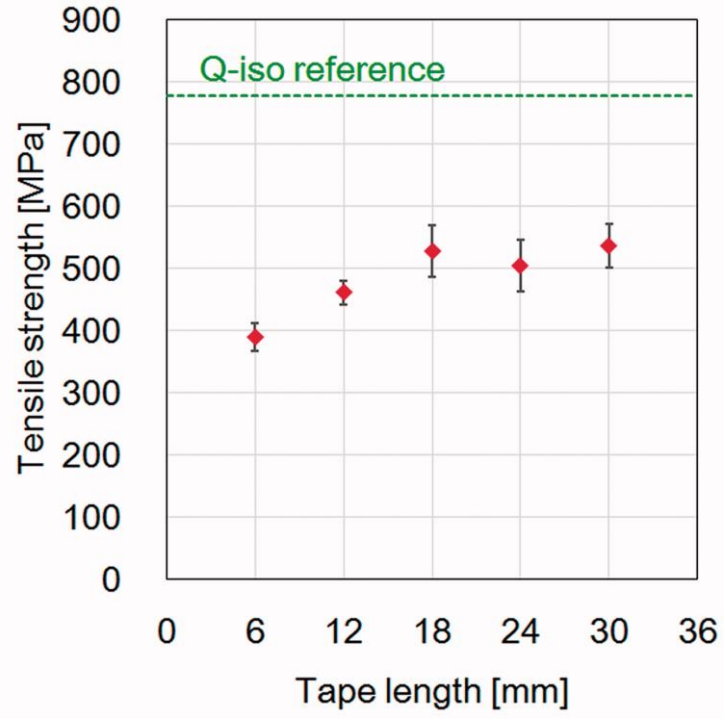
✓ **Mechanical connection still has its place in civil industry**

[1] https://carbonsteed.com.au/carbon-repairs-automotive/
[2] Scarf sanding technology for carbon fiber reinforced plastics (CFRP) airframe https://www.aero.jaxa.jp/eng/research/basic/structure-composite/scarfsanding

Challenges for bolted CFRTP-SMC structure

From the perspective of SMC material

- **Tape Geometry** has a significant influence on the mechanical property of SMC material

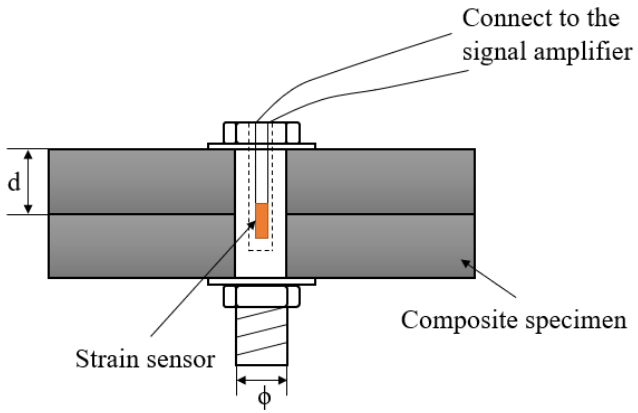


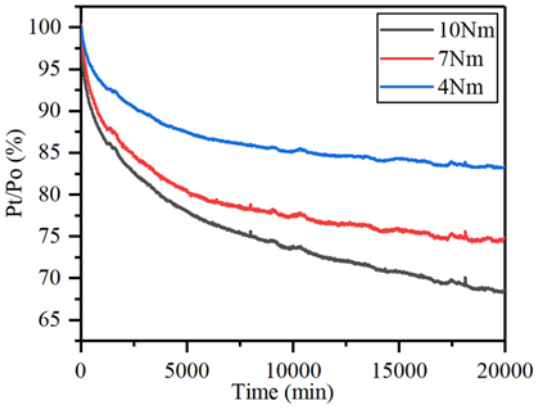
Influence of tape length on the tensile strength of CFRTP-SMC [1]

From the perspective of bolted connection

- Viscoelastic relaxation behaviour of composite material will cause a relaxation process of initial tightening preload

- Changes in the initial preload will influence the **failure mode** and **mechanical performance** of the structure





Pt/Po: preload left at time t/ initial tightening preload

Preload relaxation behavior at 70 ℃ with different initial preload

[1] Yamashita S, Hashimoto K, Suganuma H, Takahashi J. Experimental characterization of the tensile failure mode of ultra thin chopped carbon fiber tape reinforced thermoplastics. J Reinf Plast Compos 2016;35:1342 52. https://doi.org/10.1177/0731684416651134.

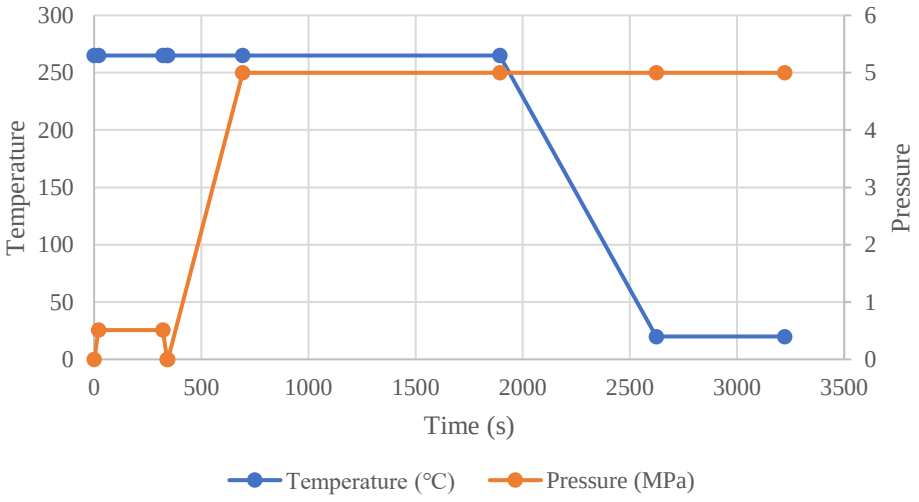
Research content

- How does tape geometry affect the static bearing failure of bolted CFRTP-SMC joints?
- How does tape geometry influence the sensitivity of the material to different preload levels?
- What is the failure mode of SMC material under bearing loading?
- How will tape geometry influence the fatigue resistance of bolted structures?

Improve performance and durability of bolted CFRTP-SMC structures

Samples and test setup

➢ Manufacturing process of CFRTP-SMC specimen



Molding parameters

Tape geometry of samples

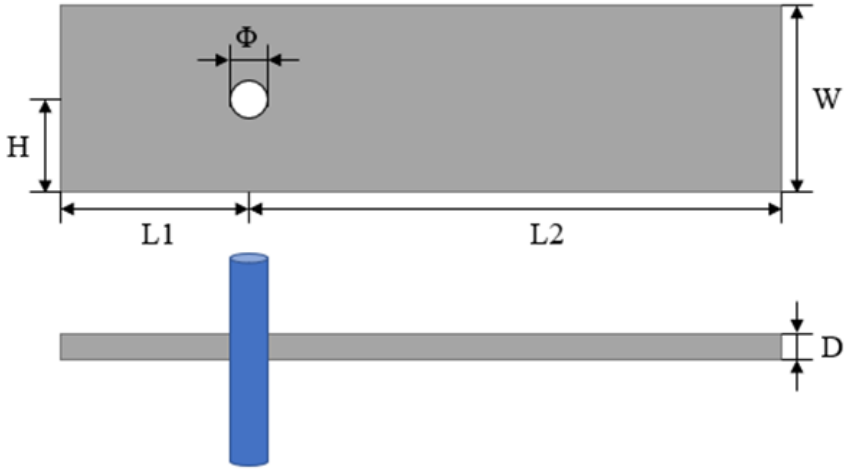
Tape width=5mm	Tape length		
Tape thickness	8mm	16.5mm	26.5mm
44μm	Material a	Material b	Material c
88μm	Material A	Material B	Material C

