Number: 1248

An Ordinary State-based Peridynamic Model for Progressive Damage Analysis of Carbon Fiber Reinforced Thermoplastics Material Based on GPU Parallel Scheme

Zhiyu Wang[1], Yi Wan[1], Jun Takahashi[1],

[1] Department of Systems Innovation,

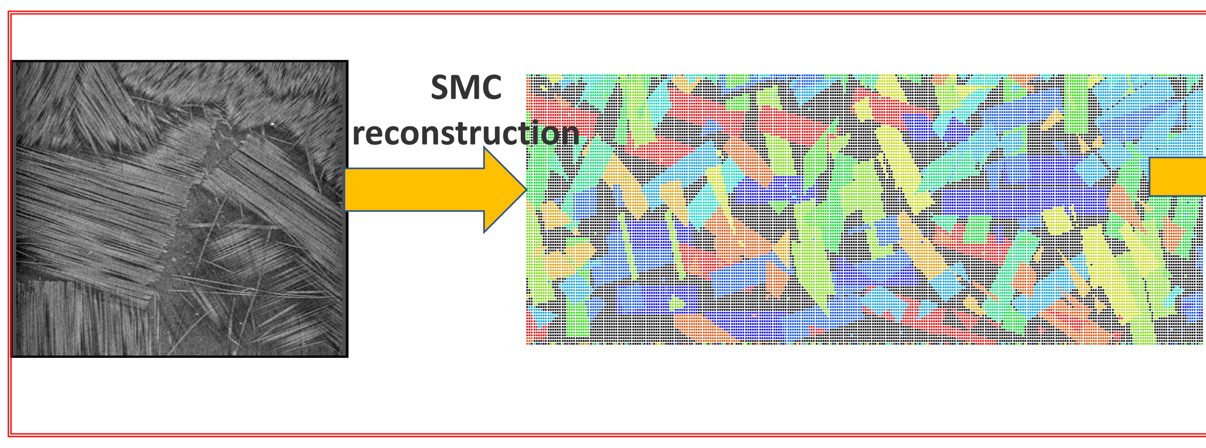
School of Engineering, The University of Tokyo

1.Background & Contributions

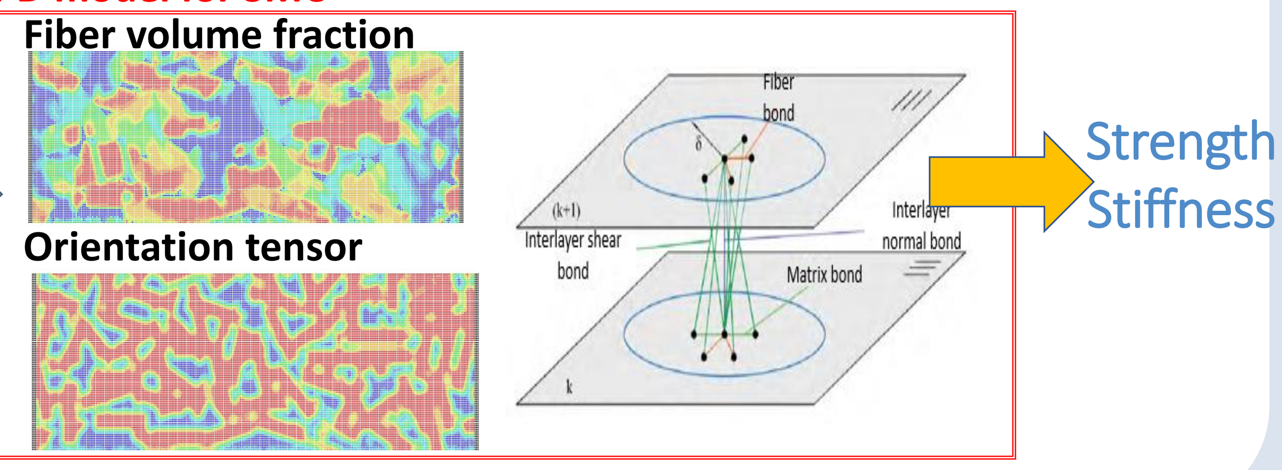
Randomly oriented strands in Carbon fiber reinforced thermoplastic sheet molding compound (CFRTP-SMC) material induce in-plane isotropic mechanical properties as well as a multi-scale structure and high heterogeneity[1][2] which makes mechanical properties and progressive damage analysis of CFRTP-SMC very challenging.

