Stony Brook University | College of Engineering & Applied Sciences

Department of Mechanical Engineering

# Temperature Effect on the Mechanics of Carbon Fiber Reinforced Polymers

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**Carbon fiber**

## Problem description

- Carbon fibers have perfect properties: high stiffness, high strength, low weight, high chemical resistance, high temperature tolerance.
- Carbon fiber reinforced polymers (CFRP) are increasingly used as a replacement of metallic materials – "material of future".
- For durable applications, the effect of harsh environments (i.e. moisture, UV radiation and extreme temperatures) on CFRP are of major considerations.
- Here the temperature effect (-100°C~100°C) is studied with static and dynamic three-point bending tests.

## Experiment method

- Specimen: 101.6 mm ×12.7 mm ×1.5 mm provided by Graphtek LLC.
- Quasi-static tests: performed using MTS Material Testing systems with a Environment Chamber integrated to enable mechanical testing at temperature -100°C ,-60°C, -20°C, 60°C, and 100°C (Fig. 1A).
- Dynamic tests: performed with a modified Split Hopkinson Pressure Bar (SHPB) facility with a liquid nitrogen cooled environmental chamber(-100°C, -60°C, -20°C, 25°C), and a high-speed imaging system (Fig. 1B).

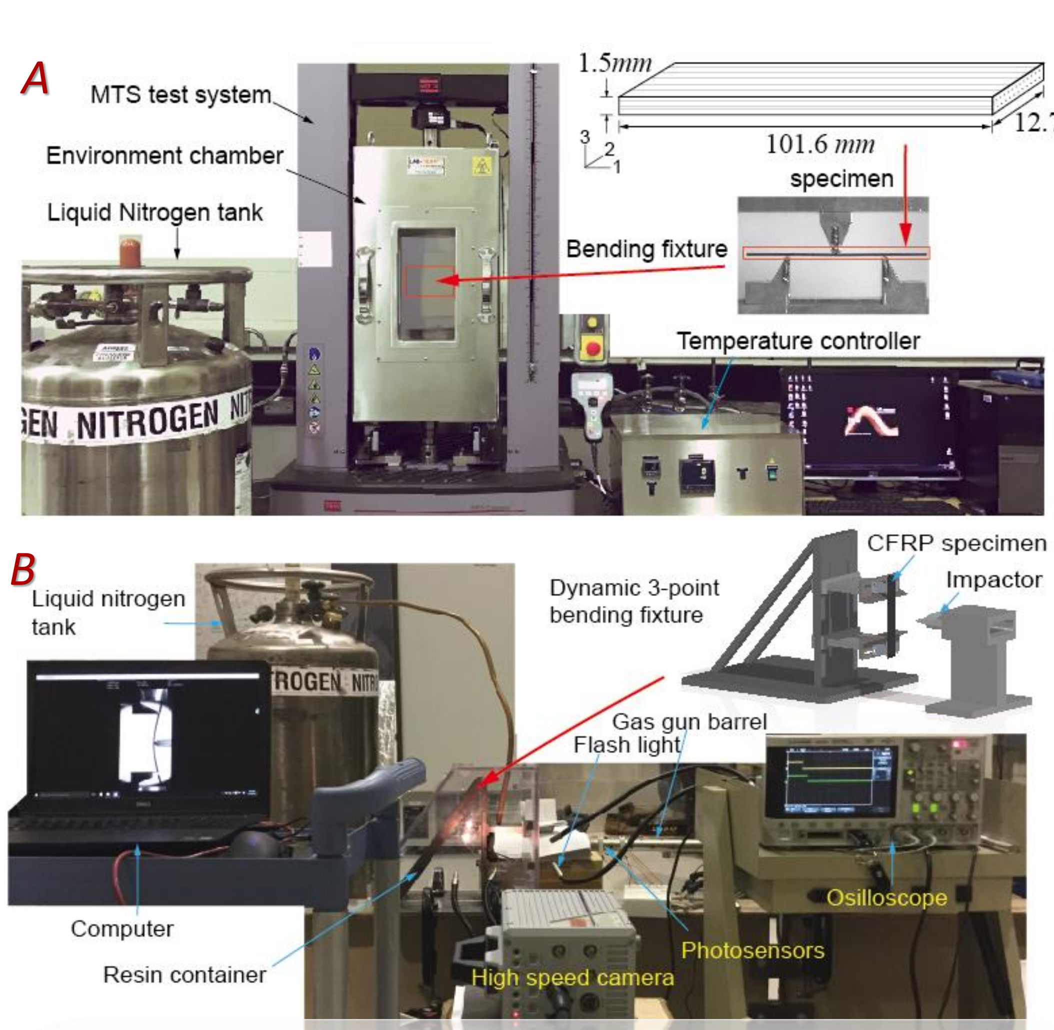


***Figure 1**. (A) Static and (B) dynamic three-point bending experiment setup. Specimen size is shown in upper right of A.*

