LOW INTERFACIAL TOUGHNESS (LIT) MATERIALS FOR EFFECTIVE LARGE-SCALE DEICING

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The Icing Problem

Figure 1. Icing on various structural surfaces. In several parts of the world, the accretion of ice can have detrimental effects on critical structural surfaces in energy and transportation applications. (A,B) The buildup of ice on a wind turbine blade can lower the production of wind energy and, under excessive buildup, even impart downtime in operations. (C) When overwhelmed with the weight of ice, the High Voltage (HV) powerline cables and towers can collapse, resulting in severe economic and power transmission losses. (D) Icing on the deck of an Alaskan shipping vessel[1] can shift it's center of gravity thereby risking capsizing and loss of life. The ice coverage areas of these structures can be exceedingly high (>1000 m^2). Consequently, even with extremely icephobic coatings (τ_{ice} < 100 kPa[2]), structures with large surface areas would require prohibitively high forces to detach entire sheets of ice from the surface.

Fundamentals

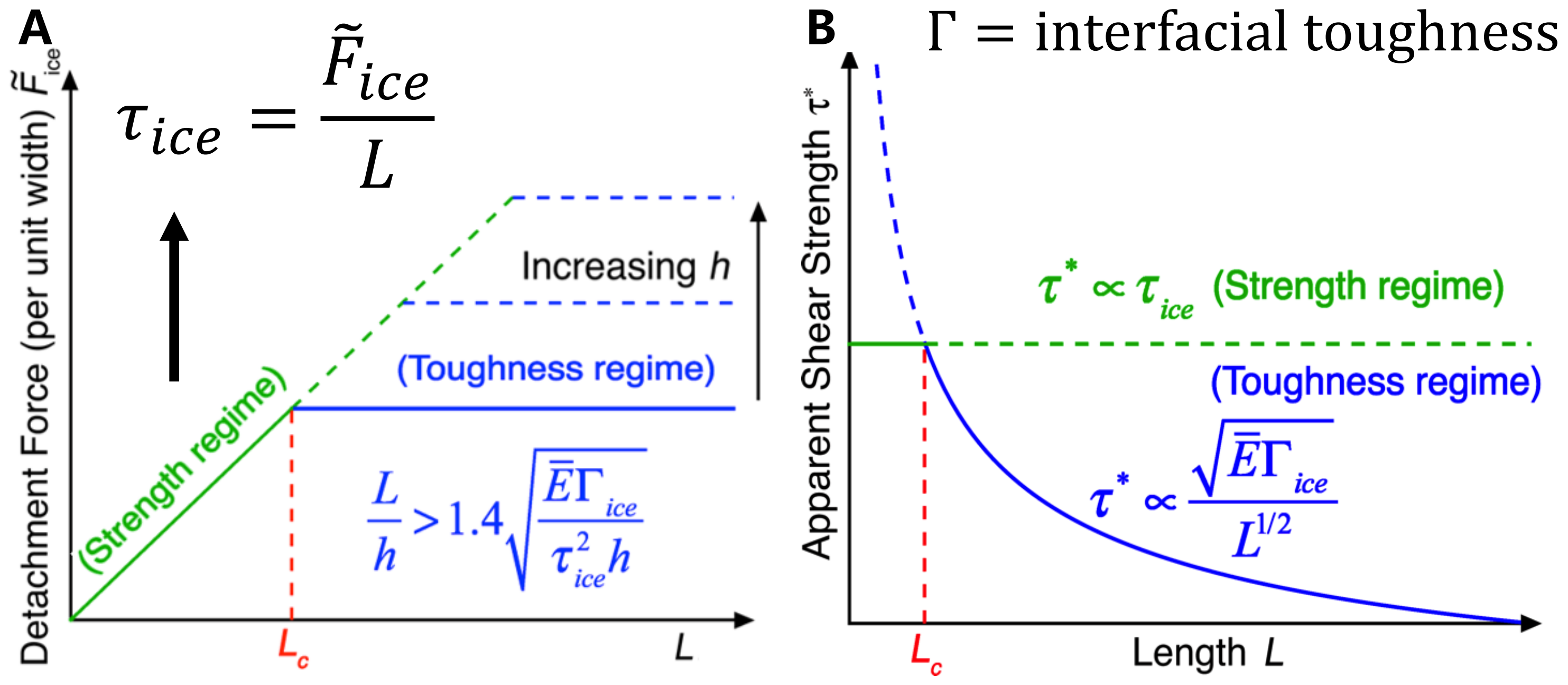
Figure 2. Strength vs. toughness.
According to cohesive zone models of fracture[3]:

When interface length is <L_c:

- Shear strength, τ_{ice}, controls fracture
- Force is proportional to interface length
- Spontaneous rupture along the interface

When interface length is >L_c:

- Interfacial toughness, Γ, controls fracture
- Force is independent of interface length
- Crack propagation along the interface



Experimental Design

Figure 3. Silicone vs. Polypropylene.

(A) The force per unit width required to debond ice from a silicone and polypropylene as a function of interfacial length.

For polypropylene ($\hat{\tau}$ = 320 kPa):

- The force increased linearly with the length of ice until L_c = 3.6 cm, after which no additional force was required to remove the accreted ice.

For Silicone B ($\hat{\tau}$ = 30 kPa):

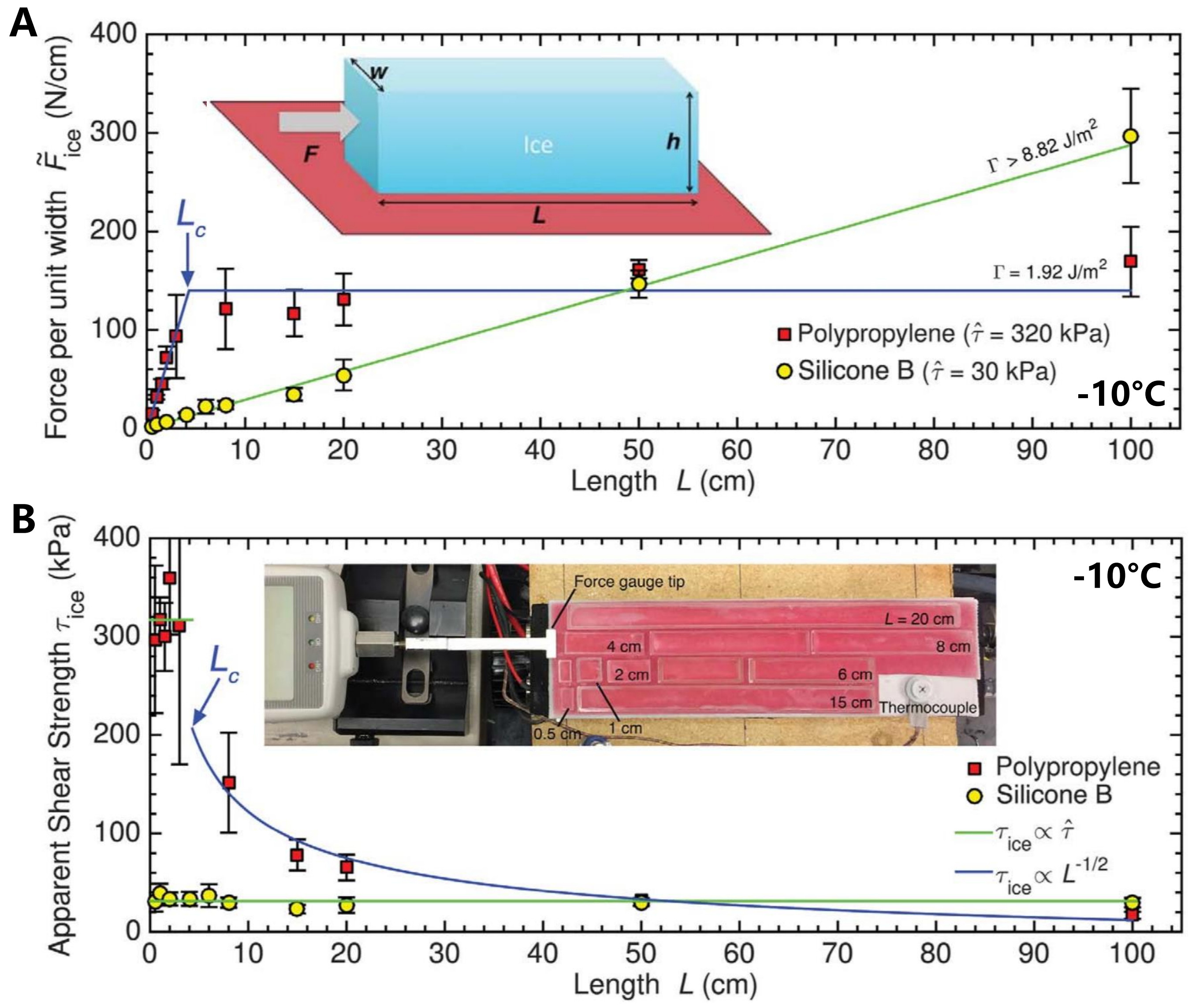
- Strength always controlled the fracture even up to 100 cm.

