Multiscale forming simulation of carbon fiber reinforced thermoplastics: an application of supercomputer

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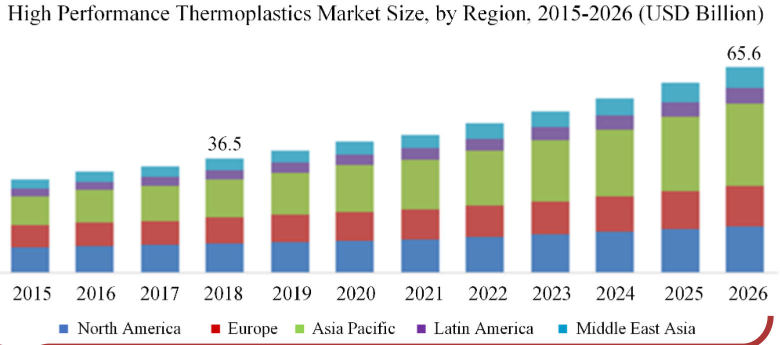
1 Background

Forming Process of Carbon Fiber Reinforced Thermoplastics

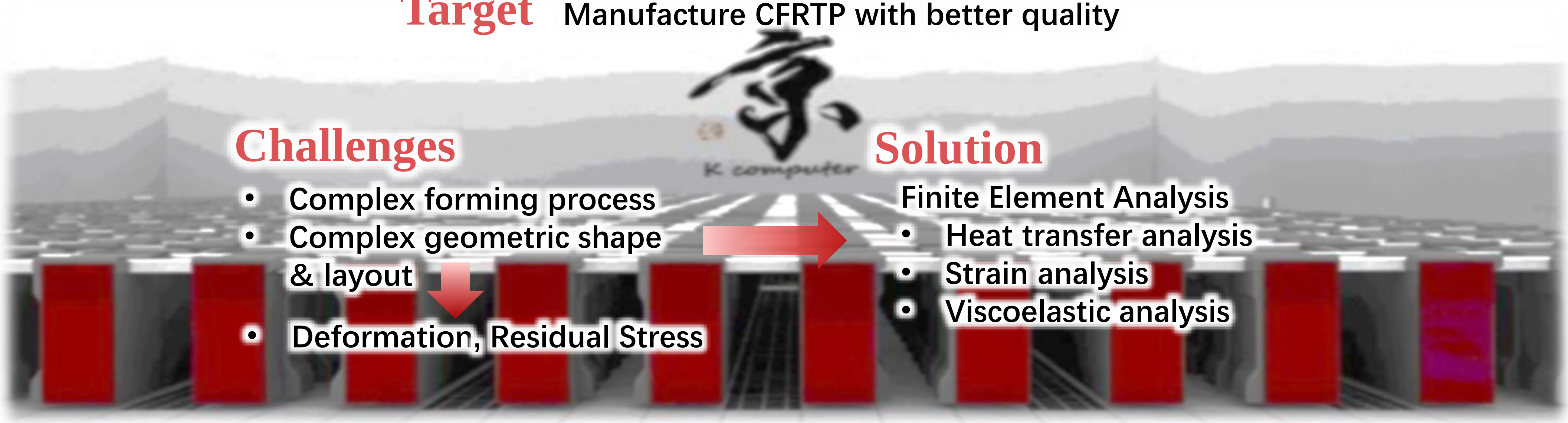
Carbon fiber reinforced thermoplastics (CFRTPs) have drawn increasing attentions from both academia and industry owing to its unique advantage of highly efficient production compared to thermosetting composite



Quoted: IHI, technical report

Commercial Forecast of High-Performance Thermoplastic Composites

Target Manufacture CFRTP with better quality



Challenges

- Complex forming process
- Complex geometric shape & layout
- Deformation, Residual Stress

Solution

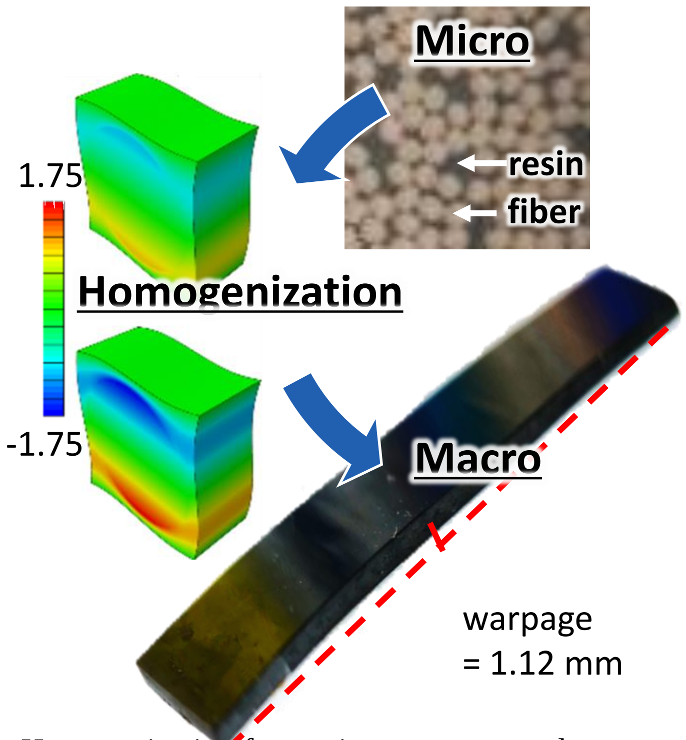
Finite Element Analysis

- Heat transfer analysis
- Strain analysis
- Viscoelastic analysis

1 Background

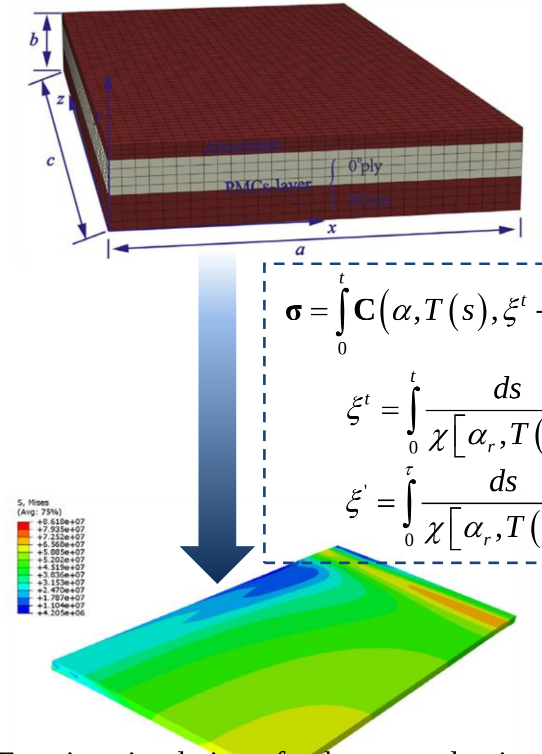
Key issues in the Forming Process Simulation

- Multiscale temperature/time-dependent material properties



Homogenization from micro to macro scale

- Modeling of three-dimensional (3D) thermo-viscoelastic material



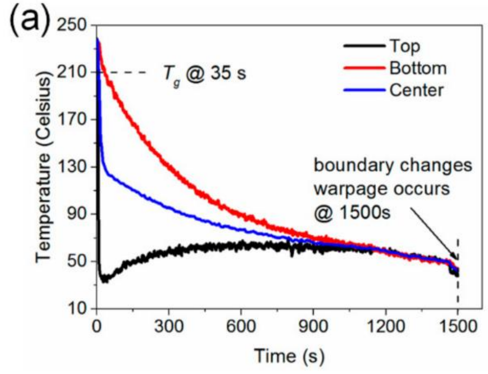
$$\boldsymbol{\sigma} = \int_0^t \mathbf{C}\left(\alpha, T(s), \xi^t - \xi'\right) \frac{\partial \boldsymbol{\varepsilon}_{eff}}{\partial \tau} d\tau$$

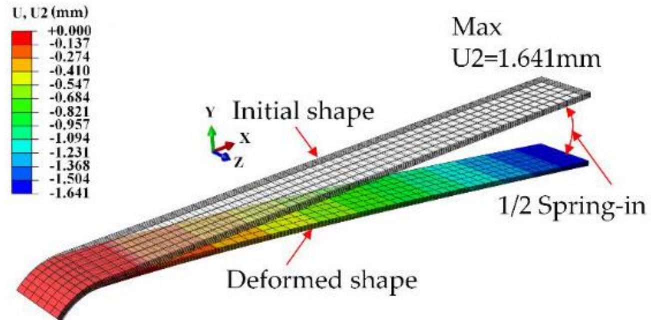
$$\xi^t = \int_0^t \frac{ds}{\chi\left[\alpha_r, T(s)\right]}$$

$$\xi' = \int_0^\tau \frac{ds}{\chi\left[\alpha_r, T(s)\right]}$$

Forming simulation of a thermoset laminate

- Temperature gradient & Tool-Part Interaction





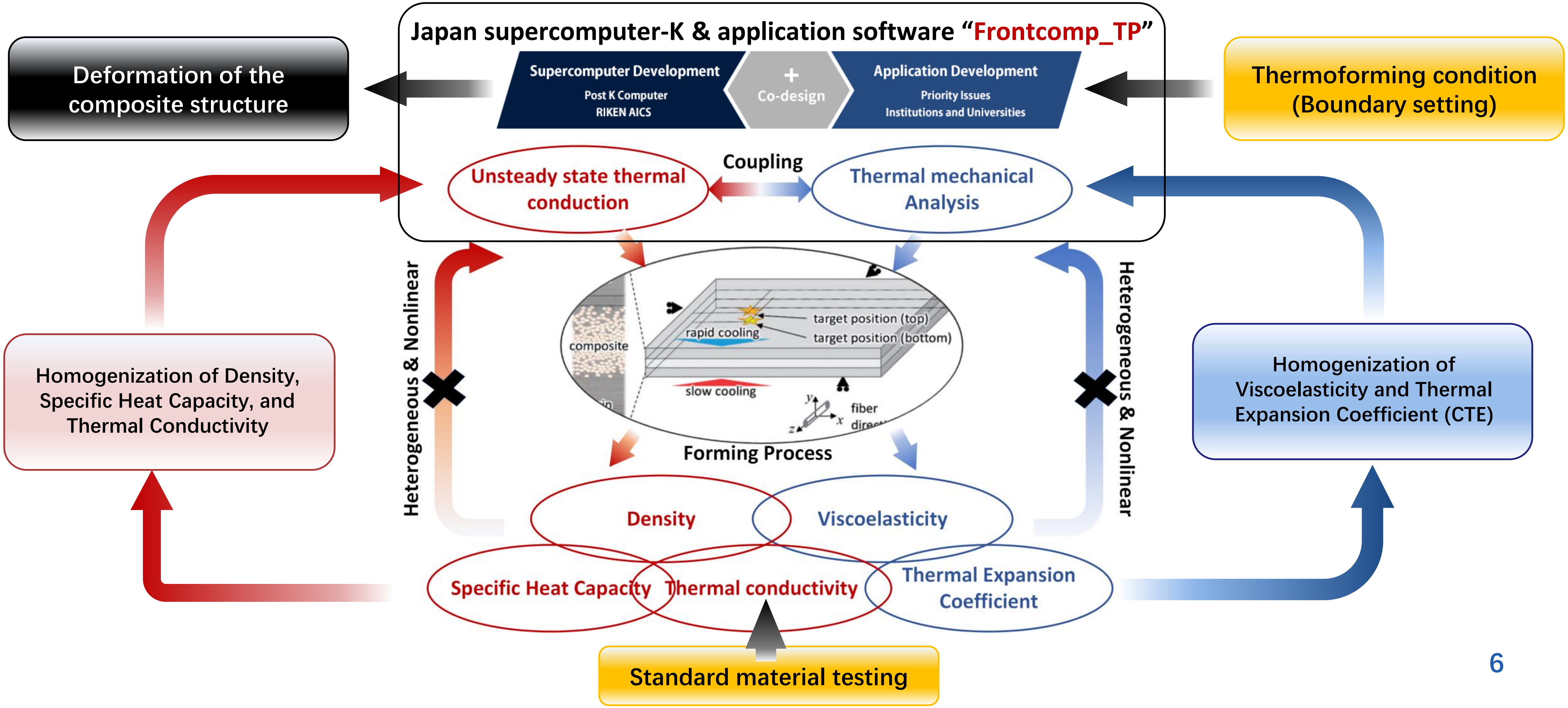
One-side cooling (Unbalanced cooling) of PEI plate
Forming simulation with/ without a shear layer