Silling [3] proposed a non-local theory of continuum mechanics called the Peridynamic (PD) theory, This approach can avoid the requirement of continuity of displacement for the derivatives of displacement in discontinuous areas.

Two-scale SMC model



PD model for SMC



2.Details about Two-scale SMC model & SMC model reconstruction

●Micro-Scale

- Fiber orientation tensor

$$a_{ij} = \oint_S p_i p_j \psi(\boldsymbol{P}) d\boldsymbol{P}$$

$$a_{ijkl} = \oint_S p_i p_j p_k p_l \psi(\boldsymbol{P}) d\boldsymbol{P}$$

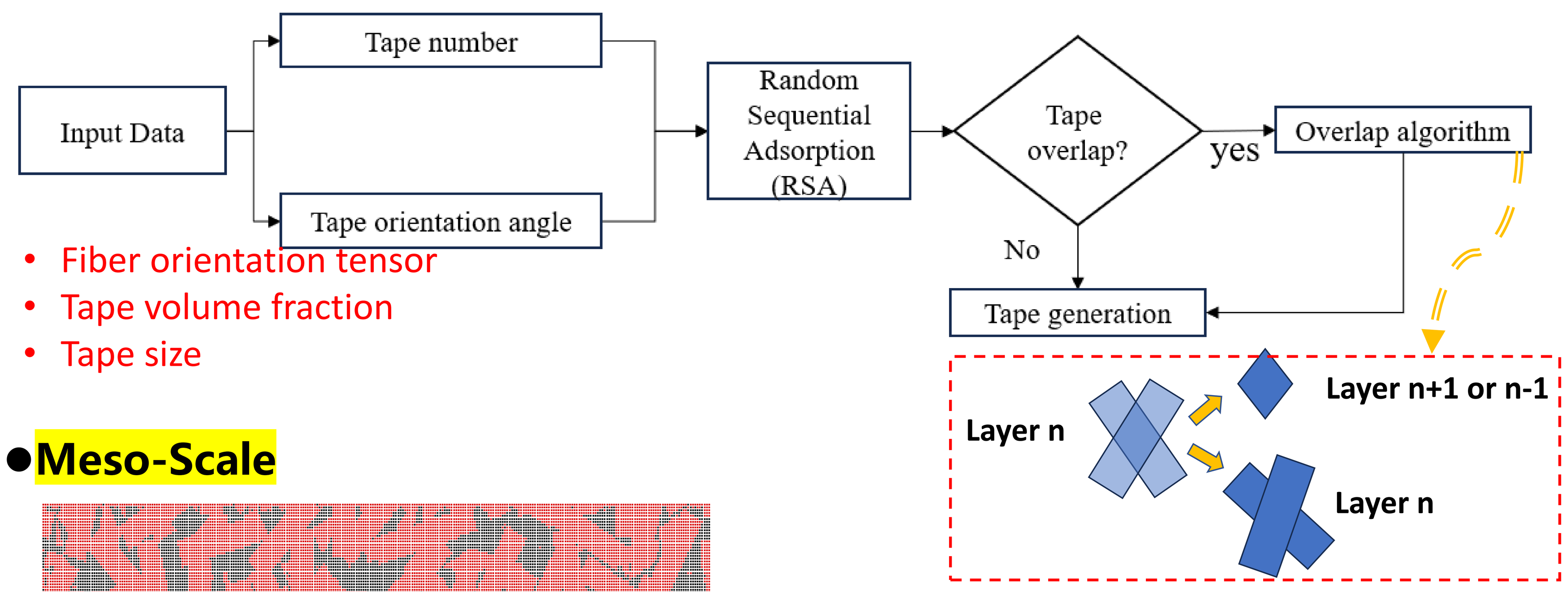
- Fiber volume fraction

reconstruction [4]