(B) Apparent shear strength, τ_{ice}, versus interfacial length (L).

When L < 50 cm :
τ_{ice} (silicone B) < τ_{ice} (polypropylene)

When L > 50 cm :
τ_{ice} (silicone B) > τ_{ice} (polypropylene)

τ_{ice} (polypropylene) at 100 cm = 12 kPa (icephobic??)



References

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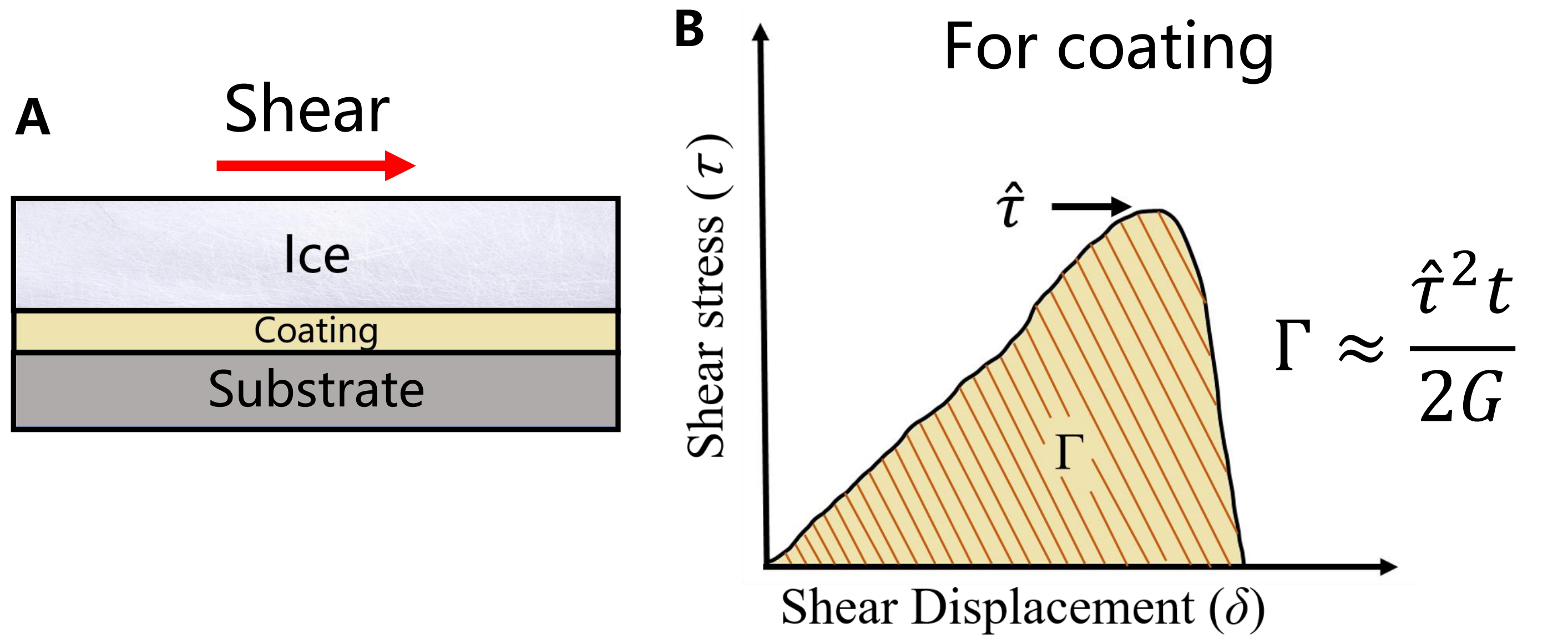
3. **R. B. Sills, M. D. Thouless, *Int. J. Solids Struct.* 55, 32–43 (2015)**
4. **A. Dhyani, K. Golovin, M. D. Thouless, A. Tuteja, *Science*, 364, 371-375 (2019)**