There are three key issues in the forming process simulation of CFRTP.

Quoted:
Composite Structures, 2015, 129: 60-69.
Materials, 2018, 11: 464(1-18).
Materials, 2020, 13(20): 1-13.

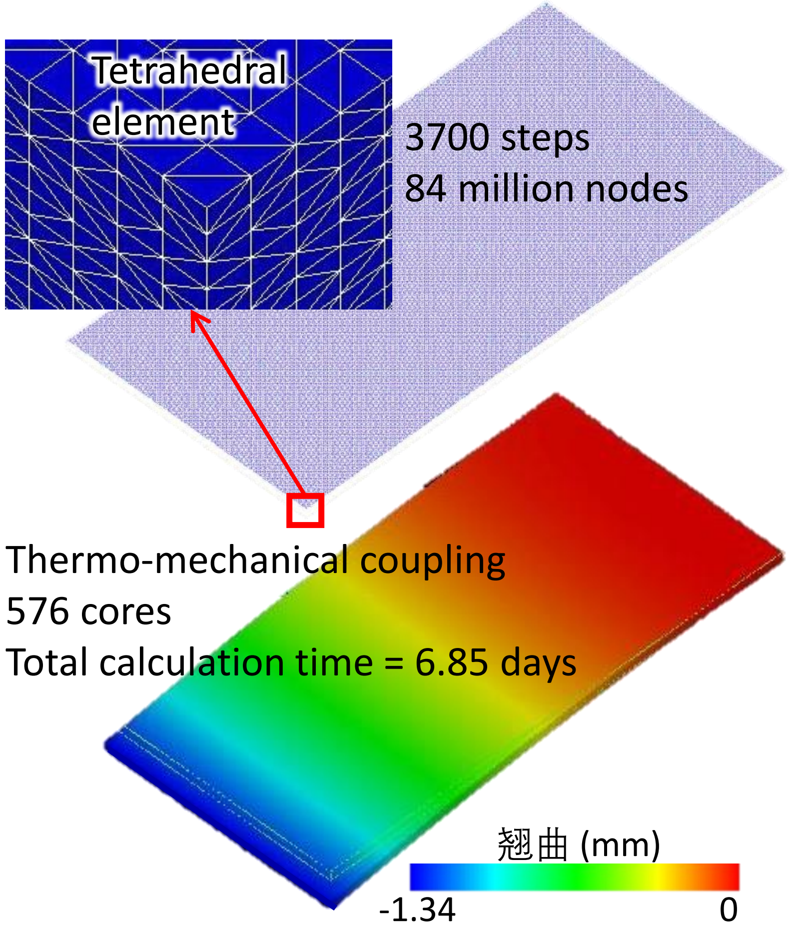
1 Background

Multiscale Simulation of the Forming Process

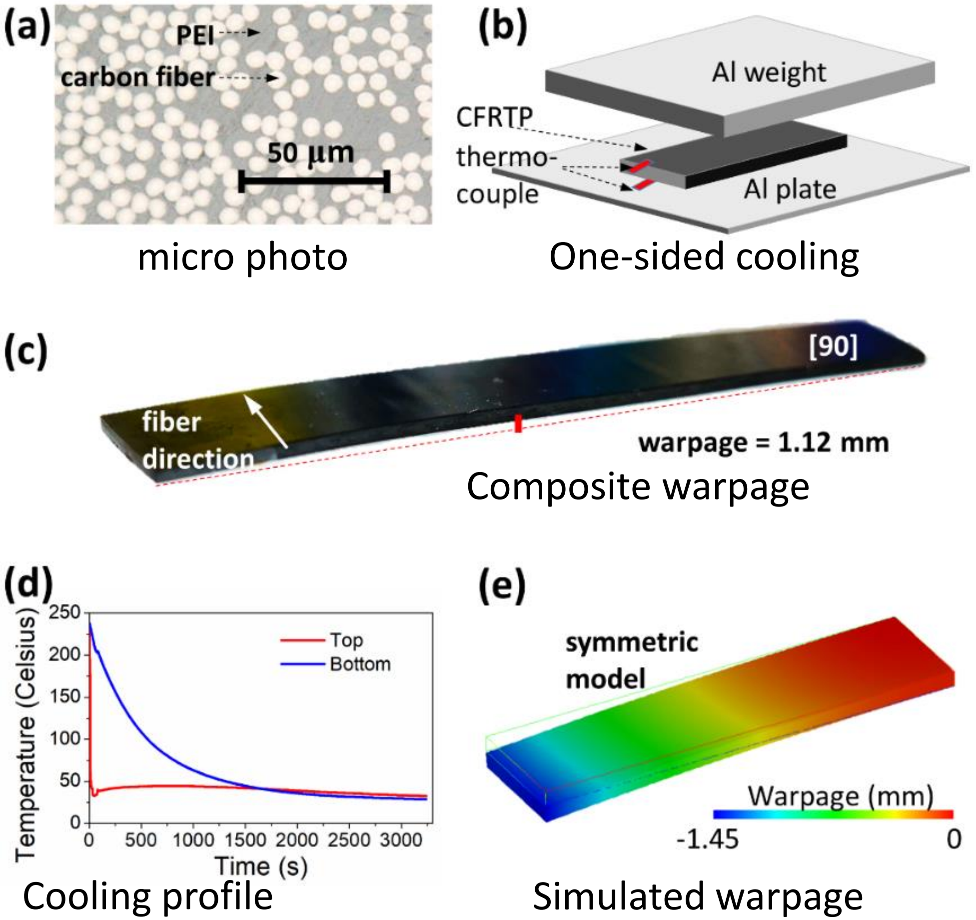


1 Background

FrontCOMP



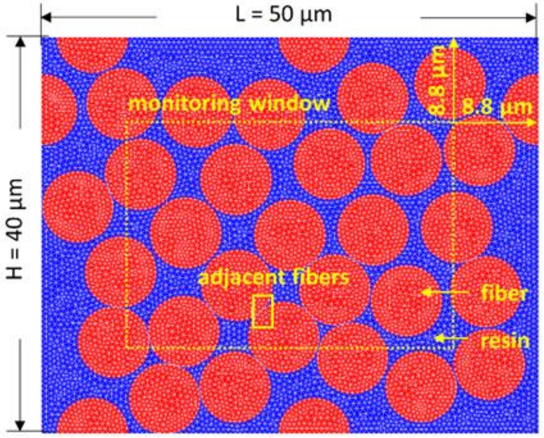
Massively parallel computing

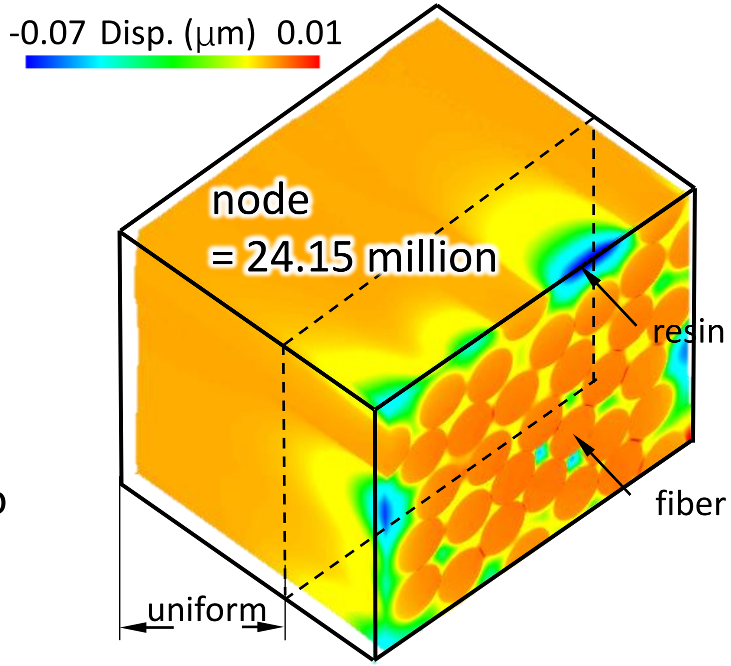


Experiment verification

1 Background

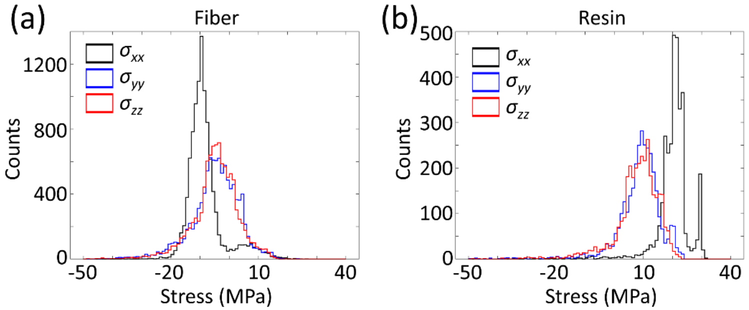
Simulation of long fiber composite



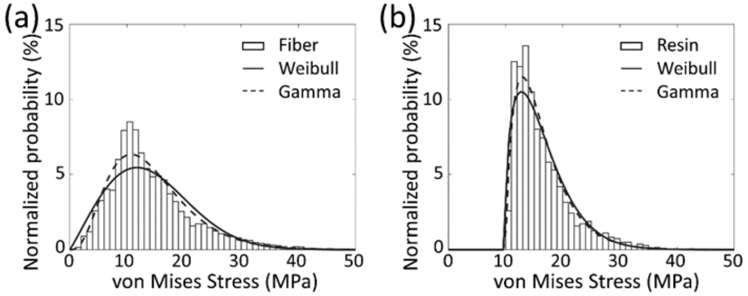


Using shear lag principle to extract useful information

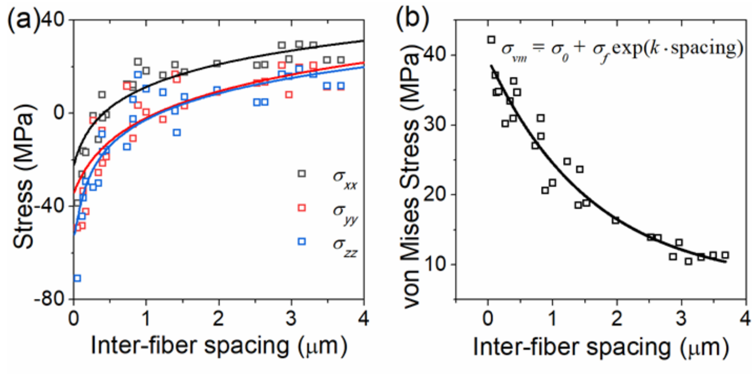
A large three-dimensional model of randomly distributed long fiber was established and solved, and the statistical distribution of the residual stress was given



Normal stress distribution



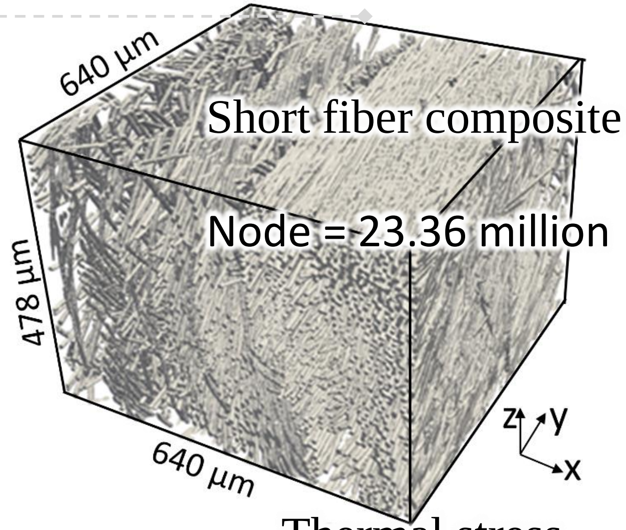
Stress within fiber and resin