Volume fraction of carbon fiber, resin and voids for the samples

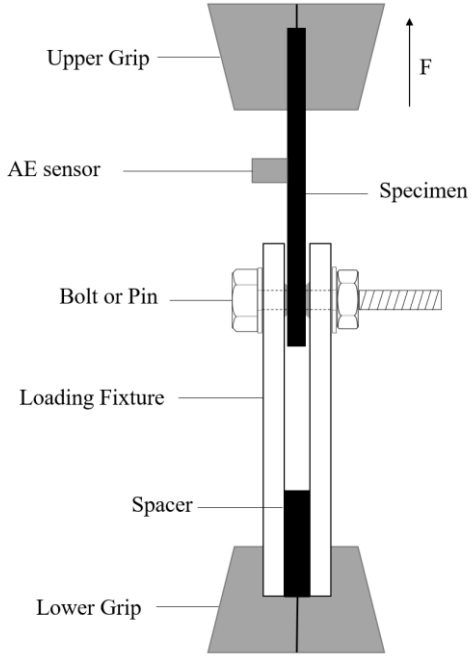
Material	Vf	Vr	Vv
a	49.80%	49.17%	1.03%
A	49.83%	49.16%	1.01%
b	50.65%	48.73%	0.61%
B	50.14%	48.98%	0.88%
c	50.00%	48.88%	1.12%
C	50.90%	48.71%	0.39%

Static bearing test

Reference standard	ASTM 5961
Testing machine	UTOGRAPH AG-Xplus 100 kN (Shimadzu universal testing machine)
Loading speed	1mm/min
Material	CFRTP-SMC(PA6)
Specimen dimensions	H: 15mm
	L1: 30mm
	L2: 85mm
	W: 30mm
	D: 4mm
	Φ: 6mm
Initial preload (Provided by a torque wrench)	Pin loaded
	0Nm
	7Nm
	10Nm



Specimen configurations



Test setup

$$F^{bru} = P^{max}/(k \cdot D \cdot t)$$

F^{bru}: bearing strength

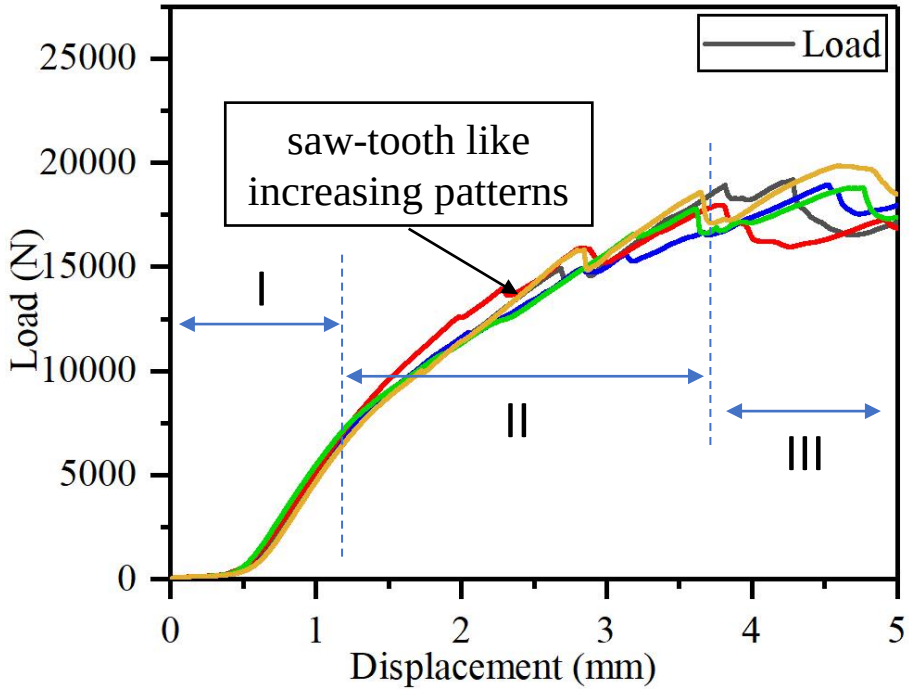
P^{max}: static bearing load

k=1 (single fastener),

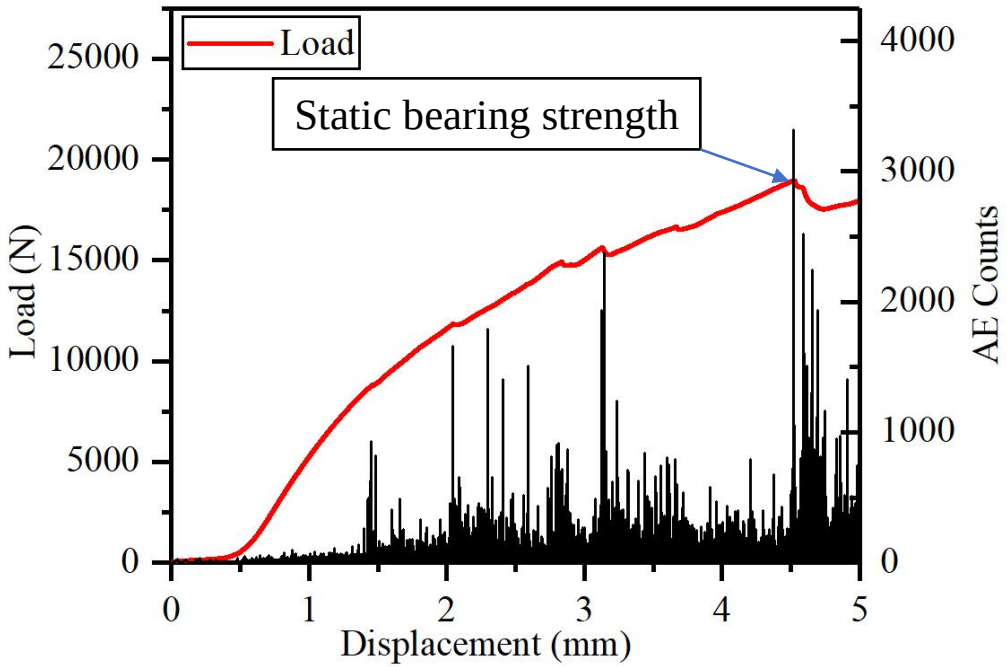
D= hole diameter,

t= specimen thickness

Typical bearing process



Typical load-displacement curves for material b
(Initial preload= 0Nm)

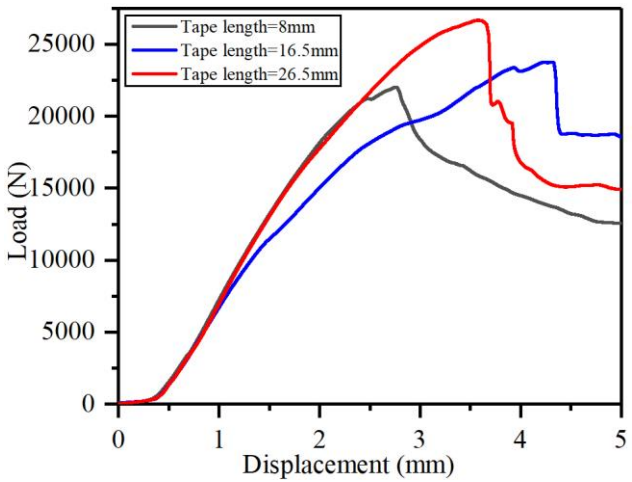


AE counts during loading process
(Material b, initial preload= 0Nm)

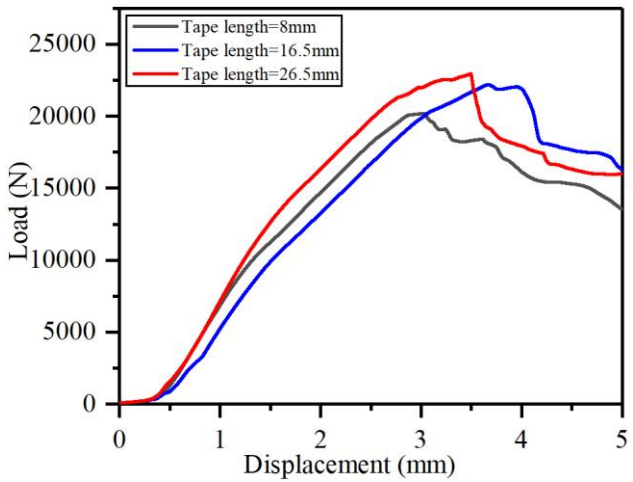
- ✓ The load displacement curves can be divided into three stages
- ✓ The increase of AE (acoustic emission) counts indicate that the damage will expand after entering stage II
- ✓ Due to the characteristics of CFRTP-SMC, after reaching static bearing strength the material still maintains a certain strength