Probability density function of FOD

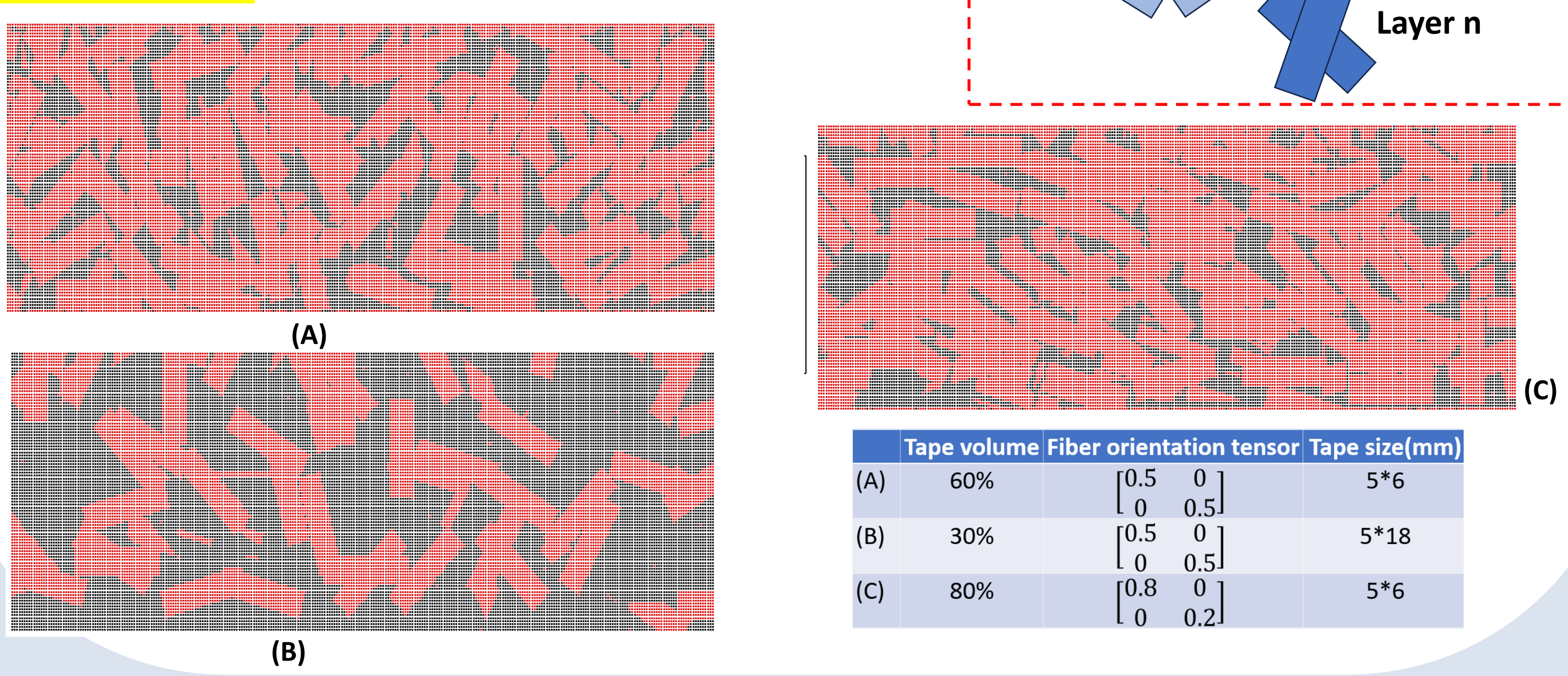
$$\psi(\boldsymbol{P}) = \frac{1}{4\pi} + \frac{15}{8\pi} b_{ij} f_{ij}(\boldsymbol{P}) + \frac{315}{32\pi} b_{ijkl} f_{ijkl}(\boldsymbol{P}) + \cdots$$

●SMC reconstruction



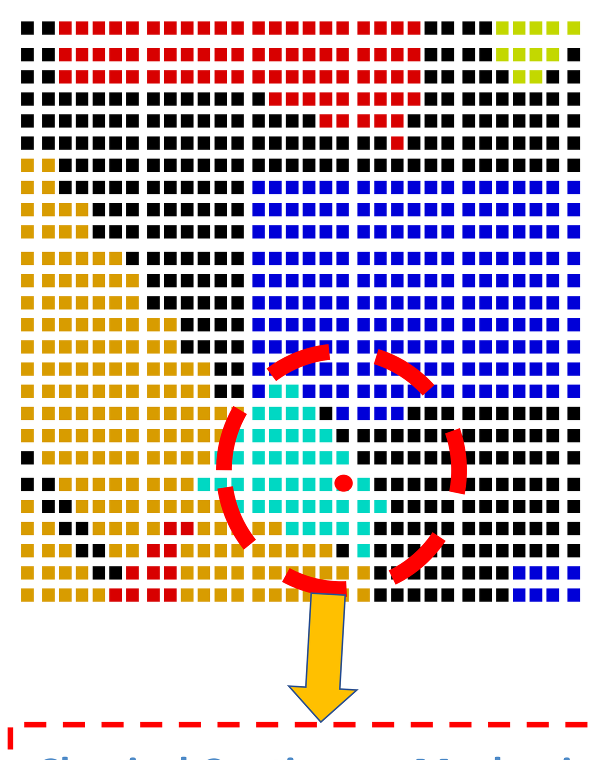
- Fiber orientation tensor
- Tape volume fraction
- Tape size