## Results: static 3-point bending

- **CFRP is stiffer, stronger and tougher at lower temperatures**: both flexural modulus, flexural strength, flexural strain at break, and energy absorption increase significantly at lower temperatures (Fig. 2).
- The force displacement curves (Fig.2A) are characterized by a linear elastic regime followed by a stress drop, and part of the specimens show post break strength.
- This is related to: 1) temperature dependency of polymer mechanical property; 2) thermal stress generated when temperature changes.

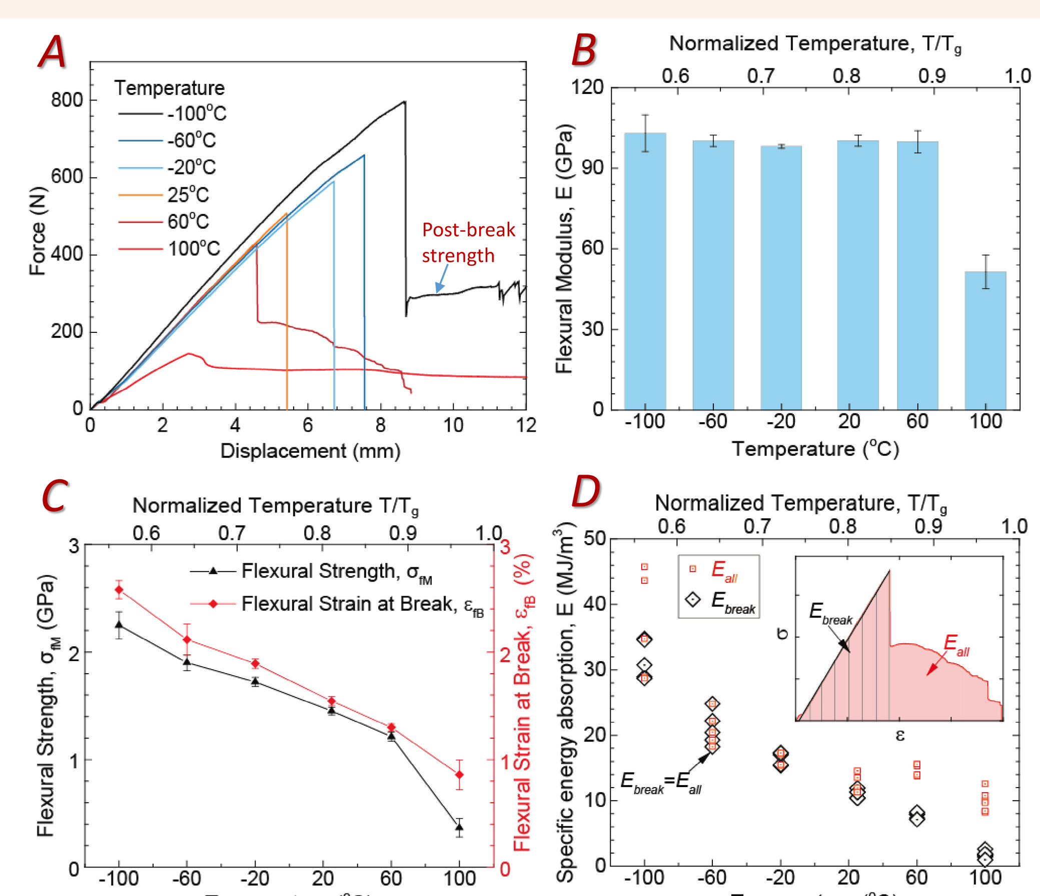


***Figure 2**. Static 3-point bending results at various temperatures: (A) force displacement curves, (B) flexural modulus, (C) flexural strength and flexural strain at break, and (D) energy absorption per volume.*