Influence of tape length on the static bearing strength

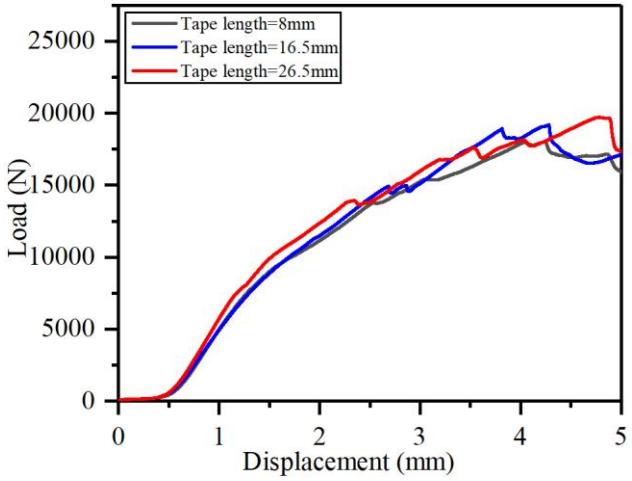
➢ **Tape thickness= 44μm**



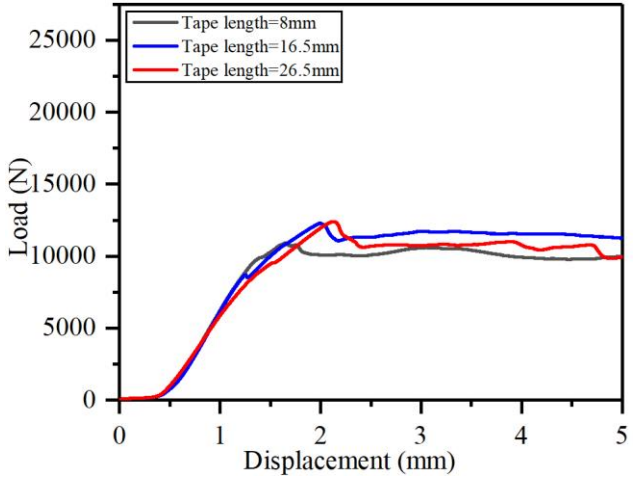
10Nm



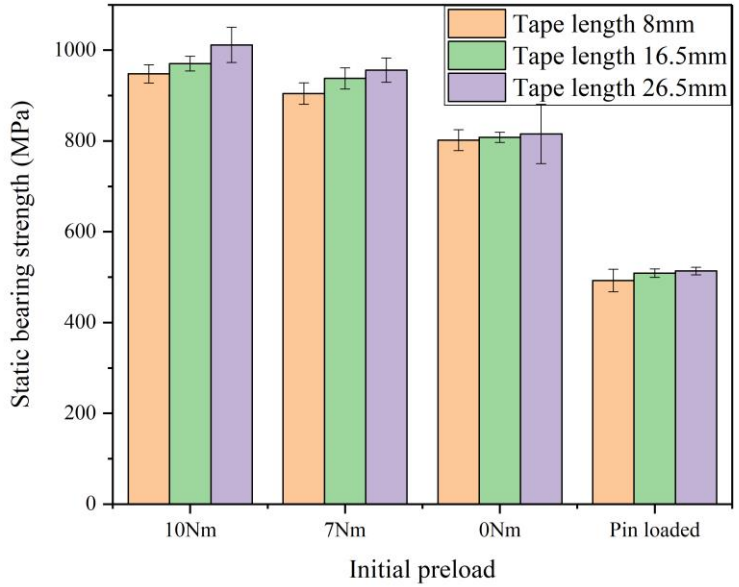
7Nm



0Nm



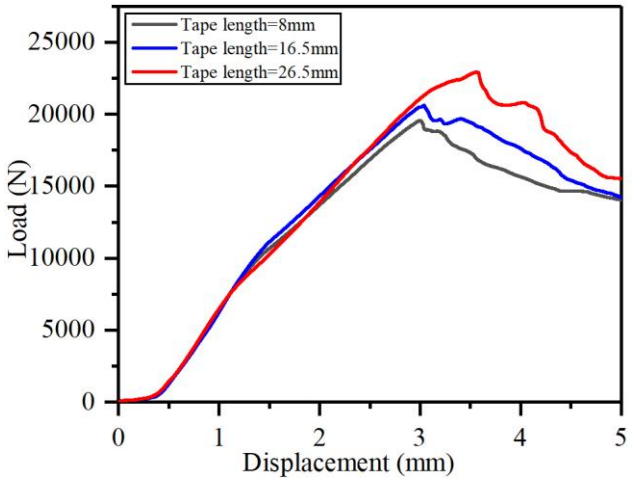
Pin loaded



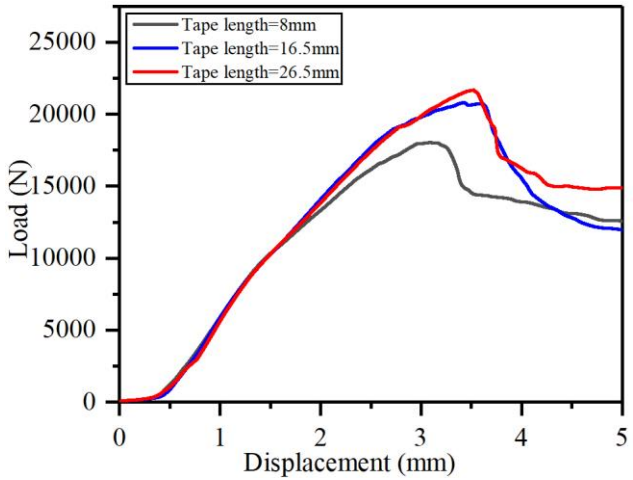
- ✓ There is a positive relationship between tape length and static bearing strength
- ✓ By increasing tape length from 8mm to 26.5mm static bearing strength increased by 6.74%, 5.73%, 1.71% and 4.24% under different preload levels
- ✓ For the bolted samples, variance of static bearing strength is larger when the tape is longer