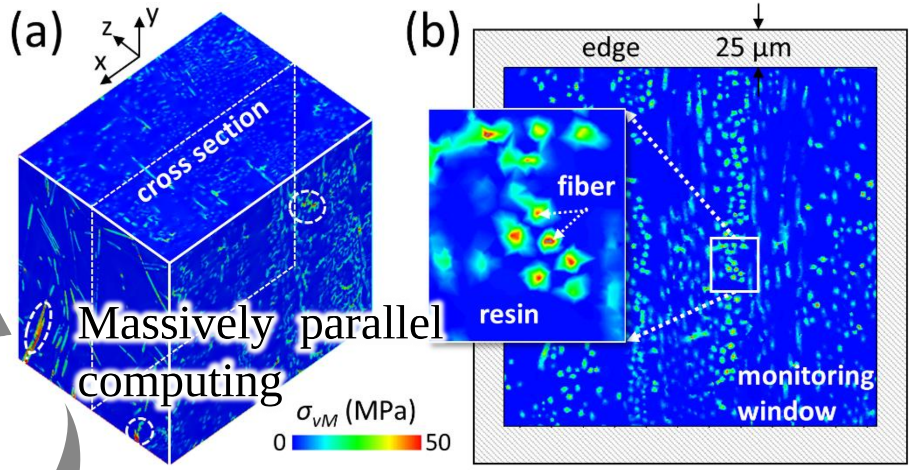


Relation between inter-fiber spacing & stress

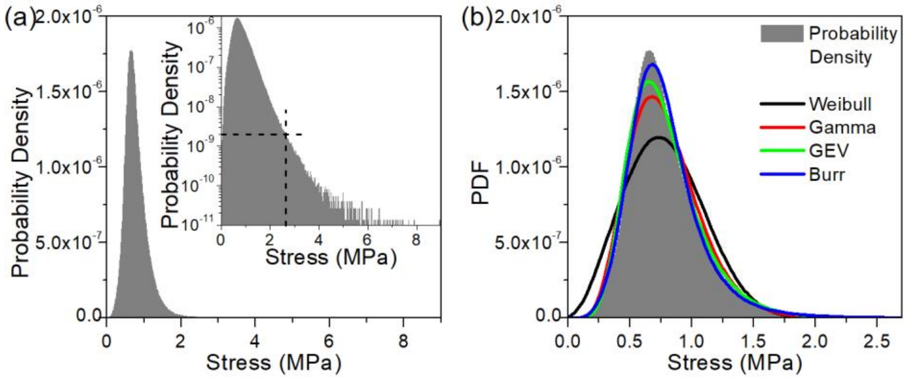
1 Background

Simulation of short fiber composite

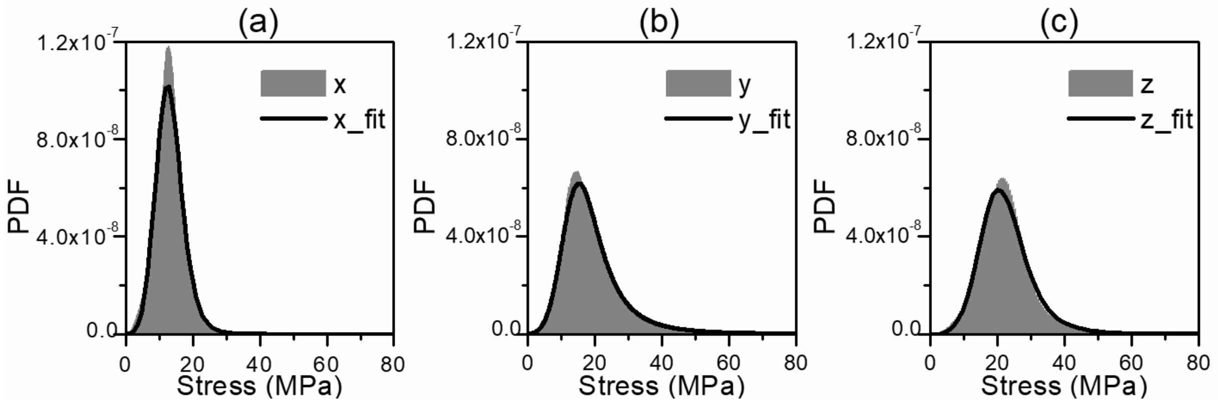




Thermal stress



Stress under mechanical loading



Large-scale finite element analysis of short fiber composites yields the statistical distribution of Burr function under thermal/mechanical loading, which explains the influence of microscopic stress on material strength

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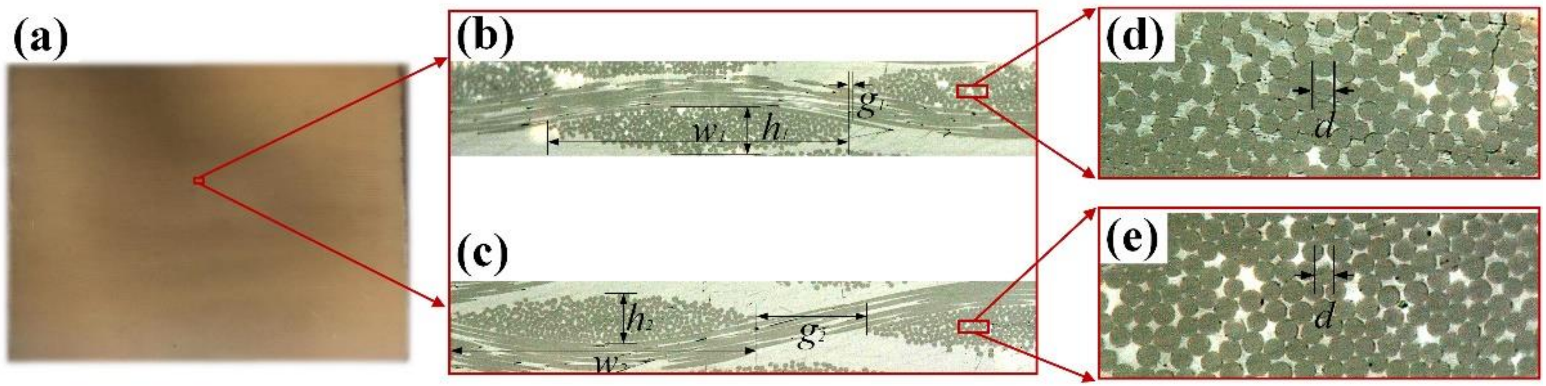
3 AH Method Implementation

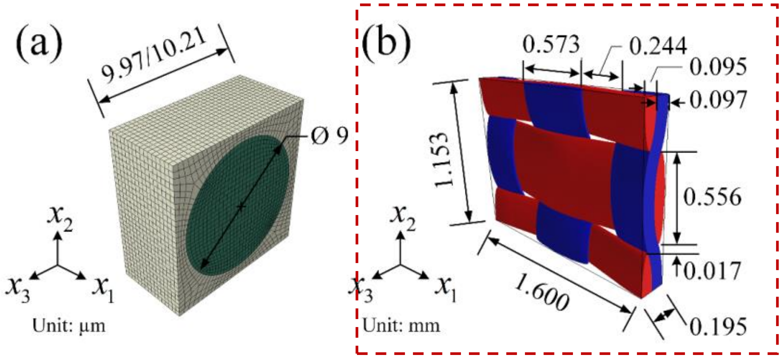
3.1 Forming Process and Two-Step Homogenization

GF/PEI woven fabric composites

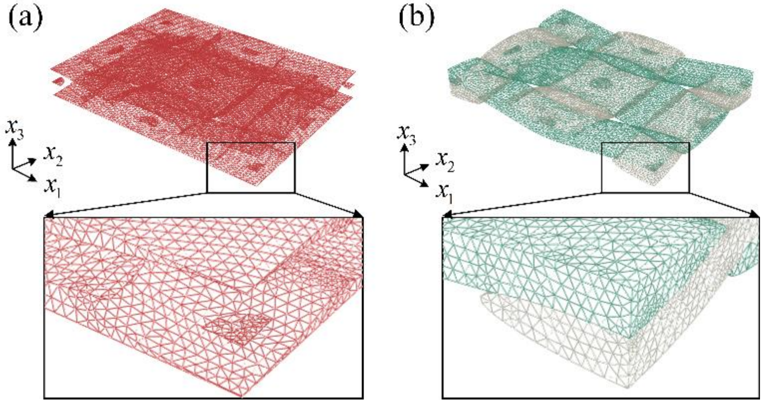


GF/PEI woven fabric composites

Two-Step Homogenization



UD-RVE and WF-RVE



FE model of the WF-RVE

Homogenization of thermal conductivity:
Node Number: 137949;
Element type: DC3D4.