Material Design and Testing

Figure 4. Traction-separation law for an ice-coating interface.

(A) If ice delamination causes deformation of the coating, then the strain energy of this deformation must be considered as a contribution to the effective toughness, between the ice and substrate.

(B) One can consider the toughness of an interface to be given by the area under the force displacement curve of the entire interface, including the coating.



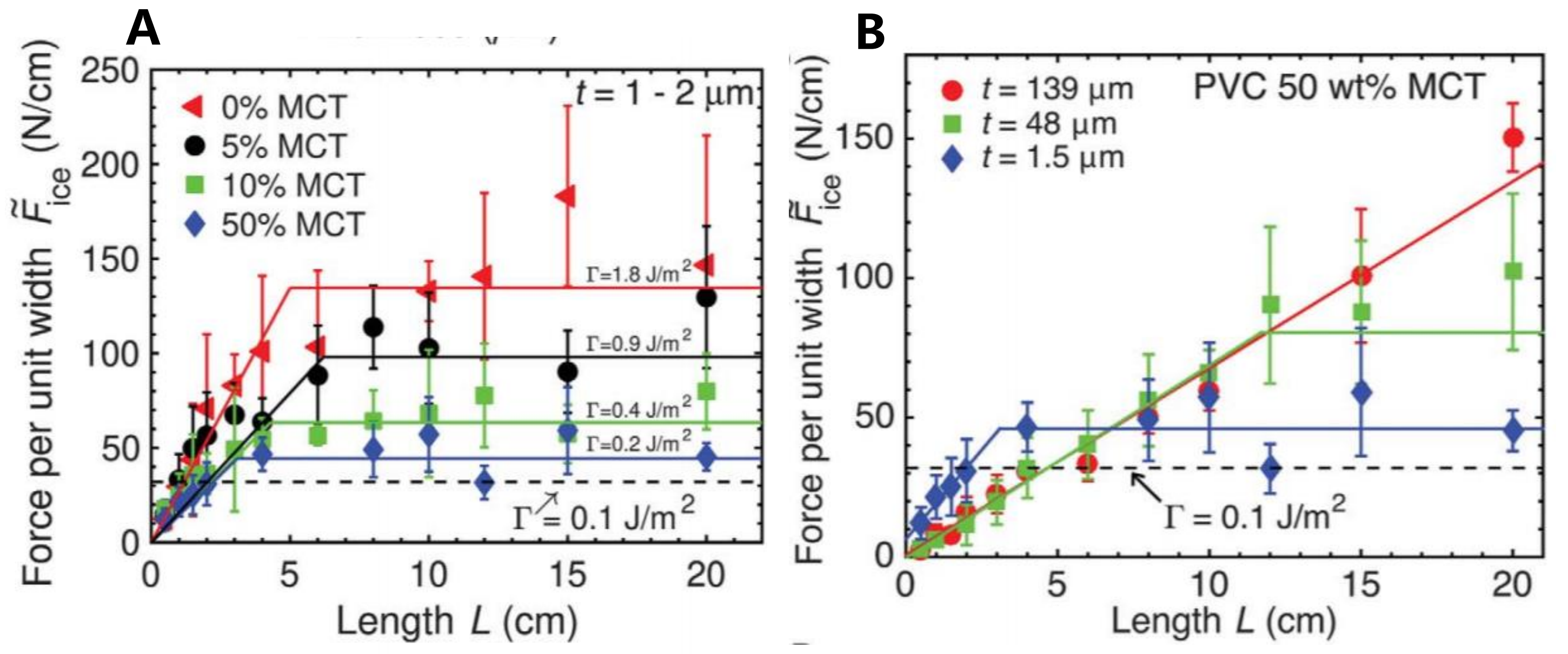