Influence of tape length on the static bearing strength

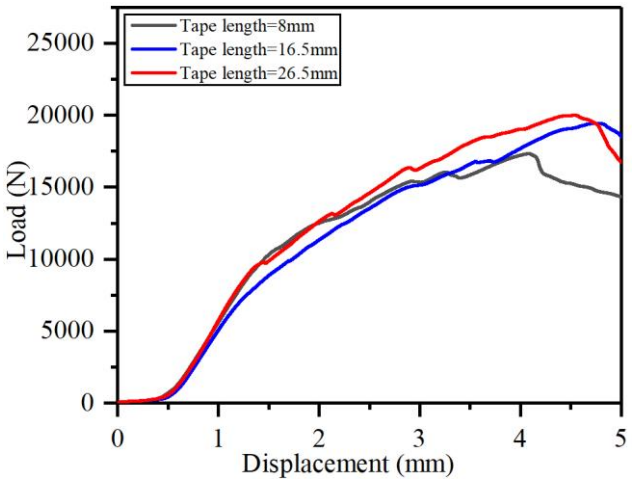
➢ **Tape thickness= 88μm**



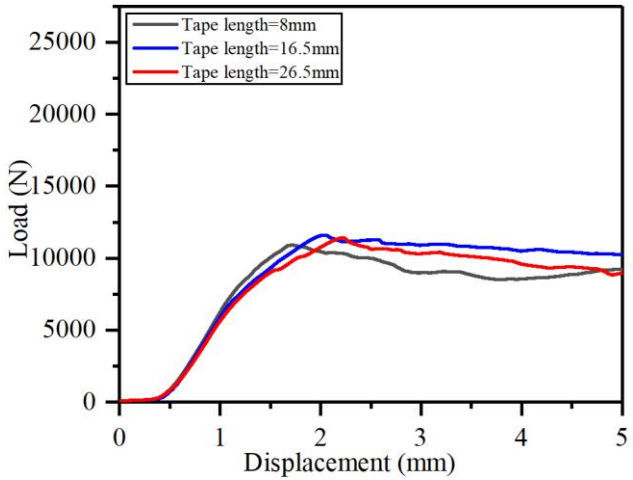
10Nm



7Nm



0Nm



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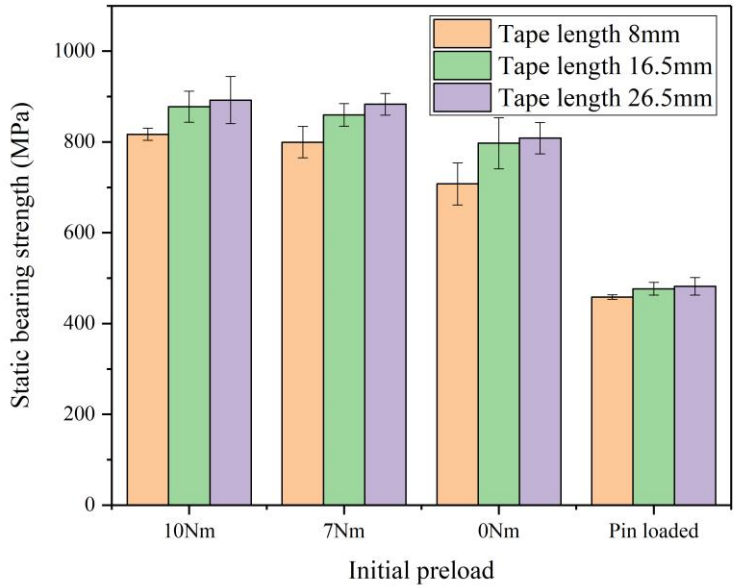
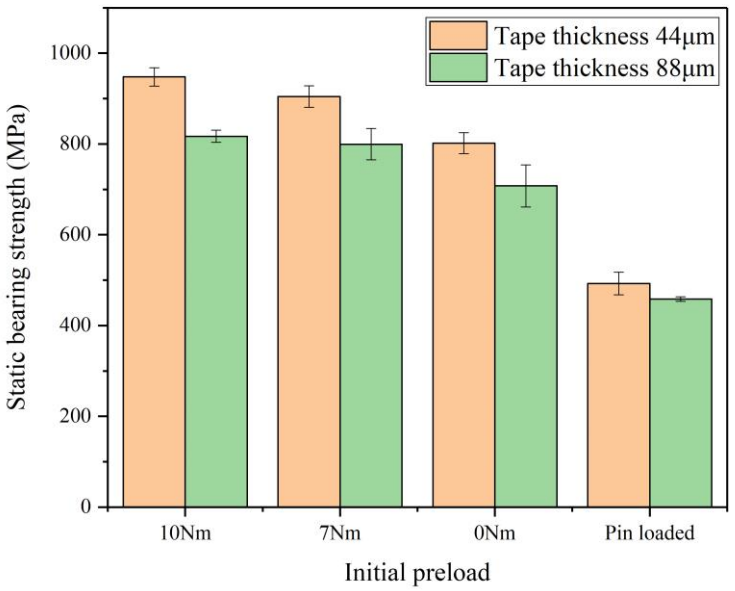
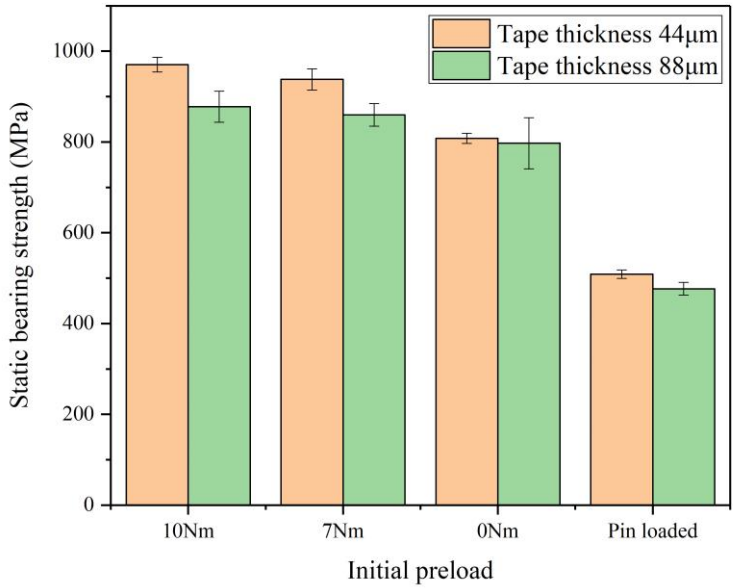


- ✓ By increasing tape length from 8mm to 26.5mm static bearing strength increased by 9.21%, 10.51%, 14.24% and 5.14% under different preload levels
- ✓ The positive relationship remains the same

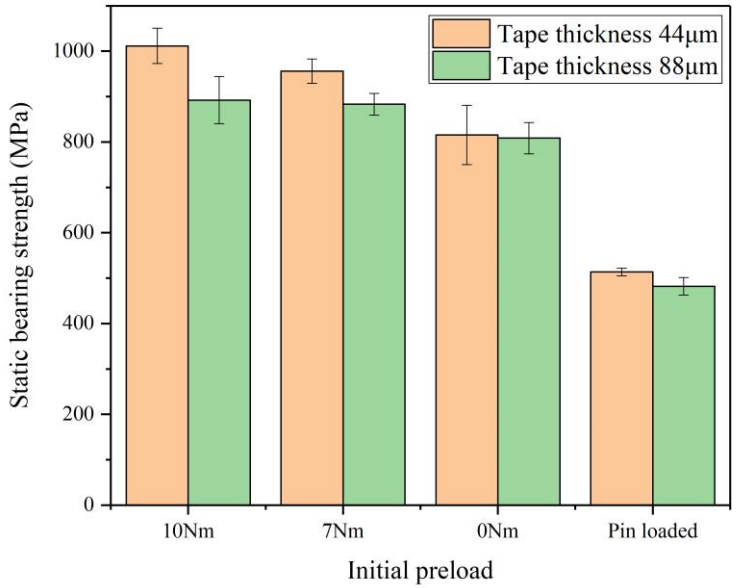
Influence of tape thickness on the static bearing strength



Tape length=8mm



Tape length=16.5mm



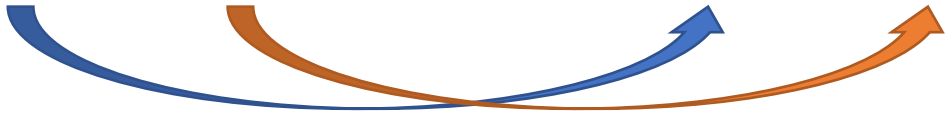
Tape length=26.5mm

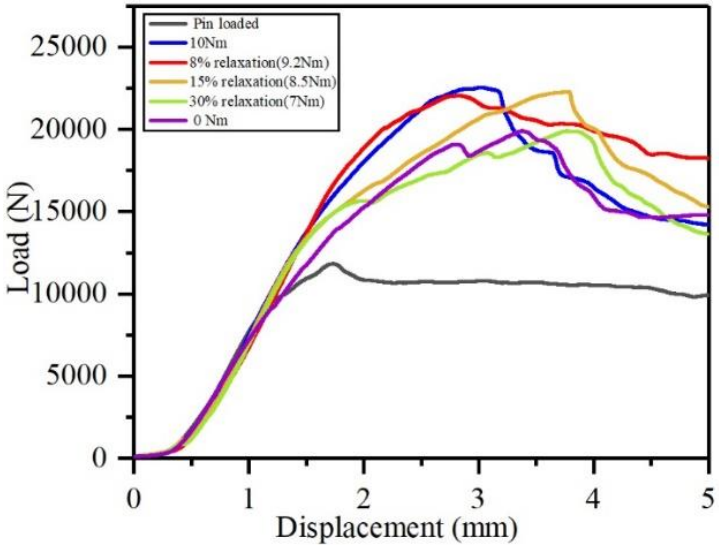
- ✓ A negative relationship between tape thickness and static bearing strength was observed
- ✓ By increasing tape thickness from 44μm to 88μm, the reduce of static bearing strength will be at most 13.79% considering different tape length and initial preload conditions

Influence of tape thickness on the sensitivity to preload

Relative static bearing strength loss caused by initial preload decrease

	Tape thickness 44μm			Tape thickness 88μm		
Tape length	10Nm	7Nm	0Nm	10Nm	7Nm	0Nm
8mm	100%	-4.58%	-15.41%	100%	-2.15%	-13.39%
16.5mm	100%	-3.37%	-16.73%	100%	-2.08%	-9.15%
26.5mm	100%	-5.48%	-19.39%	100%	-1.03%	-9.40%