Homogenization of viscoelastic & CTE:
Nodes number: 90510.
Element type: C3D4;

Two-step homogenization of woven fabric (WF) structure is developed using new strategy

AH Method Implementation

3.2 AH Implementation for Unsteady-State Thermal Conduction

Analytical Homogenization of Effective Density and Specific Heat Capacity:

$$V_f(T) = \frac{M_f/\rho_f(T)}{M_f/\rho_f(T) + M_{resin}/\rho_{resin}(T)} \quad \text{(a)}$$

$$\rho^h(T) = \rho_{warp}(T)V_{warp}(T) + \rho_{weft}(T)V_{weft}(T) + \rho_m(T)V_m(T) \quad \text{(b)}$$

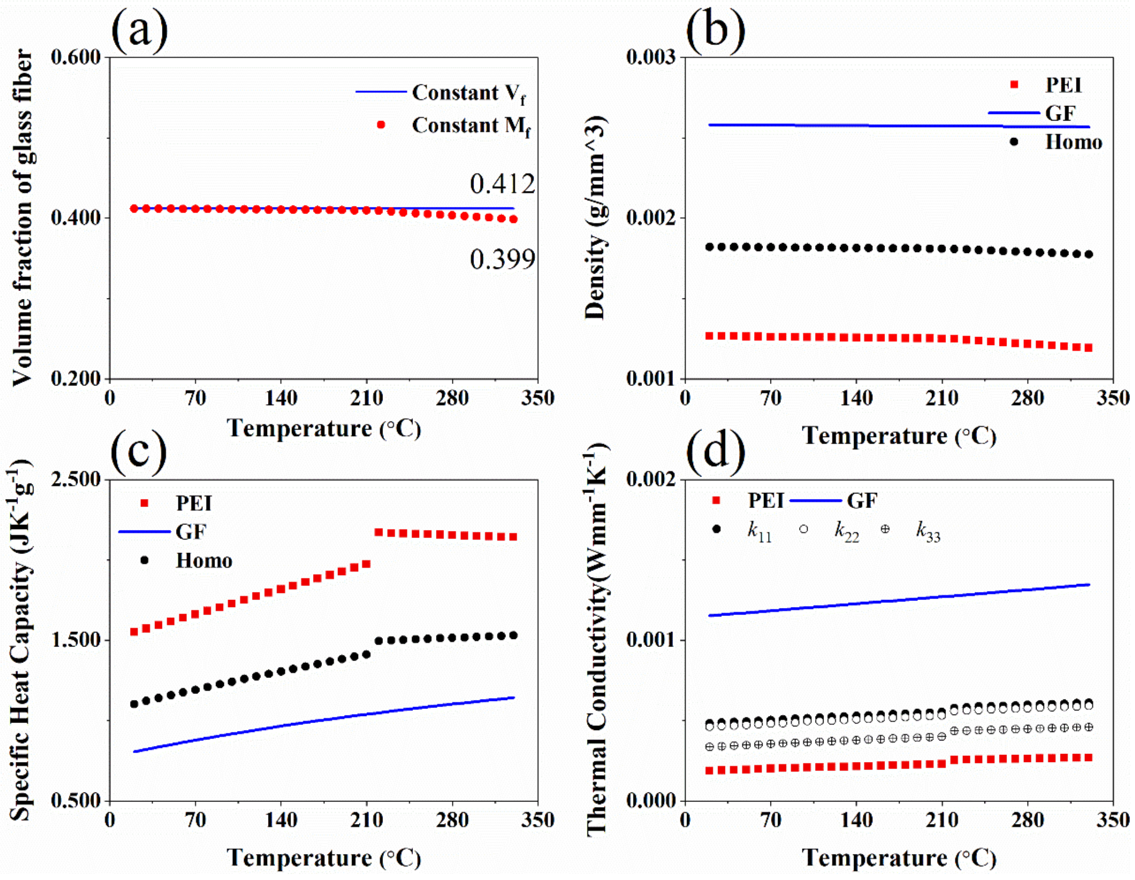
$$Cp^h(T) = Cp_{warp}(T)M_{warp}(T) + Cp_{weft}(T)M_{weft}(T) + Cp_m(T)M_m(T) \quad \text{(c)}$$

Effective Thermal Conduction Tensor:

$$k_{ij}^h = \left\langle k_{ij}(\mathbf{y}, T^\epsilon)\left[\mathbf{I}H(t) - \frac{\partial \chi^i(\mathbf{y}, T^\epsilon, t)}{\partial y_i}\right]\right\rangle_Y \quad \text{(d)}$$

Temperature-dependent

In contrast to the conventional AH method, the new space-time AH method can model temperature-dependency during the AH homogenization.



AH of thermal properties

: Cartesian Coordinate Vector; : Time; : Temperature; : Density; : Specific Heat Capacity; : Thermal Conductivity Coefficient; : Heat Flux; : Heat Source;
: Heterogeneous Fields/Heterogeneous Composite, , : the order of the asymptotic expansion series, volume averaged operator .

3 AH Method Implementation

3.3 AH Implementation for Linear Viscoelasticity

New Time-domain AH method

Integral Form Equation of Characteristic Displacement Tensor:

$$u_i^{(1)}(\mathbf{x},\mathbf{y},t) = -\frac{\partial \chi_i^{kl}(\mathbf{y},t)}{\partial t} * \frac{\partial u_k^{(0)}(\mathbf{x},t)}{\partial x_l}$$

$$\int_Y C_{ijkl}(\mathbf{y},t) * \frac{\partial}{\partial t}\frac{\partial \chi_k^{mn}(\mathbf{y},t)}{\partial y_l}\frac{\partial v_i(t)}{\partial y_j}dy = \int_Y \frac{\partial C_{ijmn}(\mathbf{y},t)}{\partial y_j} v_i(t)\,dy$$

One integral form characteristic displacement tensor

Effective Constitutive Equation:

$$\left\langle \sigma_{ij}^{(0)}(\mathbf{x},t)\right\rangle_Y = C_{ijmn}^h(t) * \frac{\partial}{\partial t}\frac{\partial u_m^{(0)}(\mathbf{x},t)}{\partial x_n}$$

Straightforward

Effective Relaxation Tensor:

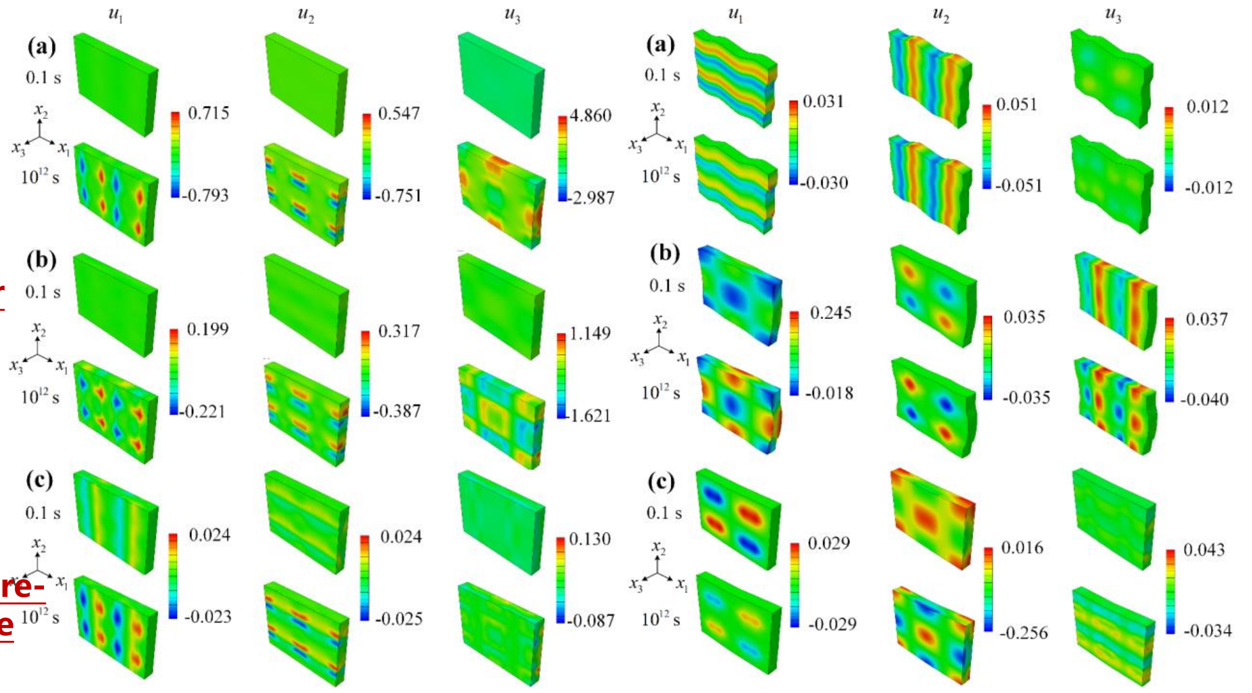
$$C_{ijmn}^H(t) = \left\langle C_{ijkl}(\mathbf{y},t) * \left[I_{klmn}\delta(t) - \frac{\partial}{\partial t}\frac{\partial \chi_k^{mn}(\mathbf{y},t)}{\partial y_l}\right]\right\rangle_Y$$

Time-Temperature Superposition Principle:

$$C_{ijkl}^h(T,\tau) = C_{ijkl}^h\left(T_0, \frac{\tau}{a_T^m}\right) = C_{ijkl}^h(T_0,t)$$

Time- and temperature-dependent effective relaxation tensor

Characteristic Displacement Tensor:



Characteristic displacement tensor components of the woven fabric composite

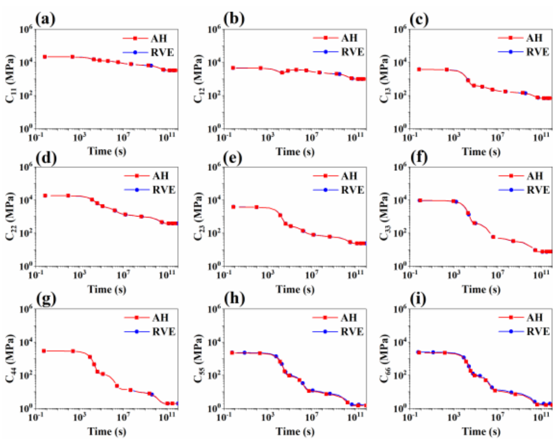
The AH method can compute time-dependent characteristic displacement tensors and the effective relaxation tensor straightforwardly, and do not need Laplace transform.