Figure 5. Controlling interfacial toughness.

(A) $\tilde{F}_{ice}$ required to fracture ice from thin PVC coatings with four different contents of MCT. A toughness-controlled regime of fracture was always observed for lengths less than 20 cm. Measurements at -10°C.

(B) $\tilde{F}_{ice}$ required to fracture ice from three different thicknesses of PVC plasticized with 50wt% MCT. Pure Van der Waals interactions correspond to a toughness of ~0.1 J/m^2.

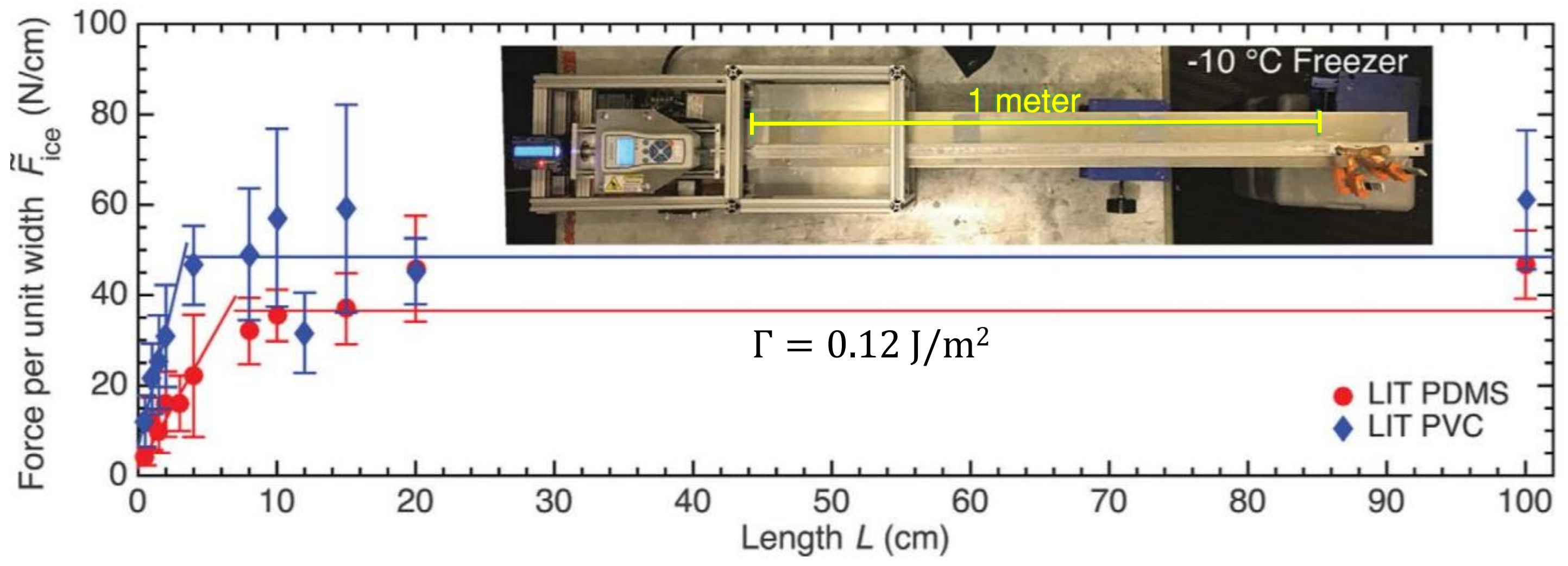


Figure 6. LIT materials.