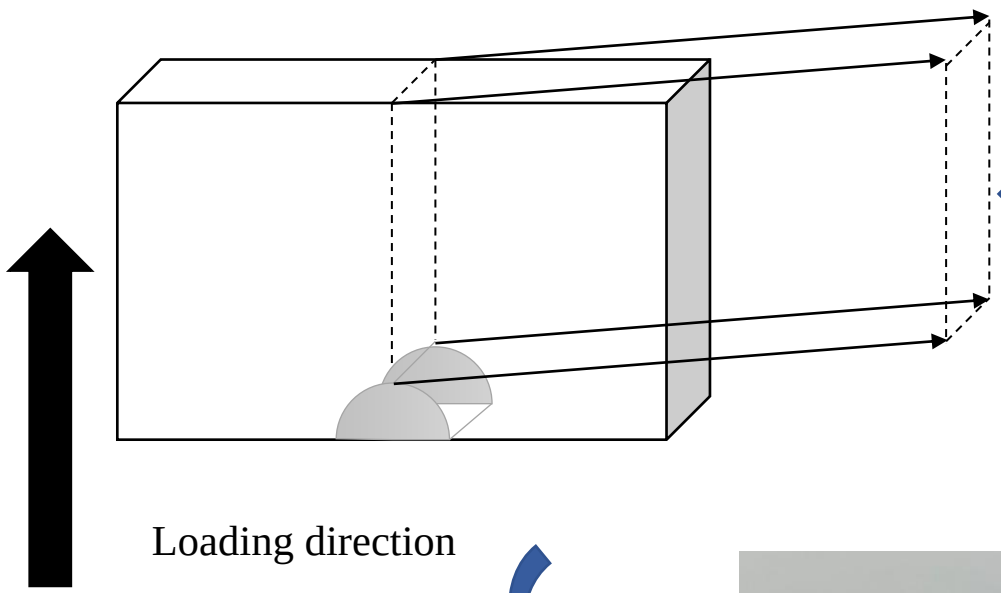


Influence of preload relaxation on the bearing strength of bolted SMC samples

- ✓ For each material, the bearing strength when the initial preload=10Nm is defined as a standard reference
- ✓ Same level of preload loss will result in **less relative decrease** in static bearing stress when the tape is **thicker**

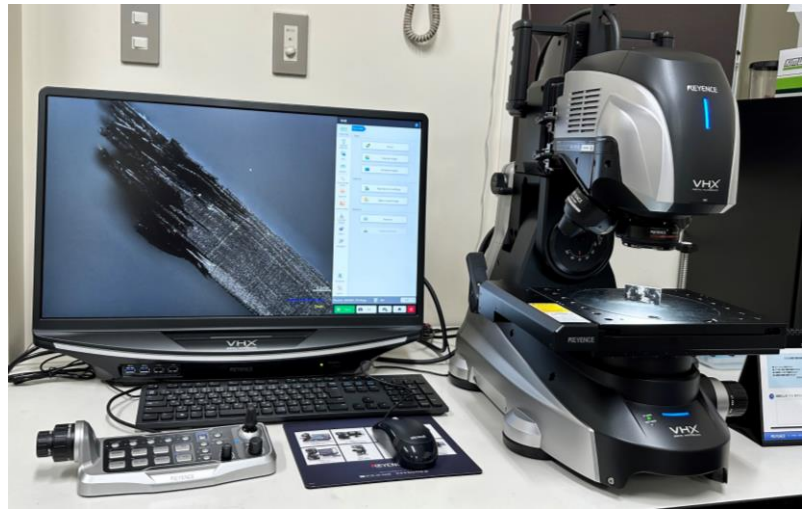
CFRTP-SMC with **thicker tapes** will have **stronger resistance** to preload relaxation

Observation of fracture morphology



Loading direction

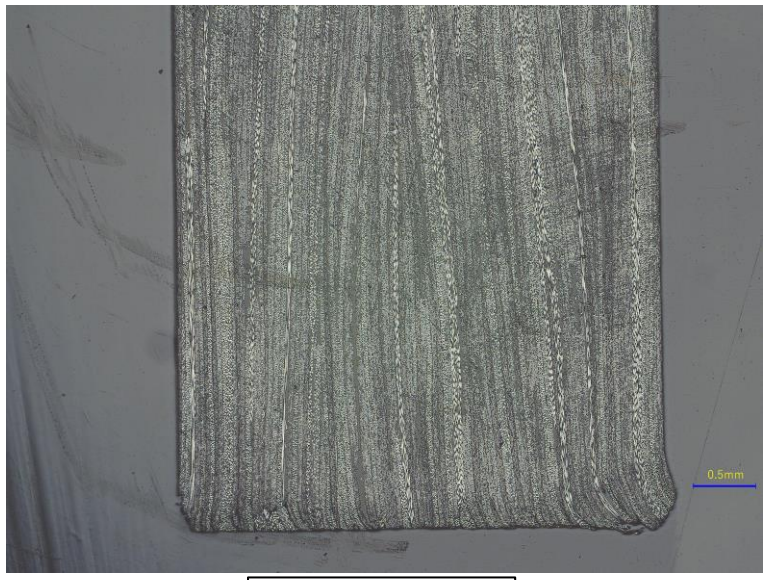
Microscope observation (KEYENCE VHX-8000)



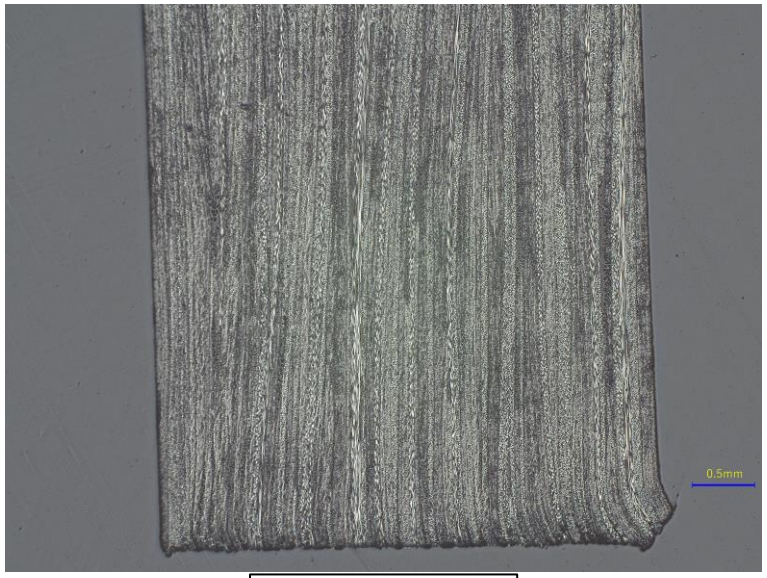
Metallographic sample

Samples before test

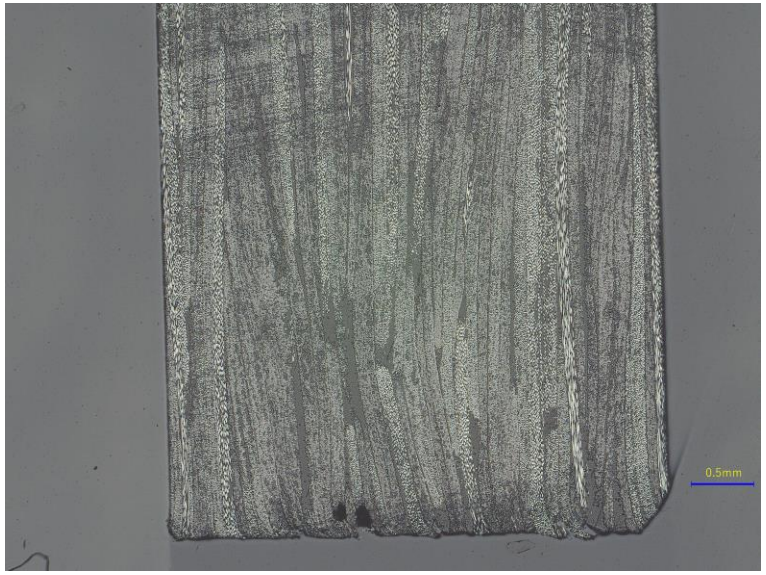
5*8*1ply



5*16.5*1ply



5*26.5*1ply



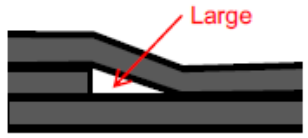
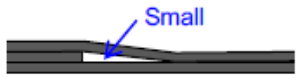
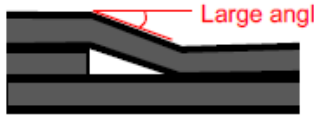
5*8*2ply