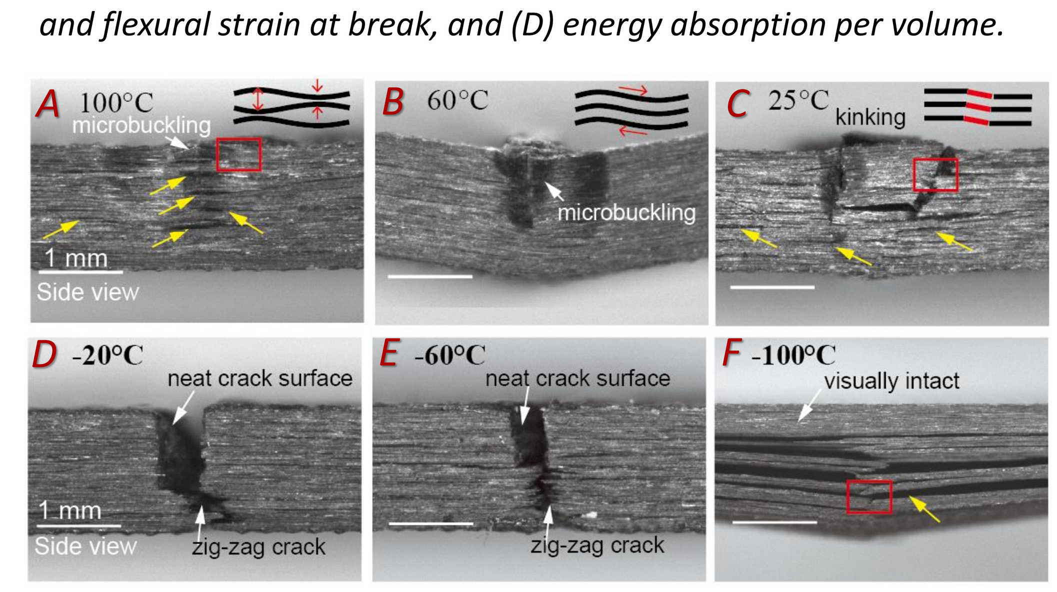


***Figure 3**. Post mortem photographs. (a) Extension mode microbuckling. (b) Shear mode microbuckling. (c) Kink band and inter-fiber cracks. (d), (e) Catastrophic damage. (f) Inter-fiber cracking at bottom layer.*

- **Rich damage patterns are observed:** buckling (Fig.3AB), kinking (Fig.3C), catastrophic cracking, inter-fiber cracking, and fiber pull out (Fig. 3F).
- Damage is highly temperature dependent, and a general trend of damage location transition from top surface to bottom surface are observed.
- SEM observation gives microscopic fractography.

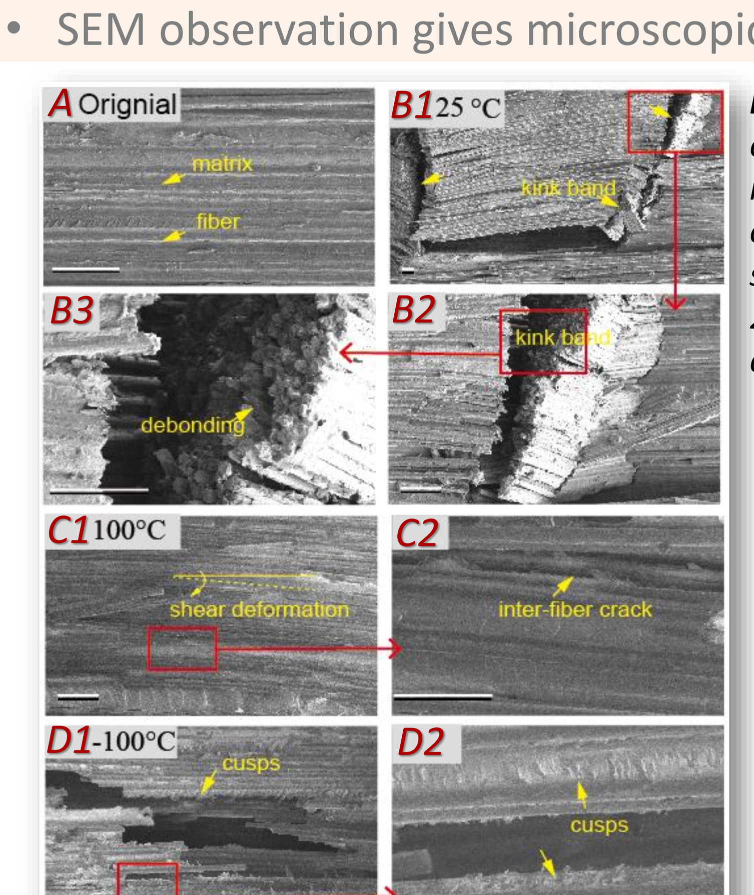


***Figure 4**. SEM image of the rectangular regions in Fig.3. (A) original specimen,& specimens at (B1-B3) 25°C, (C1-C2)100°C, and (D1-D2) -100°C.*