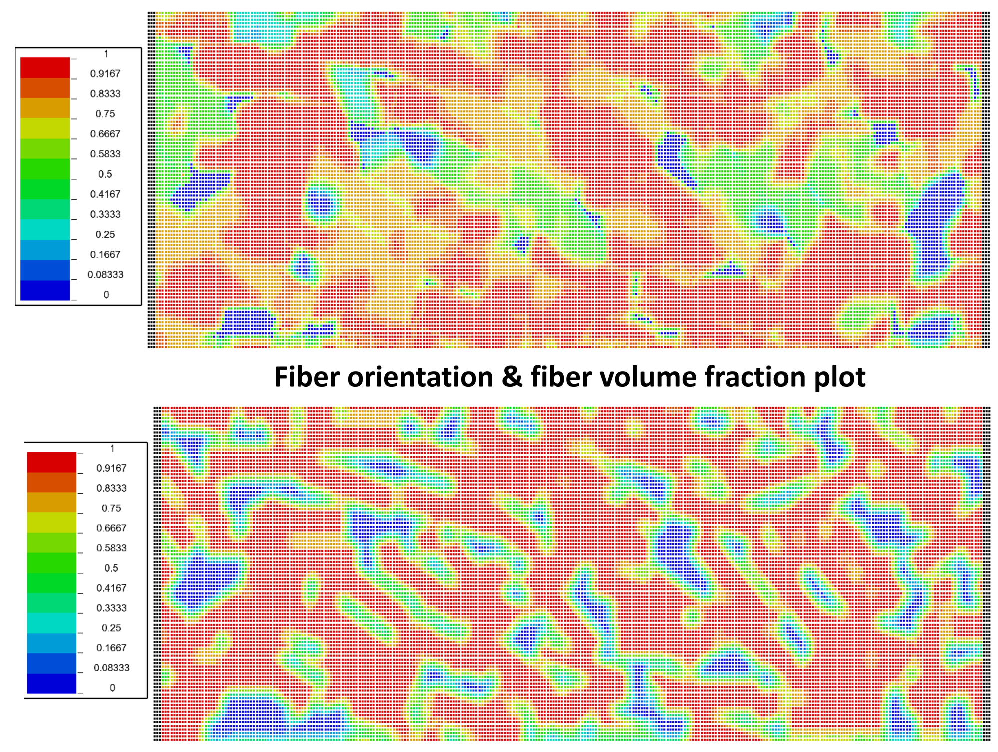
●Meso-Scale



	Tape volume	Fiber orientation tensor	Tape size(mm)
(A)	60%	$\begin{bmatrix}0.5 & 0\\ 0 & 0.5\end{bmatrix}$	5*6
(B)	30%	$\begin{bmatrix}0.5 & 0\\ 0 & 0.5\end{bmatrix}$	5*18
(C)	80%	$\begin{bmatrix}0.8 & 0\\ 0 & 0.2\end{bmatrix}$	5*6

3.Details about Peridynamic(PD) model for SMC





Fiber orientation & fiber volume fraction plot

Classical Continuum Mechanics(CCM)

- Tape volume fraction_local
- Fiber orientation tensor_local

$$[D]_{CCM\_local}$$

$$W_{CCM} = \frac{1}{2} \boldsymbol{\varepsilon}_{local}^T D_{local} \boldsymbol{\varepsilon}_{local}$$

=

Peridynamic theory(PD) [5][6]

$$\omega = \frac{1}{2} \mathbf{u}_{local}^T \mathbf{k}_{local} \mathbf{u}_{local}$$