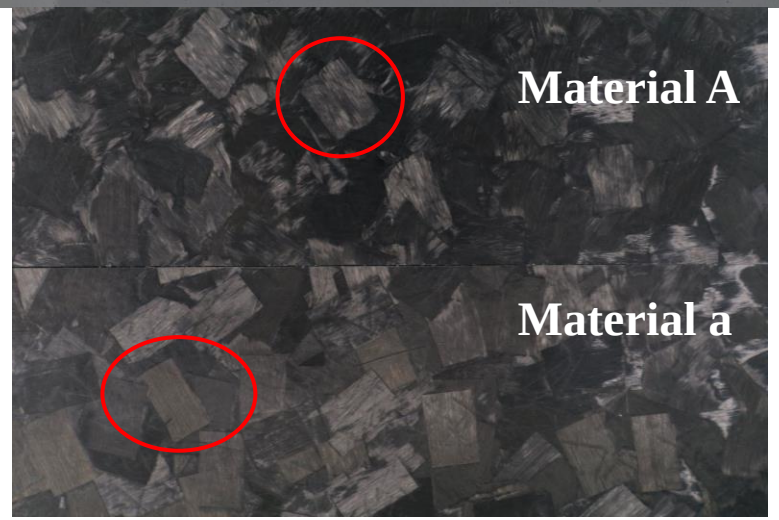
5*16.5*2ply

5*26.5*2ply

Influence of tape thickness

Comparison for thicker & thinner tape material [1]

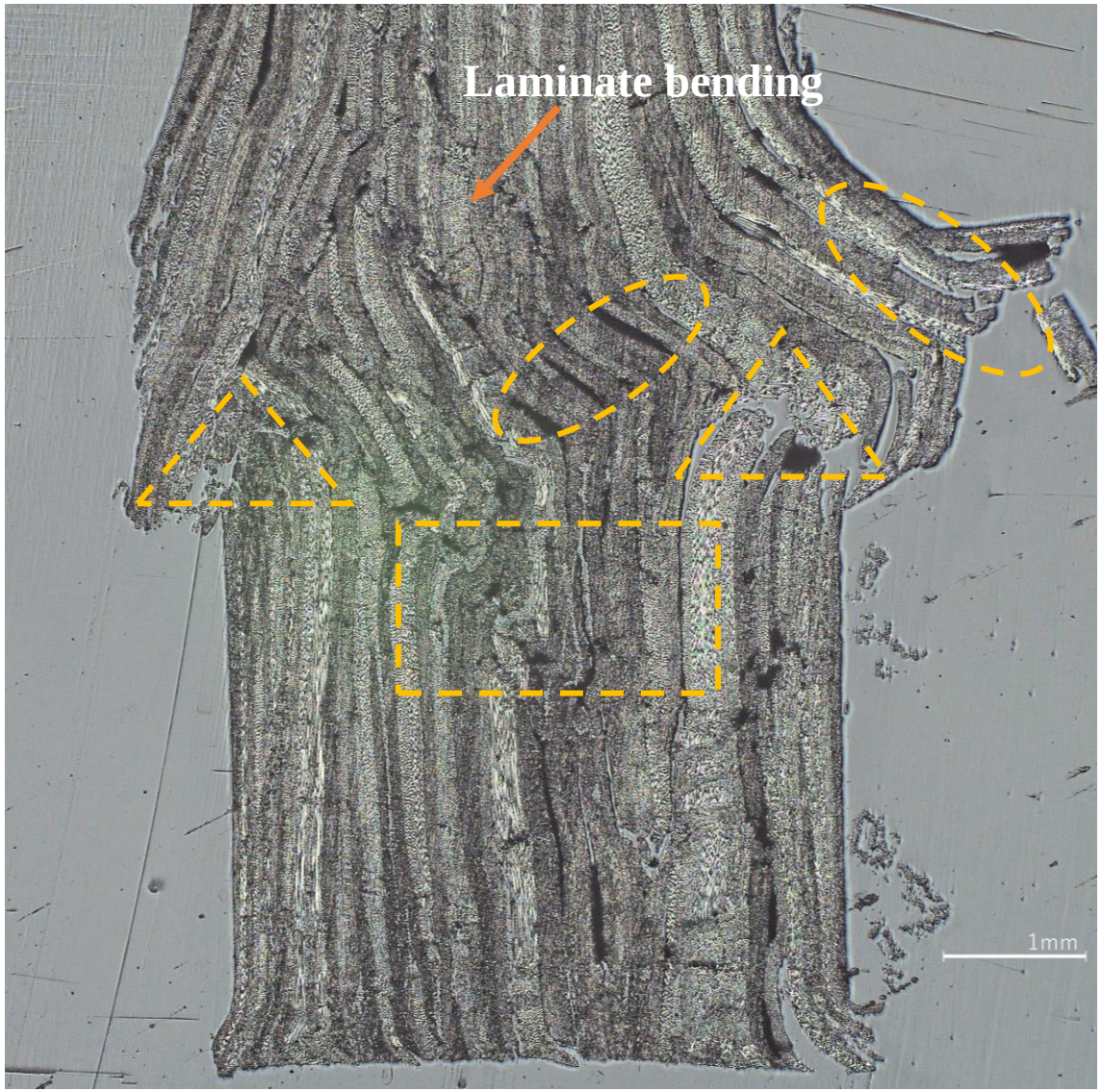
	CTT with thicker tapes	CTT with thinner tapes
Resin-rich areas at tape ends		
In-plane fiber waviness	 Winding	 Keep its original shape
Out-of-plane orientation		



✓ More resin-rich areas and winding in-plane fiber of SMC made of thicker tapes may contribute to a lower bearing strength

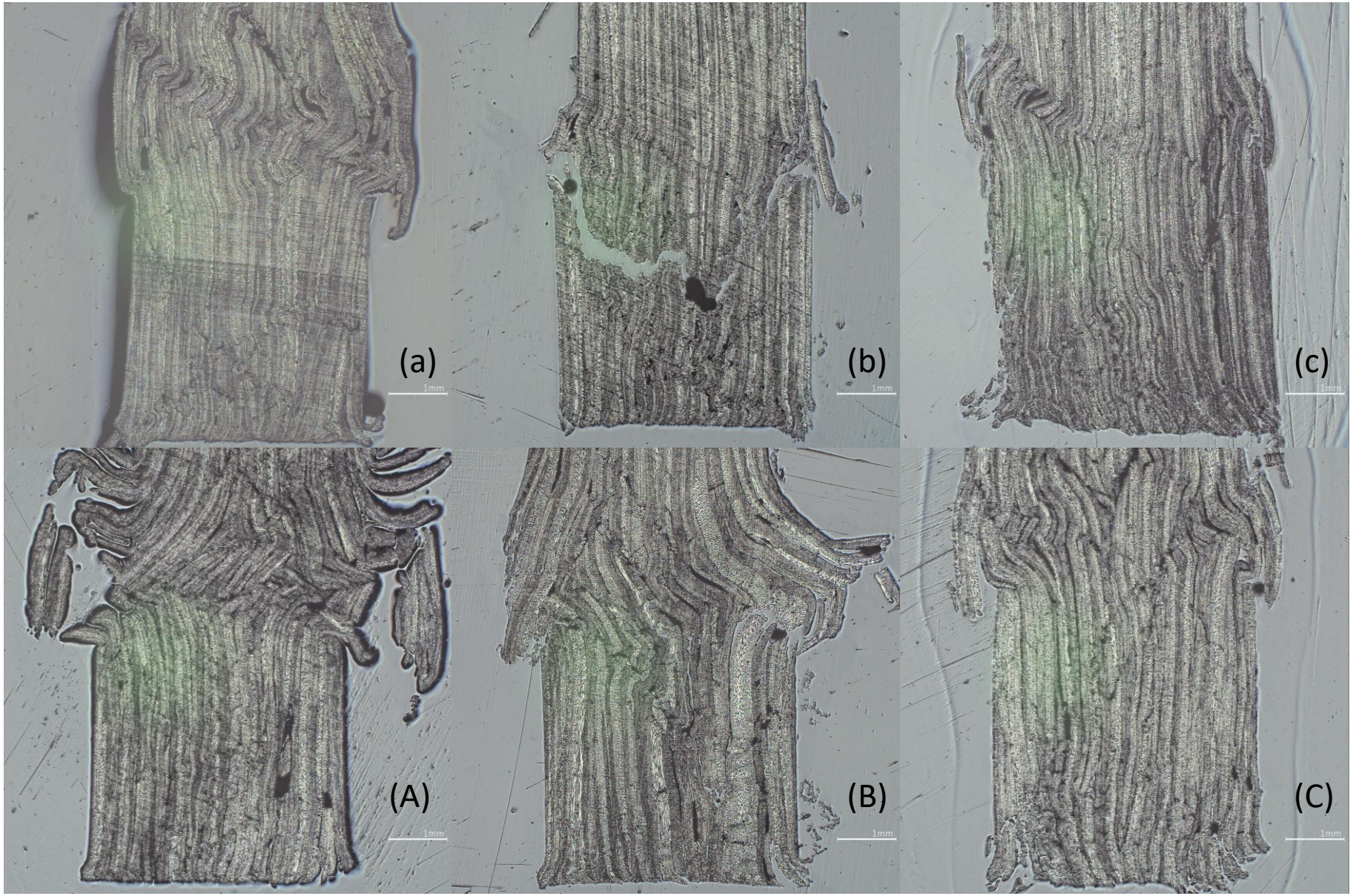
[1] Yamashita S. Effect of thin-ply on the material properties of chopped carbon fiber tape reinforced thermoplastics (CTT). The University of Tokyo, 2016.