$\mathbf{x}$ & $\mathbf{y}$: *Cartesian Coordinate Vector;* t : *Time;* σ : *Stress;* ε : *Strain;* ζ : *Time;* C_{ijkl} : *Relaxation Stiffness;* f_i : *Body Stress;* a_T^m : *Time-temperature Shift Factor of Matrix;* a_T^m *Reduced Time;* Ω^ϵ : *Heterogeneous Fields/Heterogeneous Composite,* i,j,k,l,m and $n=\{1,2,3\}$, κ : *the order of the asymptotic expansion series,* $\langle\cdot\rangle_Y$ *volume averaged operator* $\langle\cdot\rangle_Y = \frac{1}{V_Y}\int \cdot dy$.

3 AH Method Implementation

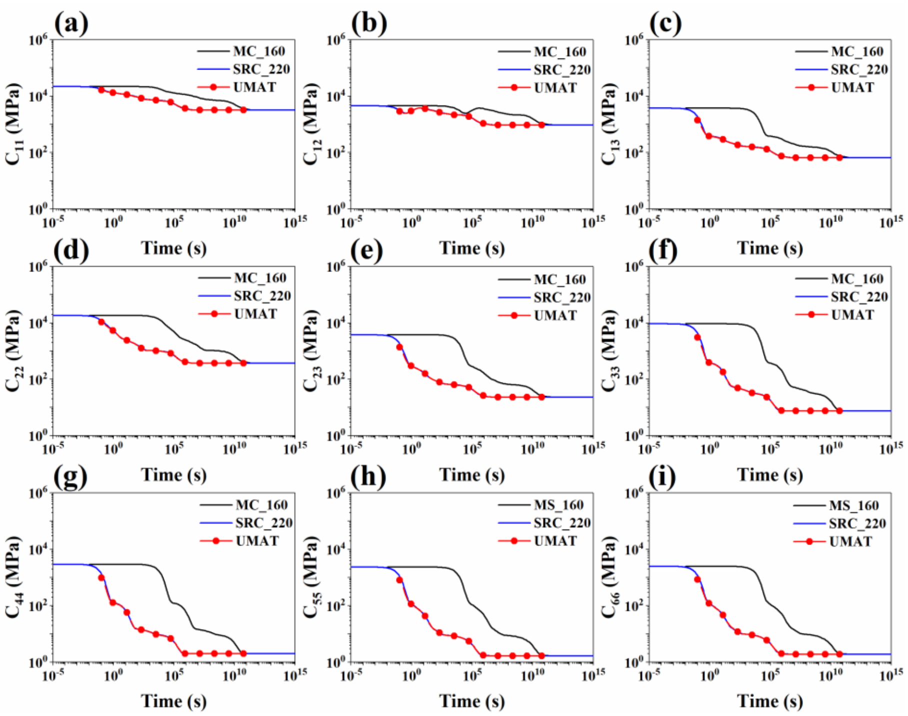
3.3 AH Implementation for Linear Viscoelasticity

Master Curves (@ 160 ℃)



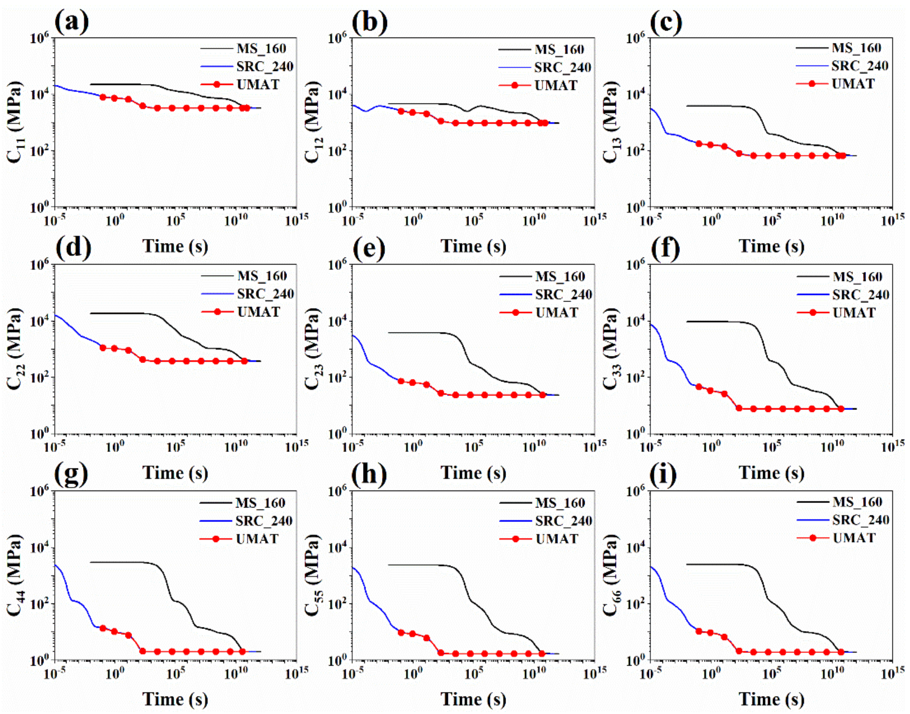
Master Curves of Effective relaxation stiffness at 160 ℃

Shifted Relaxation Stiffness (from 160 to 220 ℃)



Relaxation Curves of Effective relaxation stiffness at 220 ℃

Shifted Relaxation Stiffness (from 160 to 240 ℃)



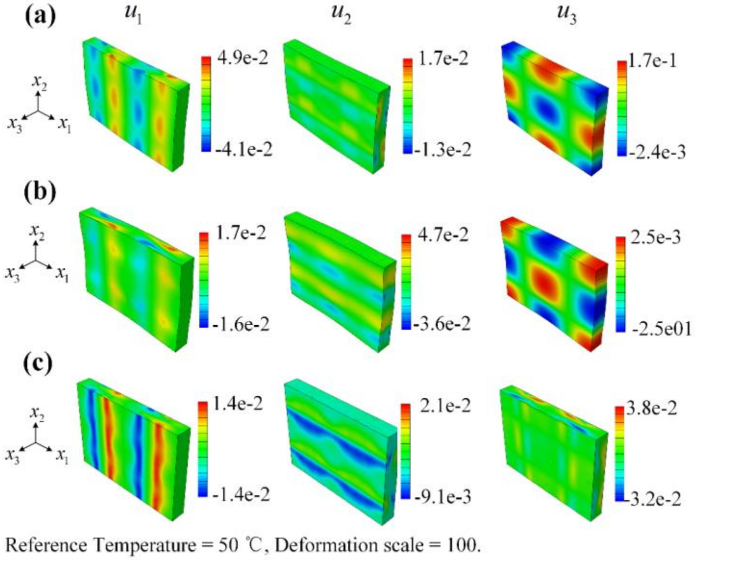
Relaxation Curves of Effective relaxation stiffness at 240 ℃

The UMAT subroutine is efficient in modeling a 3D anisotropic viscoelastic material, and the computation results are accurate. Therefore, the shortage of modeling 3D viscoelasticity in the ABAQUS is fixed.

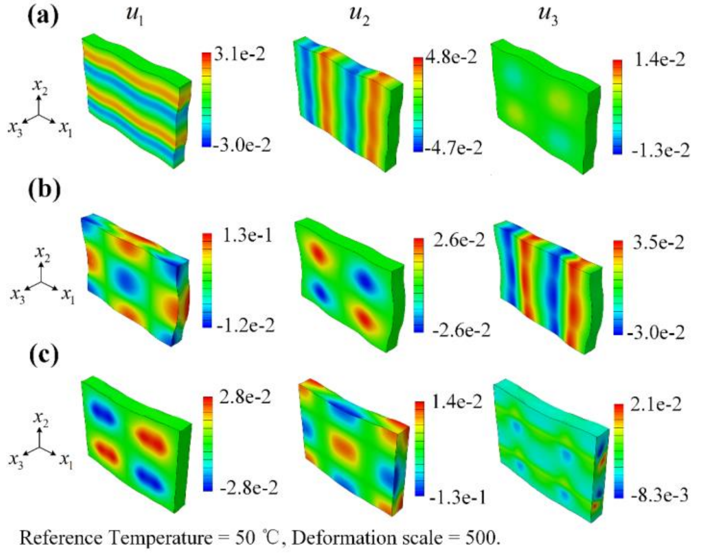
3 AH Method Implementation

3.4 AH Implementation for Thermal Expansion Coefficient

Mechanical Characteristic Displacement Tensor:

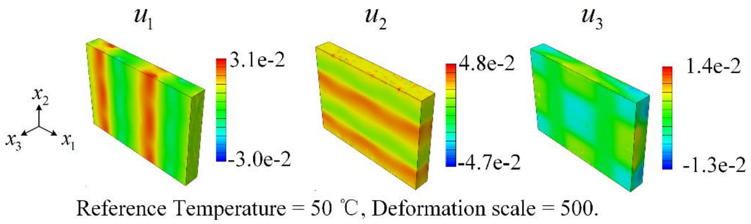


Mechanical characteristic displacement tensor in normal directions



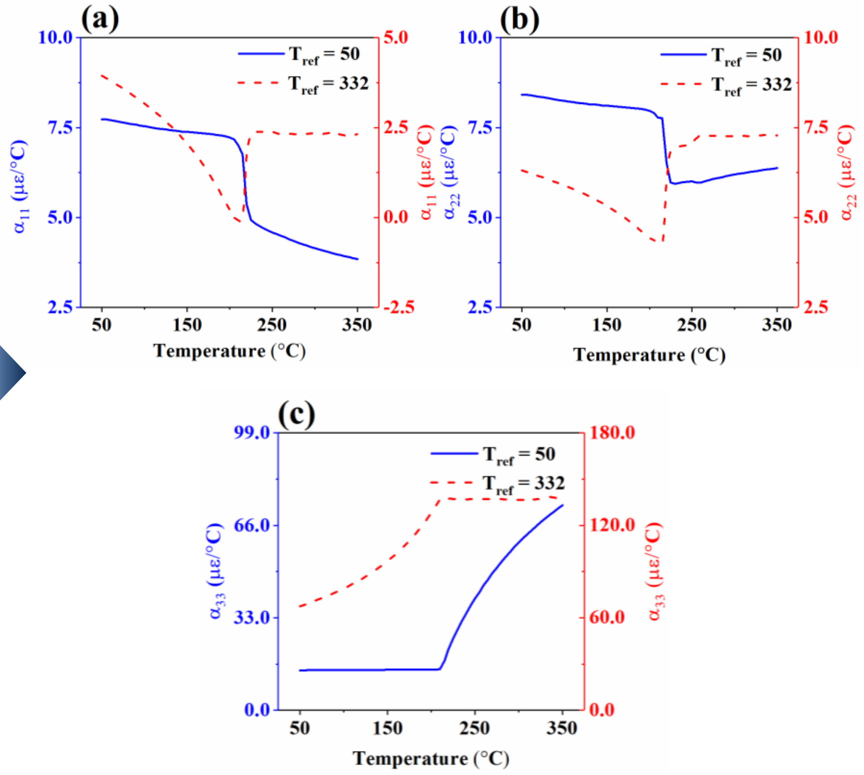
Mechanical characteristic displacement tensor in shear directions