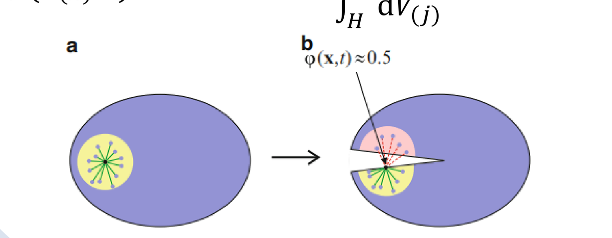
$$\mathbf{u}_{local} = \{u_i \quad v_i \quad \theta_{iz} \quad u_j \quad v_j \quad \theta_{jz}\}^T,$$

$$\mathbf{k}_{local} = \frac{1}{\xi^3}\begin{bmatrix} \xi^2 c_{ax} & 0 & 0 & -\xi^2 c_{ax} & 0 & 0 \\ 0 & 12c_{bz} & 6\xi c_{bz} & 0 & -12c_{bz} & 6\xi c_{bz} \\ 0 & 6\xi c_{bz} & 4\xi^2 c_{bz} & 0 & -6\xi c_{bz} & 2\xi^2 c_{bz} \\ -\xi^2 c_{ax} & 0 & 0 & \xi^2 c_{ax} & 0 & 0 \\ 0 & -12c_{bz} & -6\xi c_{bz} & 0 & 12c_{bz} & -6\xi c_{bz} \\ 0 & 6\xi c_{bz} & 2\xi^2 cbz & 0 & -6\xi c_{bz} & 4\xi^2 cbz \end{bmatrix}$$

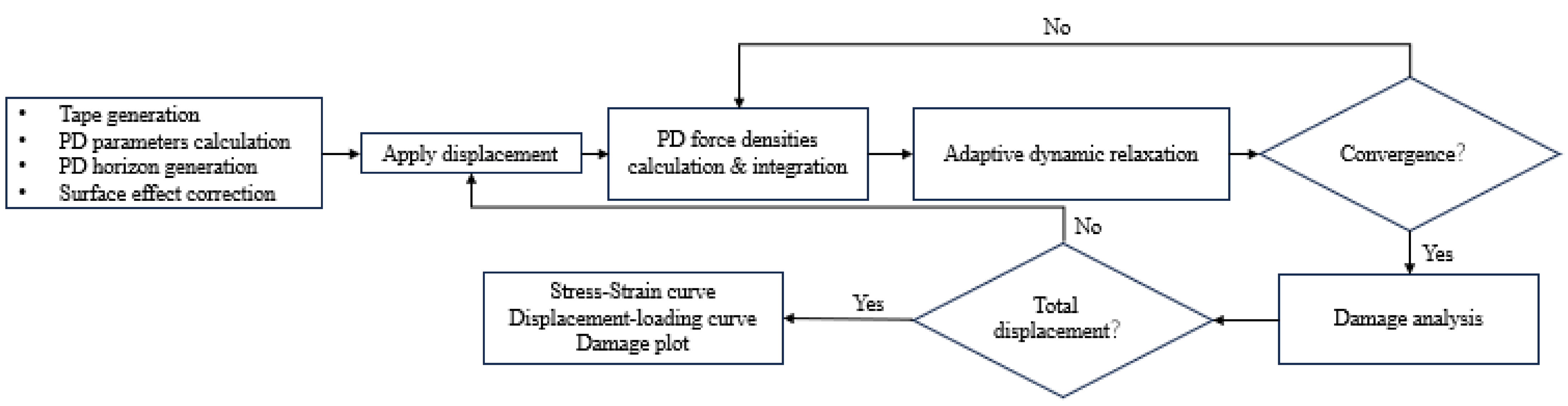
$$W_{PD} = \frac{1}{2} \int_{\hbar(\mathbf{x}_i)} \omega \, dV_{\mathbf{x}_j}$$

Local Damage(Damage factor)