A typical bearing failure (5*16.5mm*88µm-10Nm [B])



- Bearing failure is a combination of several types of damages
- Material around assembly hole is protected by the initial preload
- Buckling and delamination happened far away from actual loading area

The influence of tape geometry

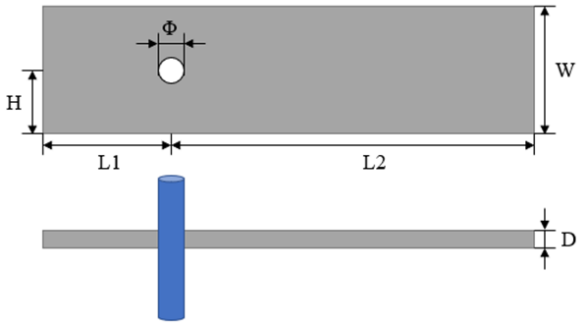


Fracture morphology of material with different tape geometry when the initial preload=10Nm

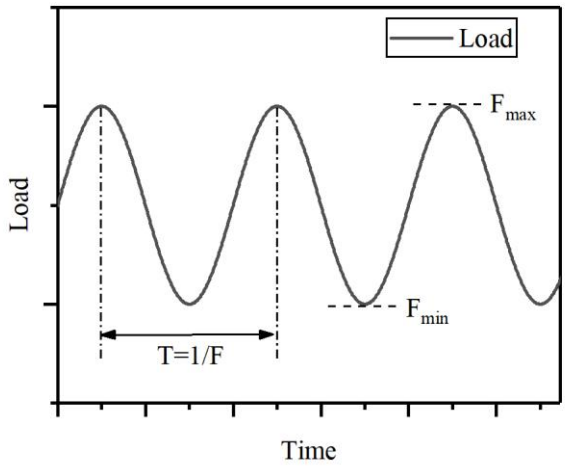
- Material with different tape geometry has similar failure mode
- Laminate bending is more sever when the tape of material is thicker

Fatigue test

Reference standard	ASTM D 6873
Testing machine	Servopulser EHF-UB5-20L 50 kN (Shimadzu hydraulic servo dynamic testing machine)
Frequency	10Hz
Stress ratio	R=0.1
Loading factor (f)	0.66
Specimen dimensions	H: 15mm
	L1: 30mm
	L2: 85mm
	W: 30mm
	D: 4mm
	Φ: 6mm
Initial preload	10Nm



Specimen configurations

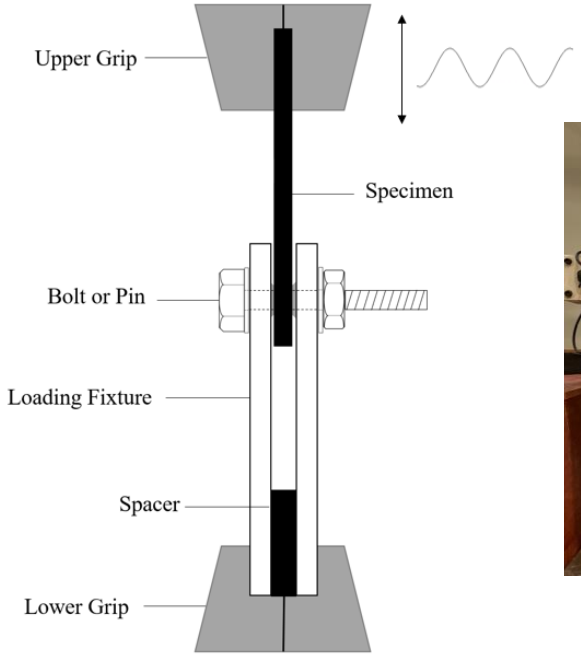


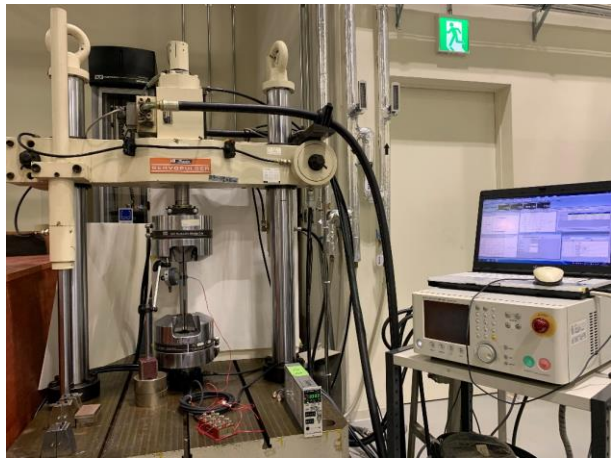
Fatigue loading profile

$$R = \frac{F_{min}}{F_{max}}$$

$$f = \frac{F_{max}}{P_{\max}}$$

$P_{\max}$: Static bearing load





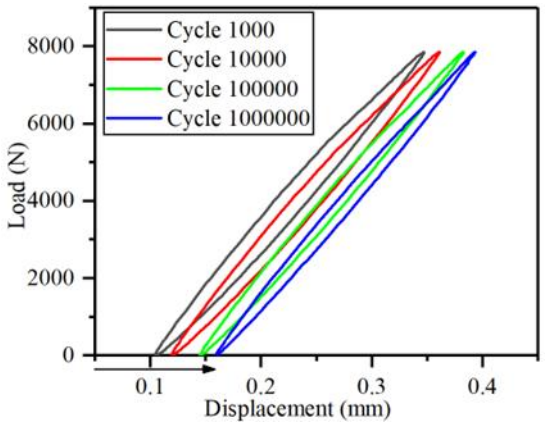
Test setup

Influence of tape geometry on the fatigue resistance

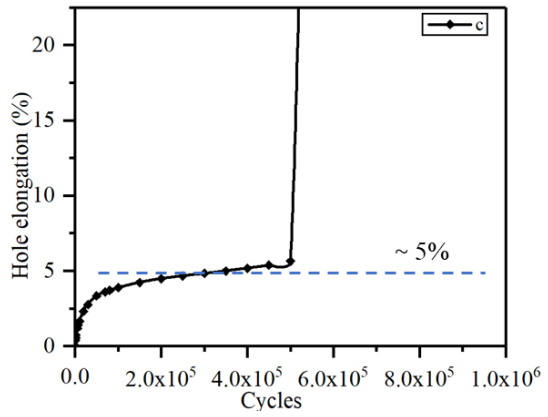
Permanent hole elongation

- The unrecoverable displacement when the specimen doesn't sustain any cyclic load
- Samples will experience repaid fatigue failure progress after reaching critical hole elongation

(defined as: $\frac{Unrecoverable\ displacement}{Hole\ diameter(6\ mm)} \times 100\%$)