Thermal Stress Characteristic Displacement Tensor:



Thermal stress characteristic displacement tensor

Effective CTE:



Temperature-dependent effective thermal expansion coefficient

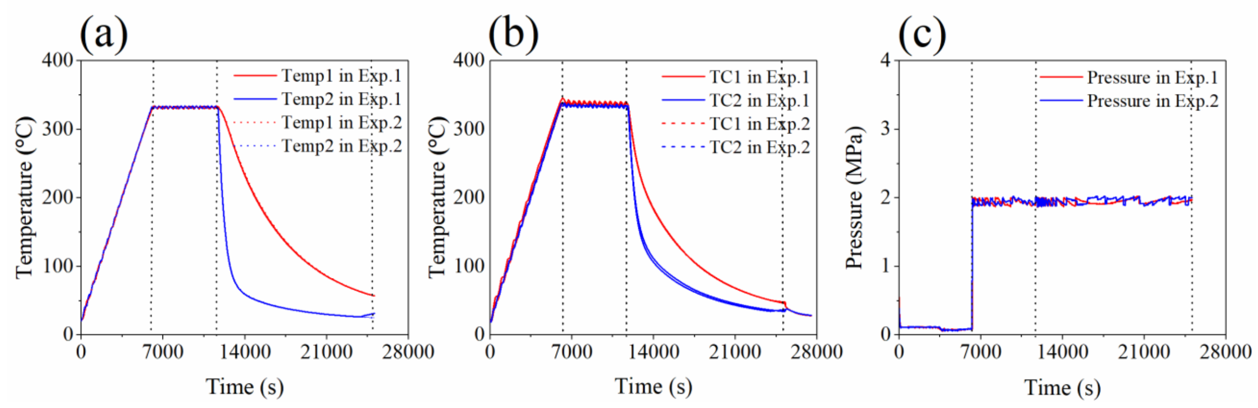
Results in Figs. 36-39 indicate that the AH implementation method is efficient to compute mechanical and thermal stress characteristic temperature tensors, as well as the temperature-dependent CTE.

Content

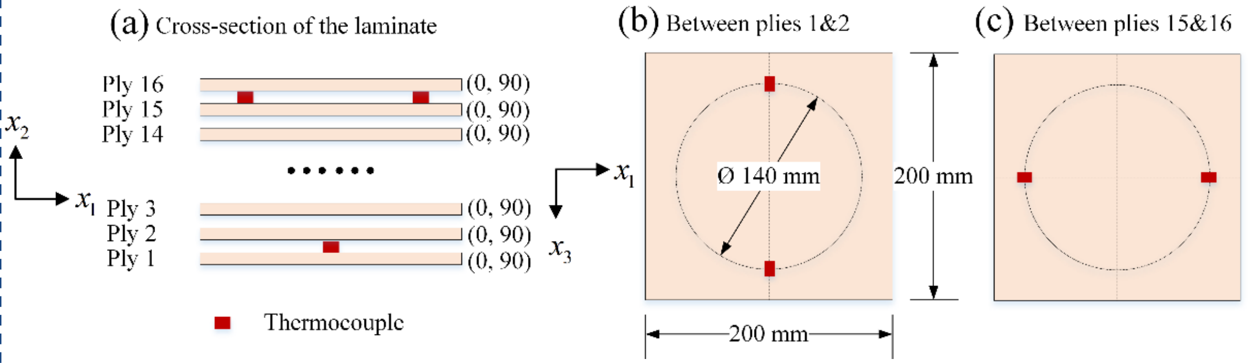
4 Research on the Forming Process of GF/PEI Laminate

4.1 Thermoforming Experiment

Forming Experiment of the GF/PEI Woven Fabric Composite

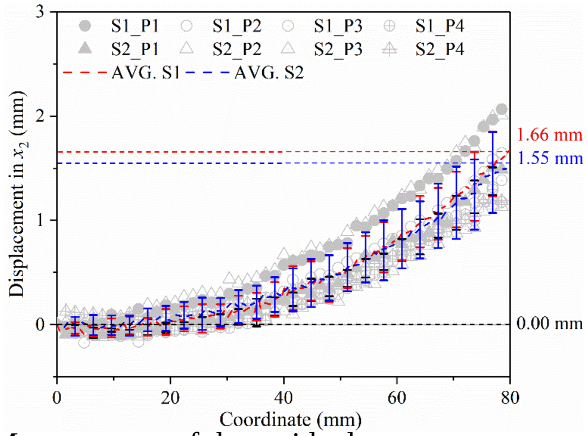


Temperature and pressure profiles during the forming process



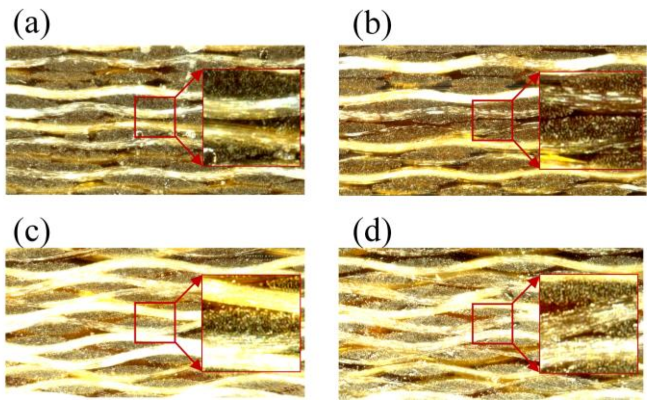
Embedded thermocouple in GF/PEI laminate

Macroscale



Measurement of the residual warpage

Mesoscale

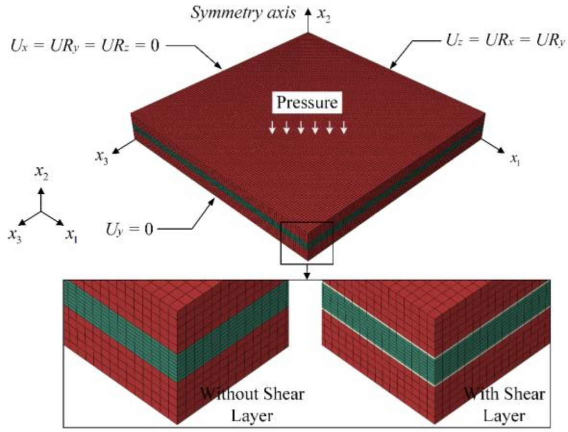


Mesoscale graphics of GF/PEI laminate

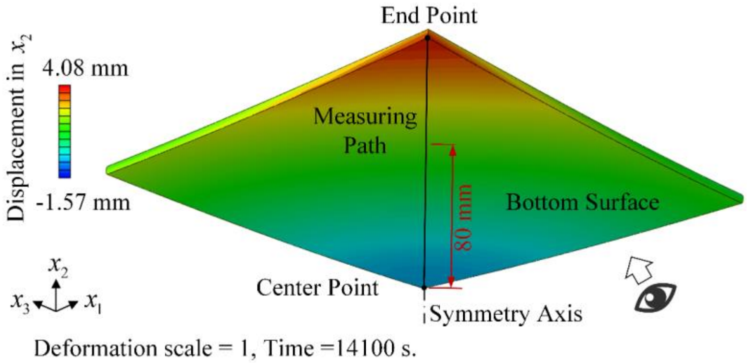
(1) The unbalanced temperature gradient causes warpage during the forming process.
(2) There are no voids in the GF/PEI woven fabric composites in the mesoscale.

4.2 Forming Simulation

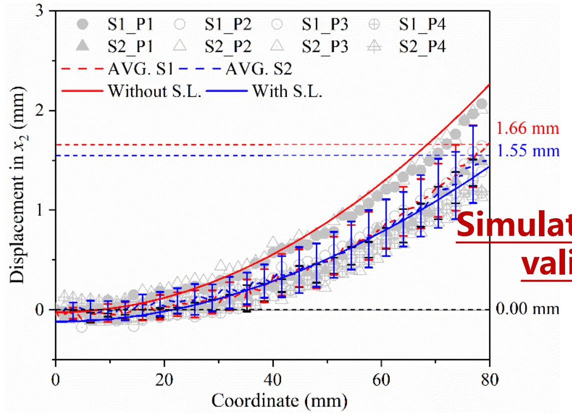
Forming Simulation and Residual Deformation



Finite element model of the ¼ laminate



Displacement contour in x_2



Warpage verification

Simulation results validation

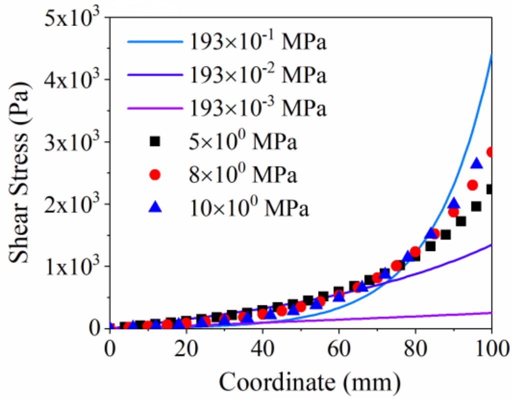
Shear Layer Model

Analytical Solution for Shear Stress:

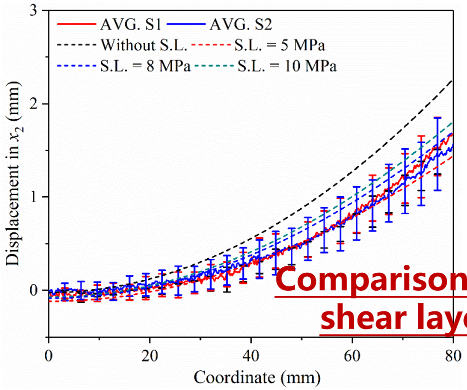
$$\tau = \frac{G_A(\alpha_2 - \alpha_1)\Delta T}{t_A \cdot \lambda} \frac{\sinh(\lambda x)}{\cosh(\lambda L)}$$

$$\lambda = \sqrt{\frac{G_A}{t_A} \frac{E_1 h_1 + E_2 h_2}{E_1 h_1 \cdot E_2 h_2}}$$

τ : Shear stress; G : Shear Modulus; ΔT :temperature change;
t_A : Shear layer thickness; h: height; α : CTE;
subscript 1 and 2 represents composite and mold.