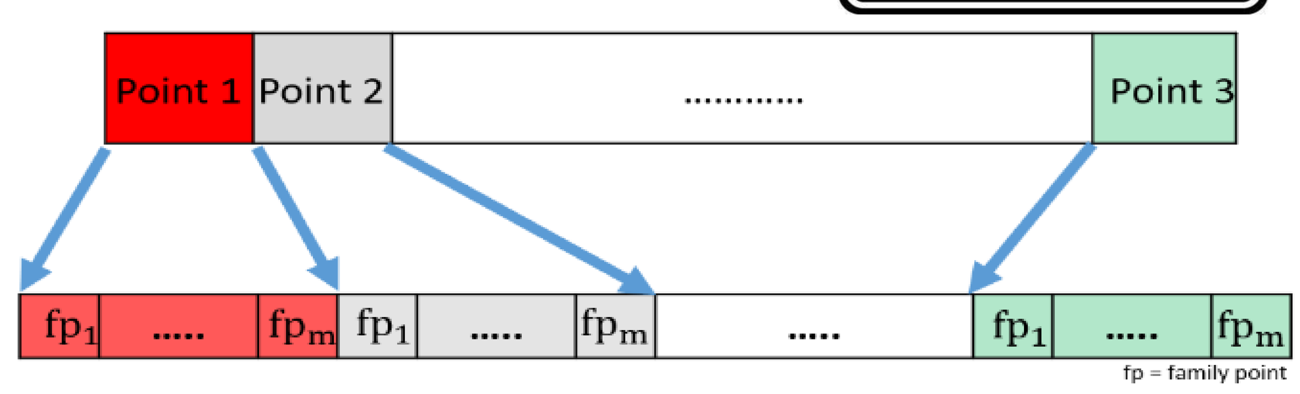
$$\varphi(\boldsymbol{x}_{(k)}, t) = 1 - \frac{\int_H \mu(\boldsymbol{x}_{(j)} - \boldsymbol{x}_{(k)}, t) dV_{(j)}}{\int_H dV_{(j)}}$$