*Critical stress of Compression*

$$\sigma_{1c}^{ex} \cong 2V_f\left[\frac{E_m E_f V_f}{3(1-V_f)}\right]^{1/2}$$

$$\sigma_{1c}^{sh} \cong \frac{E_m}{2(1+\nu)(1-V_f)}$$

$$\longrightarrow \sigma_{1c}^{ex}/\sigma_{1c}^{sh} \sim (E_f/E_m)^{1/2}$$

$$\sigma_{1c}^{kink} \cong \frac{\tau_{m,fail}}{\theta_i+\gamma}$$

*Tension*

$$\sigma_{1t}^{C} \cong \sigma_{1t}^{F}\left(V_f+(1-V_f)\frac{E_m}{E_f}\right)$$

$$E_f >> E_m \longrightarrow \sigma_{1t}^{C} \cong \sigma_{1t}^{F} V_f$$

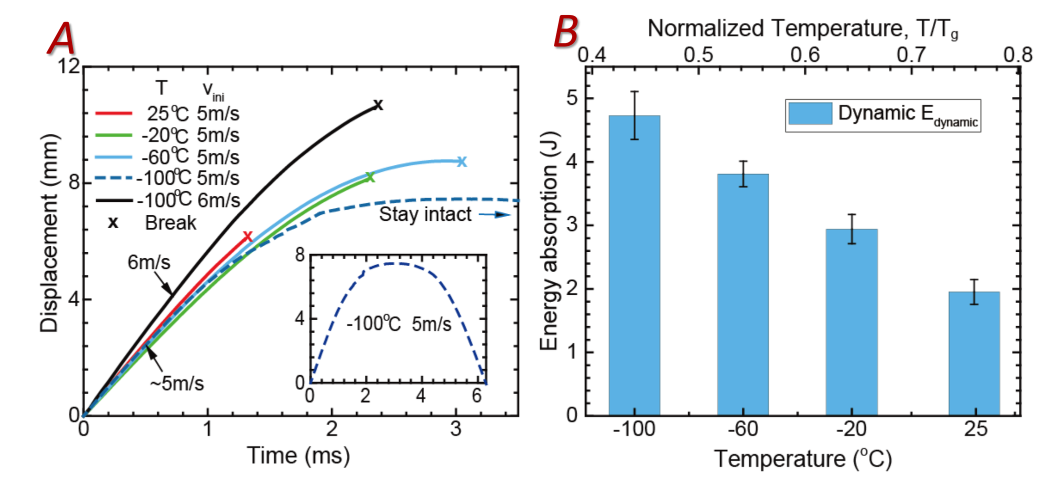


***Figure 5**. Dynamic 3-point bending results. (A) Displacement history, and (B) energy absorption at 25°C, -20°C, -60°C and -100°C.*

## Results: dynamic 3-point bending

- **Similar trend as static tests:** The displacement at breakage, and energy absorption increase with decreasing temperature (Fig. 5).
- Routine failures at 25°C (-20°C), while at -60°C delamination takes place and the specimen into several pieces, at -100°C brush shape damage.
- Temperature decrease has similar result as strain rate increase – "*t-T* equivalence".