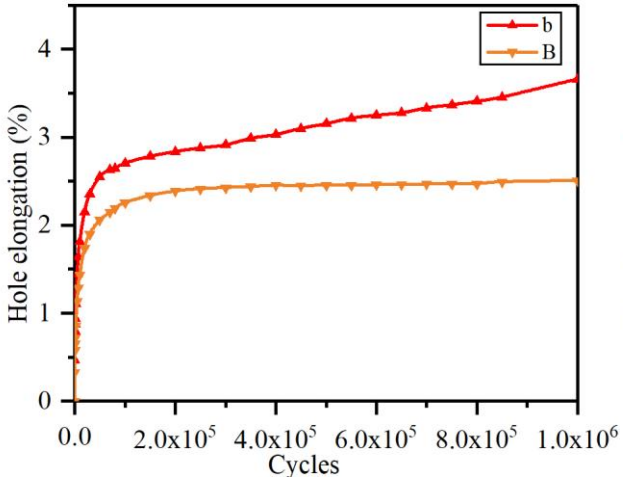


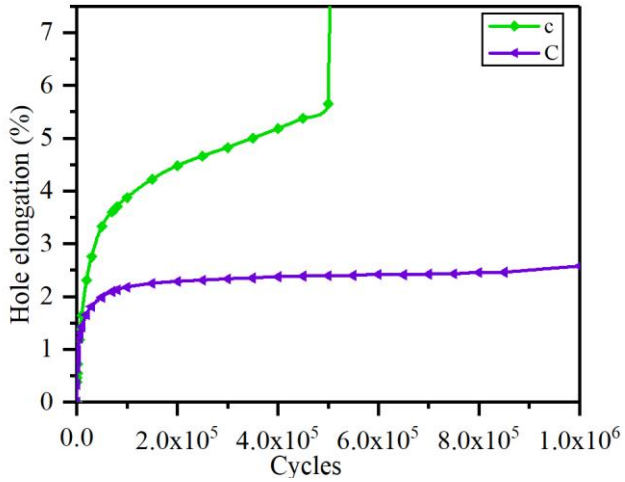
Definition of hole elongation



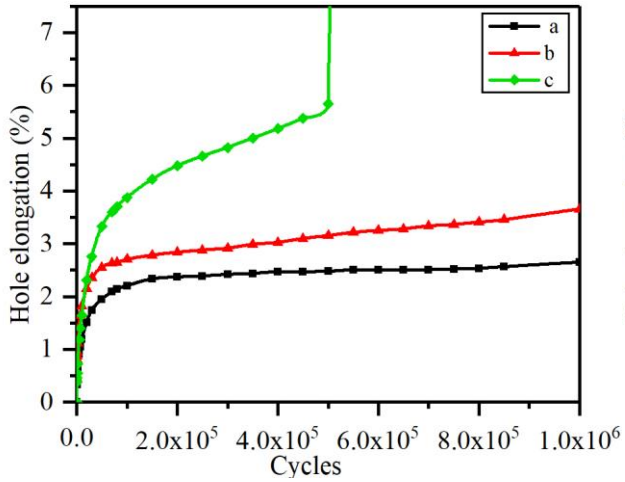
Critical hole elongation

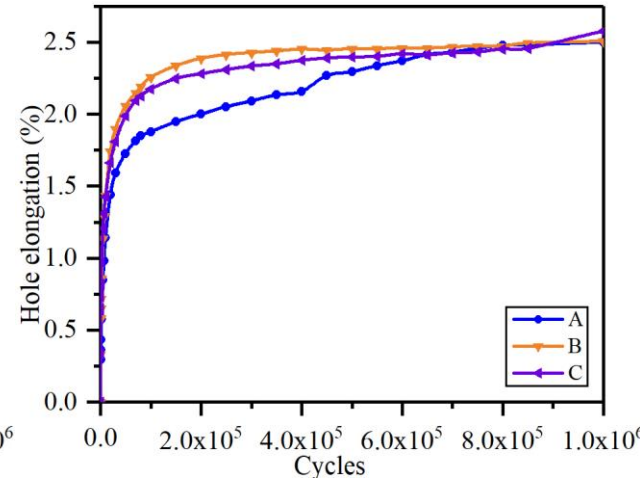
➢ The influence of tape thickness





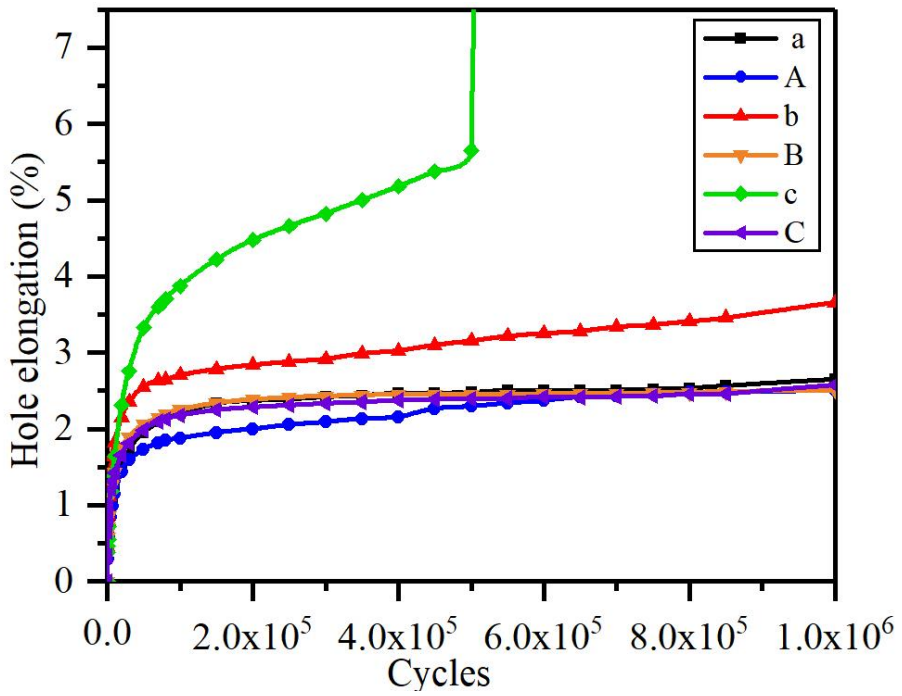
➢ The influence of tape length





Influence of tape geometry on the fatigue resistance

Tape geometry	Permanent hole elongation after 1 million cycles	
5*8mm*44μm (material **a**)	2.65%	1.00
5*8mm*88μm (material **A**)	2.50%	0.94
5*16.5mm*44μm (material **b**)	3.66%	1.38
5*16.5mm*88μm (material **B**)	2.52%	0.95
5*26.5mm*44μm (material **c**)	Failed	——
5*16.5mm*88μm (material **C**)	2.58%	0.97



The fatigue response of SMC with different tape geometry

✓ SMC with shorter and thicker tapes has stronger resistance to fatigue loading

✓ Thicker tape will reduce the influence of tape length on fatigue resistance of material

Conclusions

- The static bearing process of SMC material can be divided into three stages, AE analysis indicates that the unrecoverable damage starts after stage II.

- Tape length has a positive effect on static bearing strength, while tape thickness has a negative effect

- Increasing tape thickness will increase the resistance to preload relaxation

- Initial preload can provide a shielding effect for bearing failure, and materials with different tape geometry have similar failure mode.

- Shorter and thicker tapes will contribute to more robust resistance to fatigue loading

Thank you for your kind attention

Presentations from Takahashi-Wan lab

Name	Date	Venue	Room	Title
Zhiyu WANG	Mon	Process modelling - S1	Studio	A state-based peridynamic model for progressive damage analysis of CFRTP-SMC base
Peng XUE	Mon	Structural analysis and optimization - S2	3B	Optimization of floating vertical axis wind turbine structures using recycled carbon fiber reinforced thermoplastic
Xiaohang TONG	Tue	Mechanics of composites - S2	3A	The influence of tape geometry on the mechanical performance of bolted CFRTP-SMC joints
Zihao ZHAO	Tue	Liquid composites moulding - S2	2A	Simulation of fiber orientation during compression molding process of CFRTP-SMC
Ruochen XU	Wed	Multiscale modelling - S5	Studio	Morphology analysis and shape optimal of CFRTP-SMC based on Monte-Carlo simulation
Qian GAO	Wed	Recycling and sustainability - S3	1B	Prediction of strength and its variation of carbon fiber mat reinforced thermoplastics using Monte-Carlo method
Weizhao HUANG	Thu	Structural health monitoring - S1	Arc	Inversing spatial modulus distribution of cfrtp by a vibrational method and its hydrothermal aging application