4.Details about Numerical simulation & CUDA parallel scheme



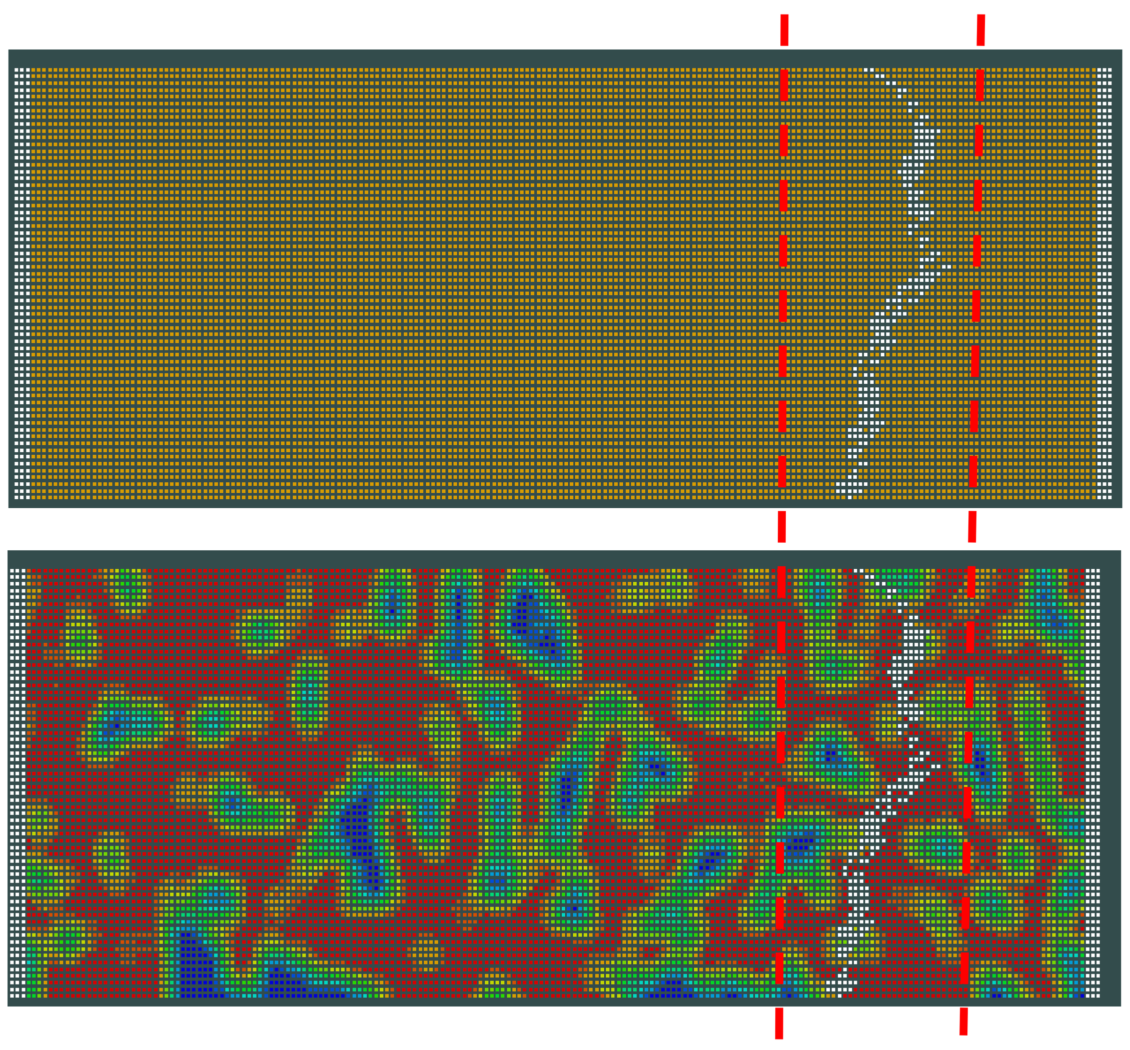
Data Structure



5.Results & Discussions

Specimen Size(mm)	Fiber orientation tensor
90*15*0.2	$\begin{bmatrix}0.5 & 0\\ 0 & 0.5\end{bmatrix}$

#	Tape size(mm)	Tape volume fraction (%)	Tensile moduli(GPa)	Strength moduli(MPa)	(PD)Tensile moduli(GPa) Avg & CV	(EXP)Tensile [7] moduli(GPa) Avg & CV	(PD)Strength moduli(MPa) Avg & CV	(EXP)Strenth [7] moduli(MPa) Avg & CV
0	5*6	79.2%	30.3	208	35.8(0.11)	39.3(0.015)	304(0.19)	391(0.06)
		91.7%	41.7	312				
		85.2%	35.2	307				
		87.1%	35.7	332				
		88.8%	36.1	360				
1	5*18	81.7%	32.4	309	36.2(0.08)	42.4(0.08)	377(0.11)	528(0.08)
		84.9%	39.1	382				
		88.2%	37.5	379				
		80.7%	34.6	402				
		89.3%	40.0	415				
2	5*30	84.5%	39.6	405	41.6(0.05)	48.4(0.04)	418(0.05)	537(0.06)
		90.2%	44.7	446				
		78.2%	39.5	421				
		86.2%	42.7	392				
		85.7%	41.3	428				



[1] Wan Y, Takahashi J. Tensile and compressive properties of chopped carbon fiber tapes reinforced thermoplastics with different fiber lengths and molding pressures. *Compos Part A – Appl Sci*,2016;87:271–81.

[2] P. Qu, Y. Wan, C. Bao, Q. Sun, G. Fang and J. Takahashi. A new numerical method for the mechanical analysis of chopped carbon fiber tape-reinforced thermoplastics. *Compos Struct*, 2018;201:857-866.

[3] Silling SA. Reformulation of elasticity theory for discontinuities and long-range forces. *J Mech Phys Solids*, 2000;48:175–209.

[4] Advani SG, Tucker III CL. The use of tensors to describe and predict fiber orientation in short fiber composites. *Journal of Rheology*, 1987;31:751-84.

[5]] Madenci E, Oterku E. PeridynamicTheory and Its Applications. 1st edition, Shanghai Jiao Tong University Press 2019.

[6] Zheng G, Shen G, Xia Y, et al. A bond-based peridynamic model considering effects of particle rotation and shear influence coefficient. *International Journal for Numerical Methods in Engineering*. 2019.

[7] Yamashita S, Hashimoto K, Suganuma H, et al. Experimental characterization of the tensile failure mode of ultra-thin chopped carbon fiber tape-reinforced thermoplastics. *J Reinfo Plastics Composites*, 2016; 35(18): 1342–1352.

Acknowledgement

This work was supported by JST SPRING, Grant Number JPMJSP2108. The authors would like to express sincere thanks to the Industrial Technology Center of Fukui Prefecture for supplying the specially developed CFRTP-SMC materials and to the members who have provided valuable information and useful discussions.