Interfacial shear stress along the laminate



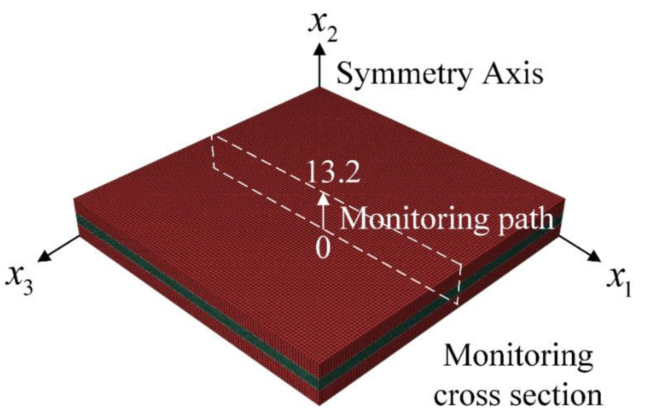
Comparison of the shear layer

Comparison of different shear layer moduli

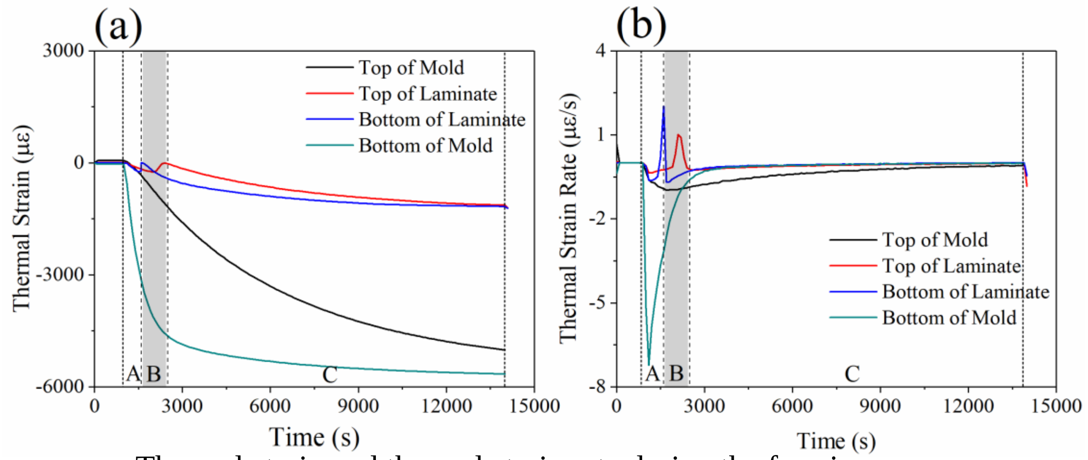
Employment of the shear layer can model the shear stress induced by the mismatch of CTE between mold and composite, and the most reasonable shear layer modulus is 5 MPa.

4.2 Forming Simulation

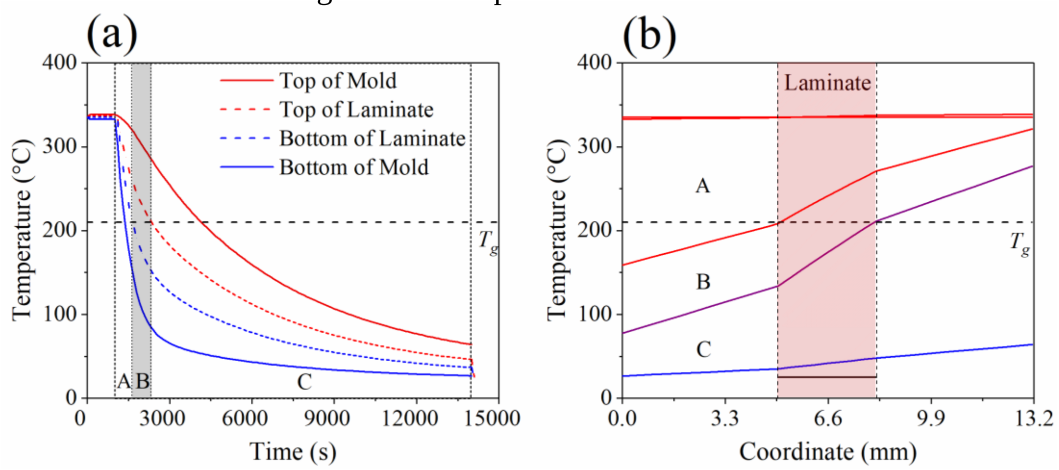
Discussion of the Temperature and Strain



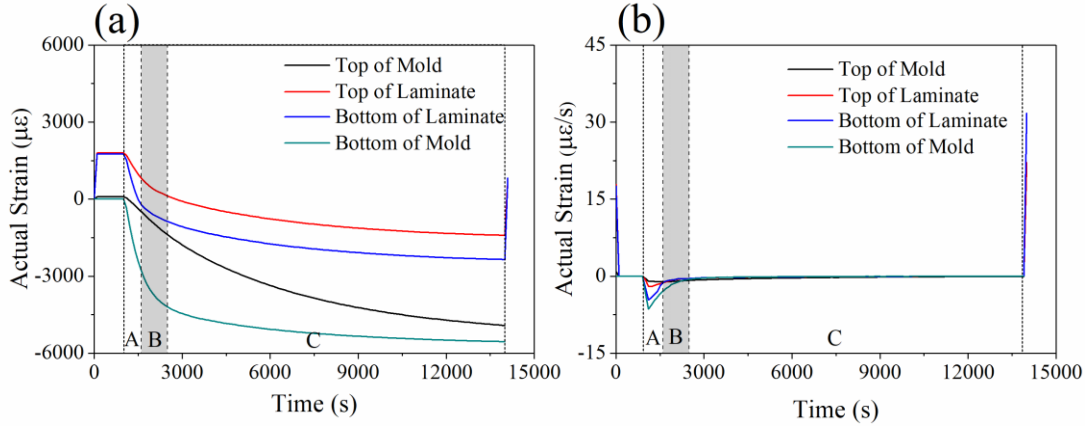
Monitoring section and path in the finite element model



Thermal strain and thermal strain rate during the forming process



Temperature change during the thermoforming process



Actual strain and actual strain rate during the forming process

The forming process can be divided into 5 stages based on the temperature profiles.

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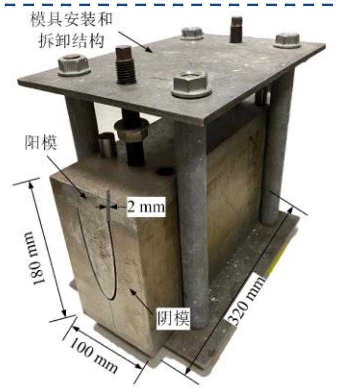
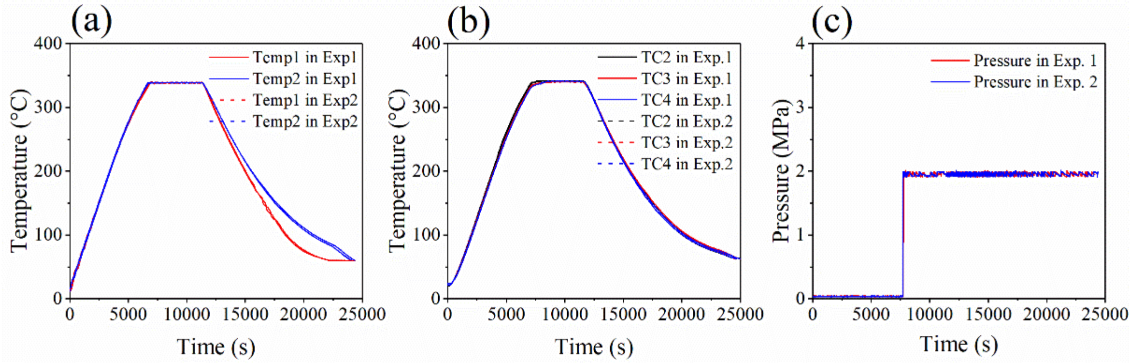
5 Research on the Forming Process of GF/PEI Wing Leading Edge

5.1 Multi-Step Thermoforming Experiment

Two-Step Fabrication Experiment of Wing Leading Edge



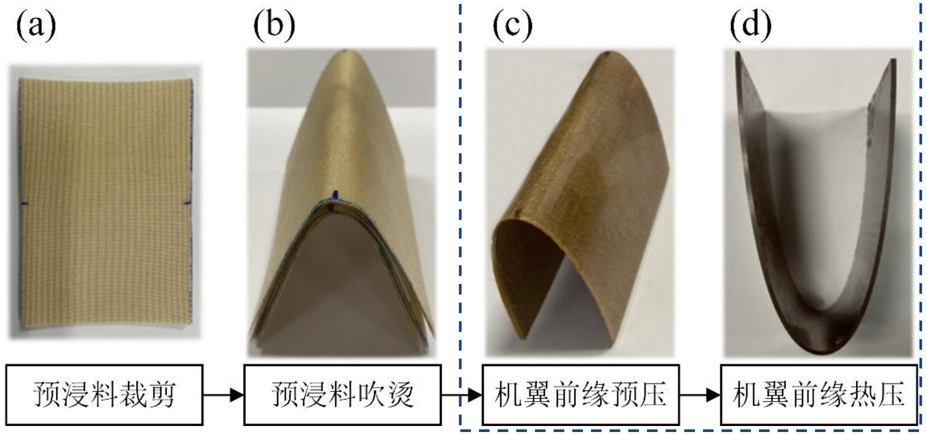
Molds for the wing leading edge



Temperature and pressure profiles during the thermoforming process

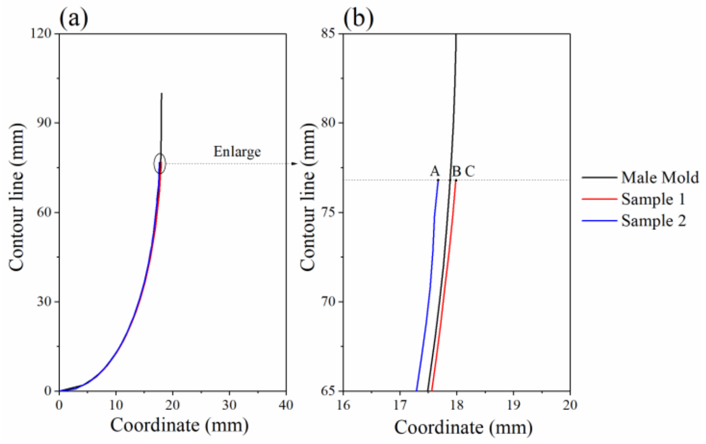
Mold, Temperature and Pressure

Prepregs



Multi-step thermoforming process

3D Scan Method



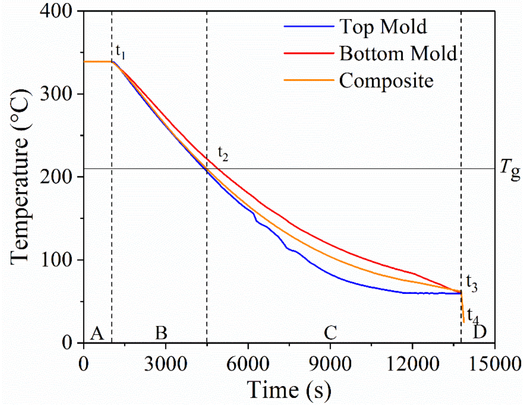
Residual Deformation

A two-step forming process is efficient to fabricate a GF/PEI composite wing leading edge.

