Reframing ice adhesion on surfaces: shear strength and toughness measurements with the horizontal push test

L. Stendardo, G. Gastaldo, M. Budinger,
V. Pommier-Budinger, I. Tagliaro, P.F. Ibáñez-Ibáñez,
C. Antonini

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Icing Hazards

- Increase of weight
- Aerodynamic losses
- Blocking of mechanisms and pressure probes

Air France 447 in June 2009: 228 people died because of blocked pressure probes

Thermal de-icing: Efficiency limits

Chemical de-icing: environmental concerns

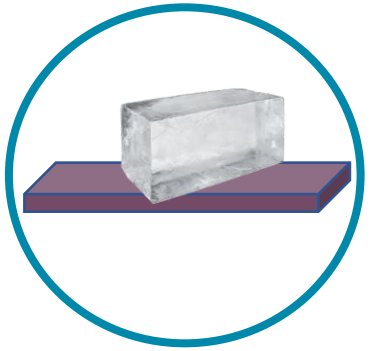
https://thepointsguy.com/wp-content/uploads/2018/10/final-touch.jpg
https://montecristomagazine.com/wp-content/uploads/2017/05/1Montecristo-Ice-Road-9.jpg
https://energiforskmedia.blob.core.windows.net/media/21263/2016-300_bild.jpg
https://www.nydailynews.com/resizer/t7t8Gh4DjhK7raBFU0-w2CbM-4A=/1200x801/top/arc-anglerfish-arc2-prod-tronc.s3.amazonaws.com/public/BC7VBTXX7UABZ4YTMPHM3GEKNY.jpg
https://blog.weatherops.com/hubfs/iceonpowerlines.jpg

SURFICE research fields

Modeling

Model ice formation, accretion and adhesion with computational tools such as FEA and molecular dynamics

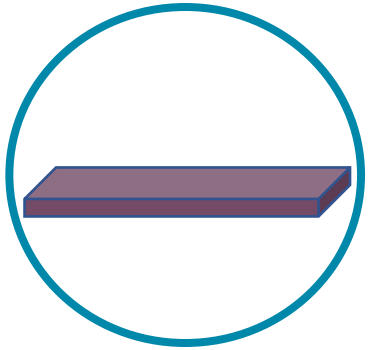
Characterization



Investigate the **physics of icing** on complex surfaces

Materials

Design novel anti-icing materials and coatings



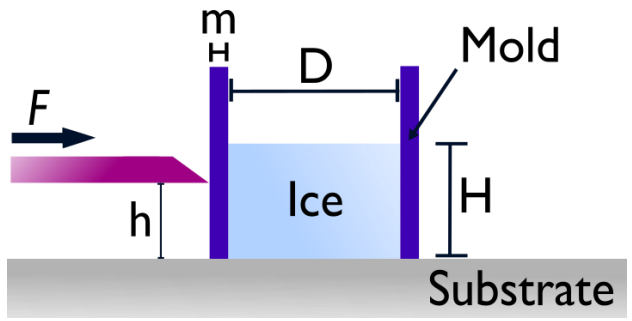
Application

Application of new technologies for ice protection **to aeronautics, energy systems and sensor technologies**

How to measure ice adhesion?

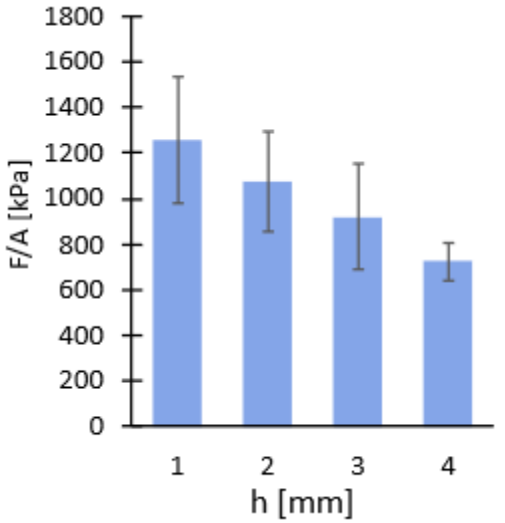
How is ice adhesion assessed in literature? → $\tau_{avg} = \frac{F_{max}}{A}$

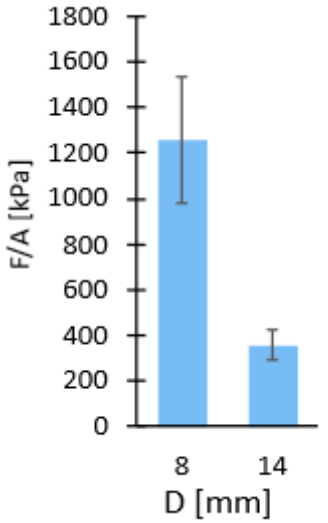
τ_{avg} is believed to be independent of the ice-substrate contact area.