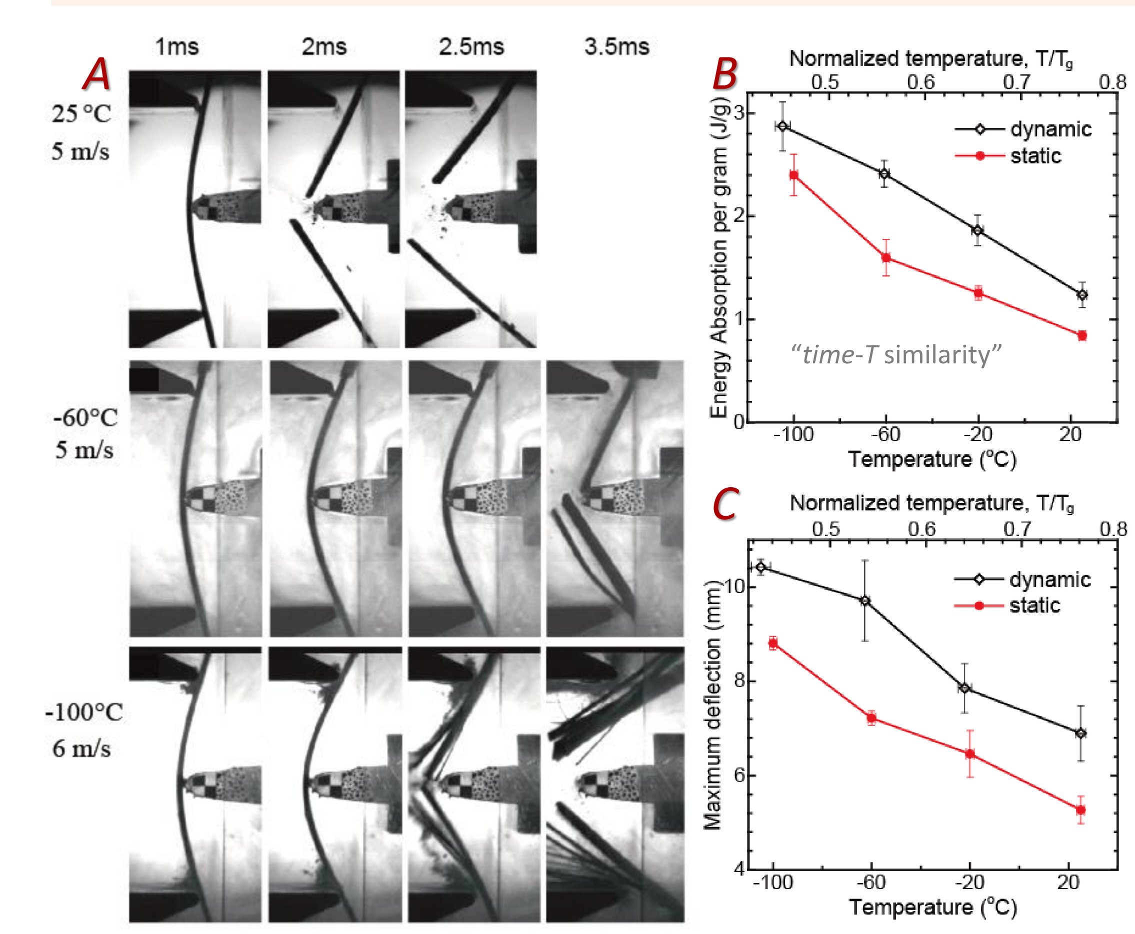


***Figure 6**. (A) Dynamic deformation of CFRP at different moments. Comparison between static and dynamic 3-point bending results: (B) energy absorption per gram, (C) maximum deflection at break.*

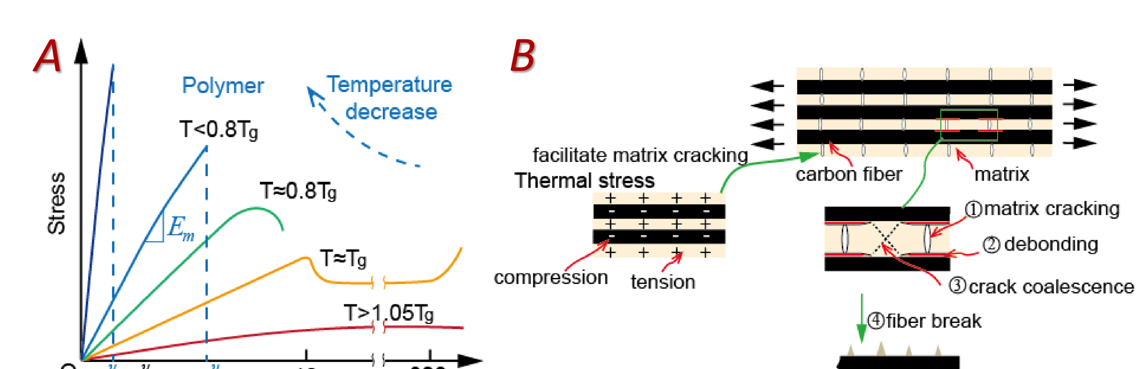


***Figure 7**. Temperature effect origin. (A)Temperature dependency of polymer. (B) Thermal stress effect, and typical cracking process of brittle matrix CFRP.*

## Conclusions

- Temperature effect of CFRP is dominated by matrix property change at varying temperature.
- The toughening mechanisms at low temperatures are:
- 1) improved critical stress of microbuckling, kinking, and ultimate tensile stress;
- 2) failure mode transition from upper layer buckling to bottom layer tensile fiber breakage, together with extensive inter-fiber cracking at lower temperatures,
- 3) forming a "brick and mortar" type microstructure when the temperature is extremely low.
- Thermal stress is the secondary factor of temperature effect.

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