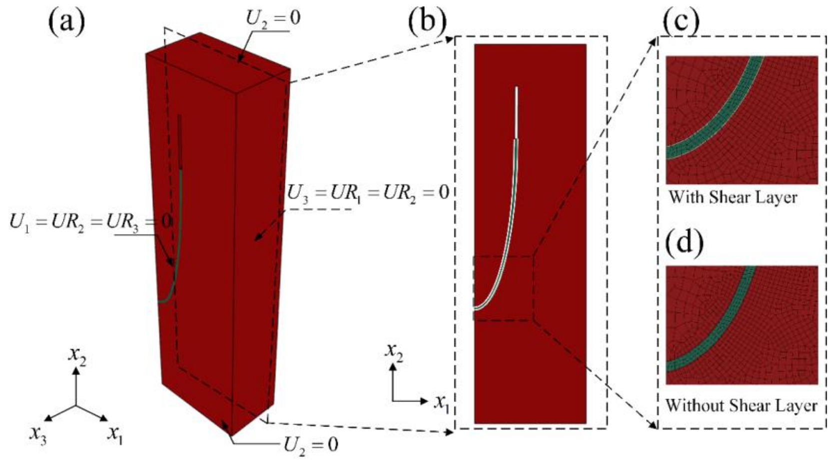
5 Research on the Forming Process of GF/PEI Wing Leading Edge

5.2 Forming Simulation

Forming Simulation

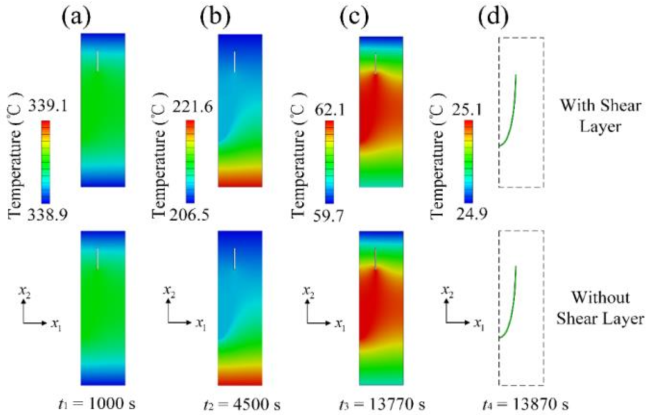


Temperature loads in the forming simulation

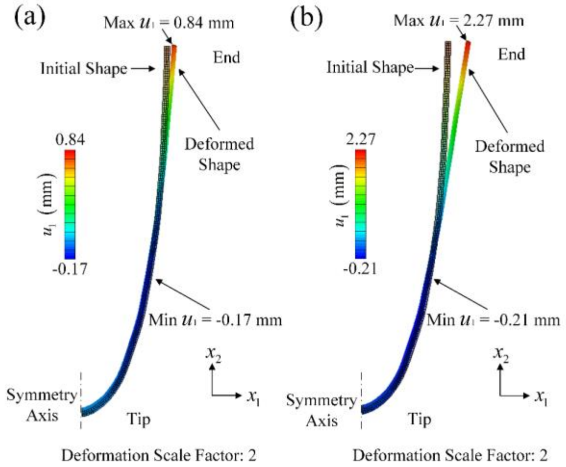


Temperature and pressure profiles during the thermoforming process

Temperature Gradient and Residual Displacement



Temperature contour during the forming process



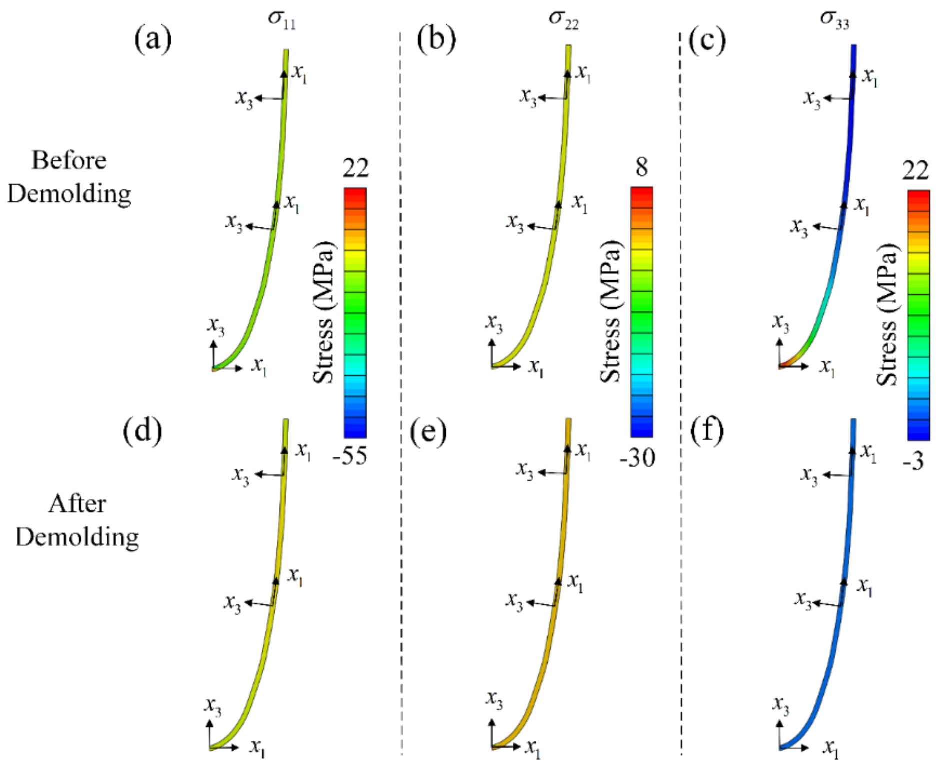
Residual deformation (a) with shear layer (b) without shear layer

Simulation result obtained by the shear layer is more accurate than the simulation result obtained by the finite element model without the shear layer.

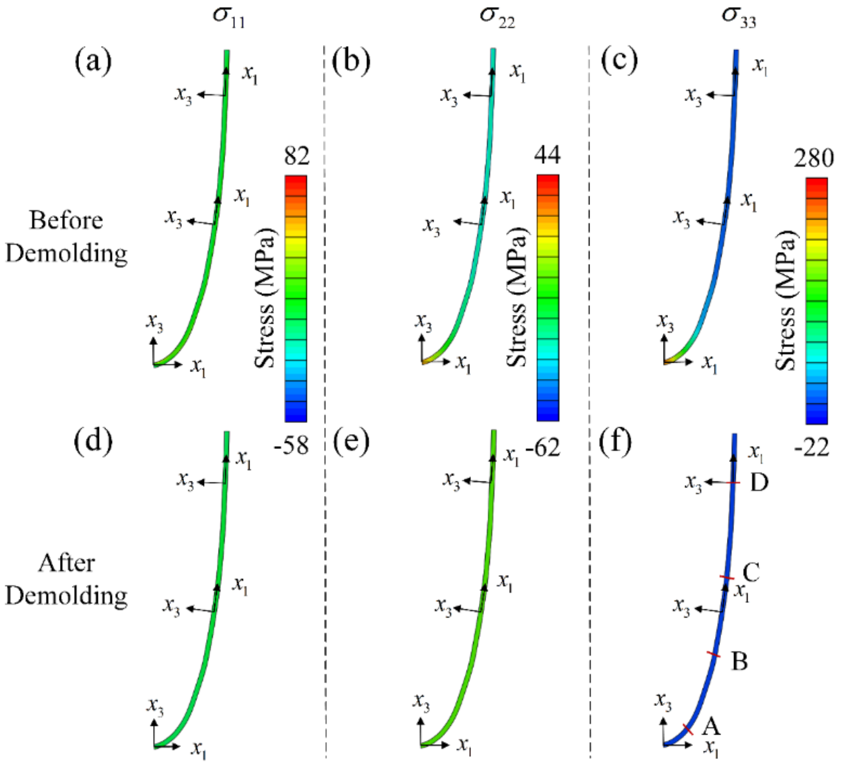
5 Research on the Forming Process of GF/PEI Wing Leading Edge

5.2 Forming Simulation

Stress Analysis:



Stress changes before and after demolding (with a shear layer)



Stress change before and after demolding (without shear layer)

σ_{11} and σ_{22} are the in-plane stress and are more balanced, σ_{11} is chosen for further warpage analysis. σ_{33} is the out-of-plane stress and has a stress gradient because the pressure varies over the shape of the wing leading edge.

Content

6 Summary

(1) Theoretical research on **asymptotic homogenization for unsteady-state thermal conduction, linear viscoelasticity and thermal expansion** in the thermo-viscoelastic composite is respectively studied and analytical methods for effective density, specific heat capacity, numerical implementation methods for effective thermal conductivity, linear viscoelasticity and thermal expansion coefficient are presented.

(2) Creating **unidirectional-RVE and woven fabric-RVE through experiment method**, calculating effective material moduli of GF/PEI composite and investigating the **temperature gradient influence on the stress, strain and residual deformation** during the forming process through experimental validation and numerical simulation.

(3) Proposing a multi-step forming technique to fabricate GF/PEI composite wing leading edge and simulating the forming process of a GF/PEI composite wing leading edge to study **temperature gradient and tool-part impacts on the residual deformation**, as well as the mechanism of warpage during the demolding process on the macroscale.

6 Acknowledgements

Acknowledgments

This work was supported in part by supported by MEXT as "Priority Issue on post-K computer" (Research and development of molding simulators for multiscale thermoplastic CFRP); in part by the computational resources of the K computer provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Project ID: hp170222), in part by the National Key R&D Program of China (2021YFF0501800), in part by the National Natural Science Foundation of China (no. 11972016), in part by the Grant of State Key Laboratory of Mechanics and Control of Mechanical Structures (no. MCMS-0517K02), in part by Chinese Scholarship Council: 201806830082, and in part by Postgraduate Research and Practice Innovation Program of Jiangsu Province (SJKY19_0171).

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Thank You!