The force required to fracture ice from the LIT PDMS (silicone + 40 wt.% silicone oil) and LIT PVC systems (1-2 μm). Even over an interfacial length of 1 m, the necessary force of fracture remained constant beyond L_c. The inset shows our experimental setup, performed in a walk-in freezer at –10°C.

Large - Scale Testing

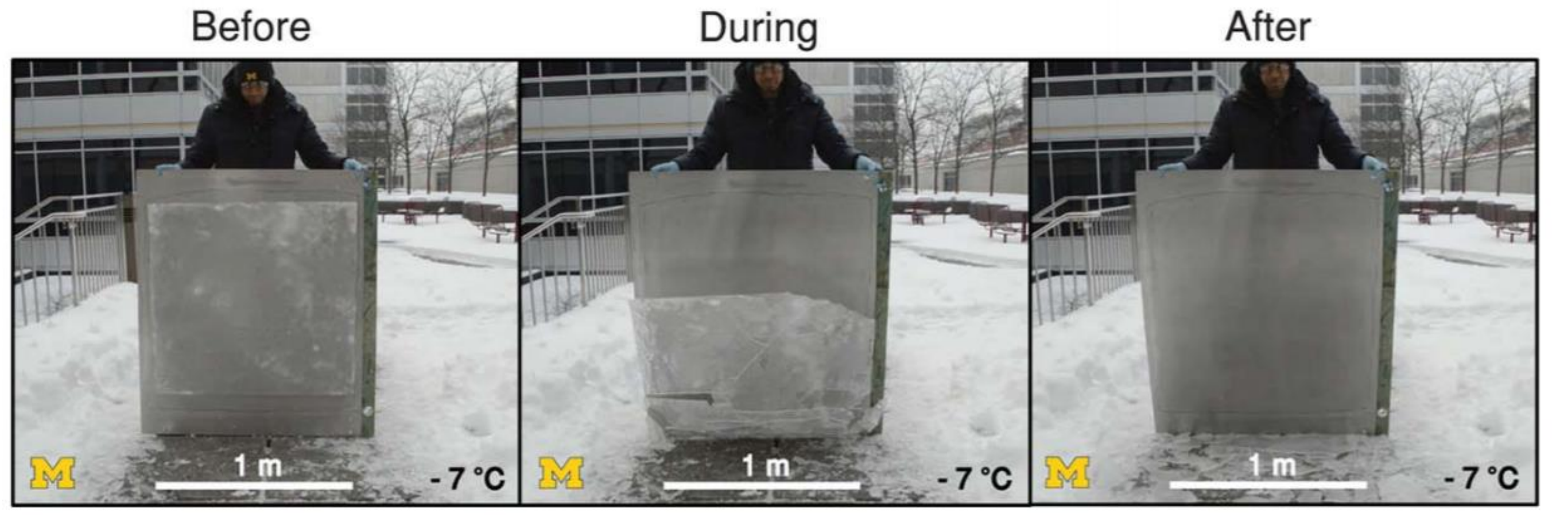
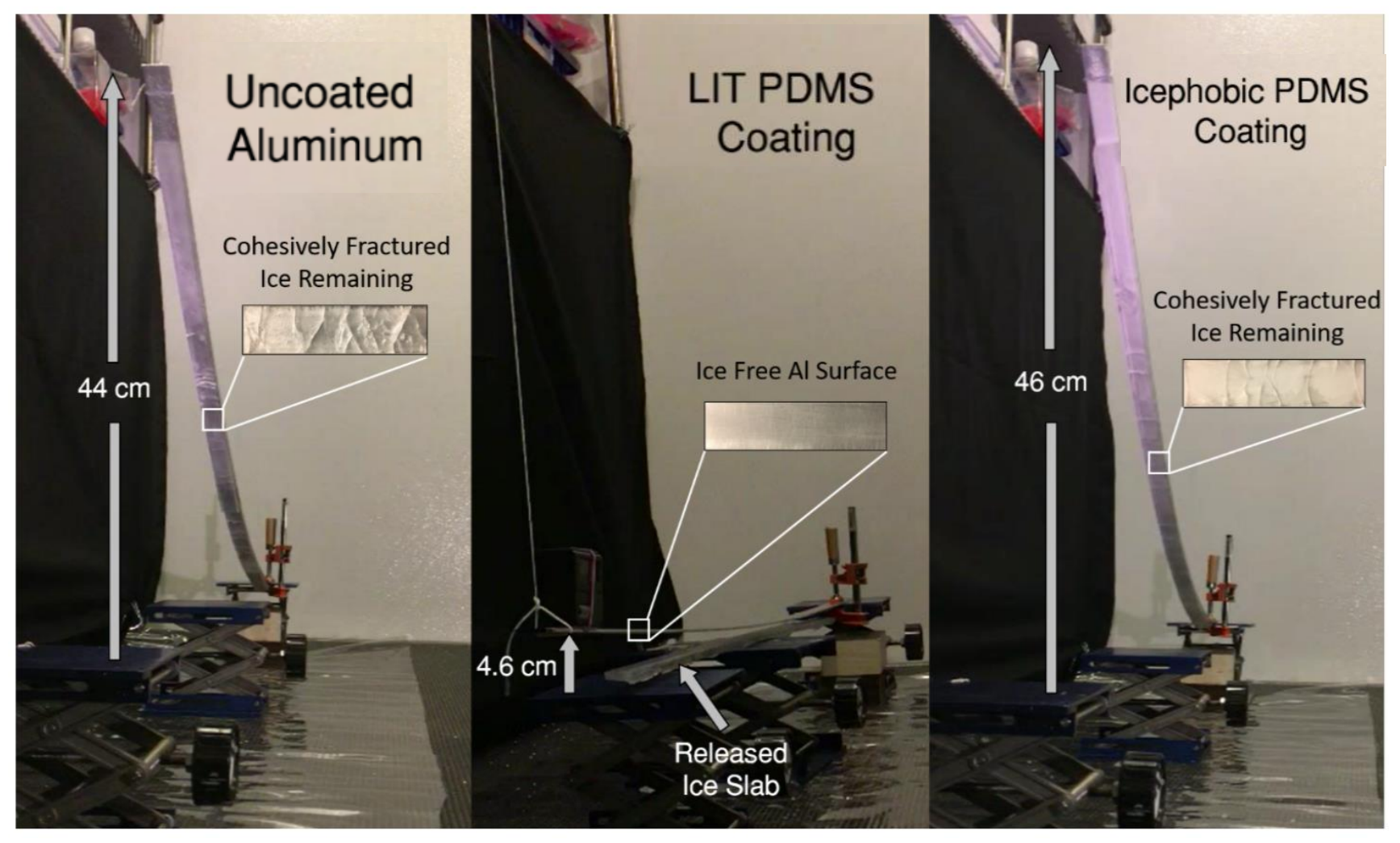


Figure 7. Chilly outdoor experiment.

Ice on a 1 m × 1 m aluminum panel coated with LIT PDMS was allowed to form in Michigan's wintery outdoors at –7°C overnight. We observed that the weight of the ice (1 cm thick), once fully frozen, was enough to completely and cleanly remove the attached ice. This yielded a τ_{ice} = 0.09 kPa.

Figure 8. Mimicking aircraft wing-tip deflection.

A comparison between uncoated and coated (with icephobic PDMS and LIT PDMS coating) aluminum beams adhered to a sheet of ice (1.0m × 0.025 m × 0.008 m) undergoing end-loaded cantilever bending tests. The entire ice slab fractured cleanly from the beam coated with the LIT PDMS coating with an extremely low deflection of 4.6 cm. The uncoated and icephobic beams remained adhered to the ice sheet at severe deflections. The ice sheet displayed cohesive fracture from the uncoated and icephobic Al beams, as shown in the insets.



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