Test conditions:

- Horizontal shear test with cylindrical ice columns and nylon molds
- Constant surface temperature & ambient conditions
- Substrate: Al-6060 aluminum alloy
  → non-degradable standard material





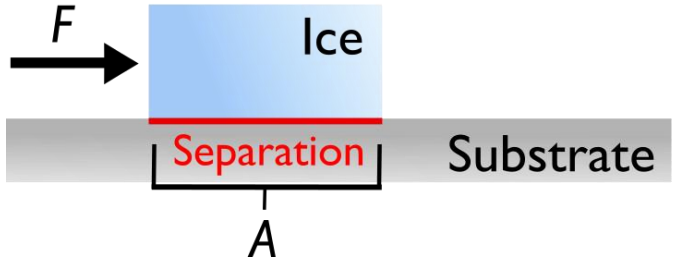
Is τ_{avg} a good measure for the critical shear stress?

τ_{avg} doesn't account for different fracture mechanisms

Stendardo, L., Gastaldo, G., Budinger, M., Pommier-Budinger, V., Tagliaro, I., Ibáñez-Ibáñez, P. F., & Antonini, C. (2023). Reframing ice adhesion mechanisms on a solid surface. *Applied Surface Science*, *641*, 158462

Fracture Mechanics

Stress-dominated



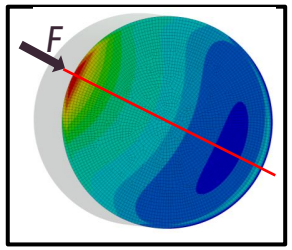
$$\tau > \tau_c, \forall\, x \in A$$

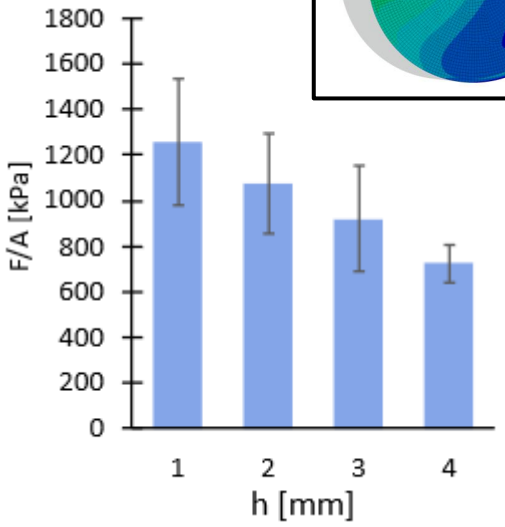
$$\Downarrow$$

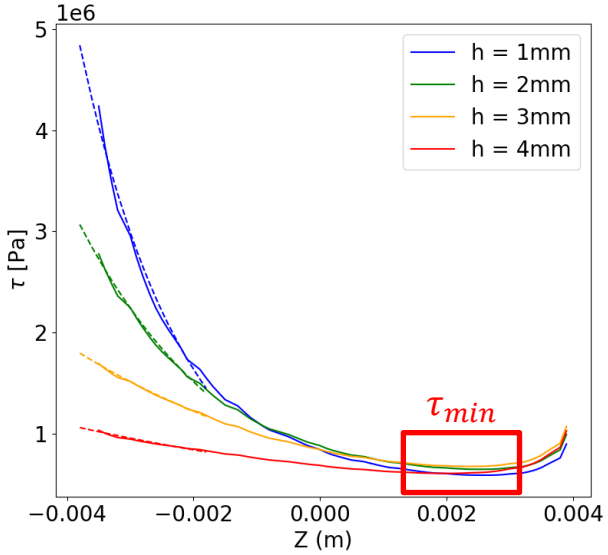
$$\tau_{min} > \tau_c$$

The minimum stress τ_{min} determines detachment

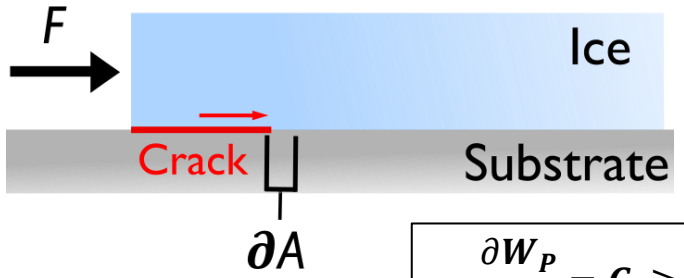
FEM Analysis





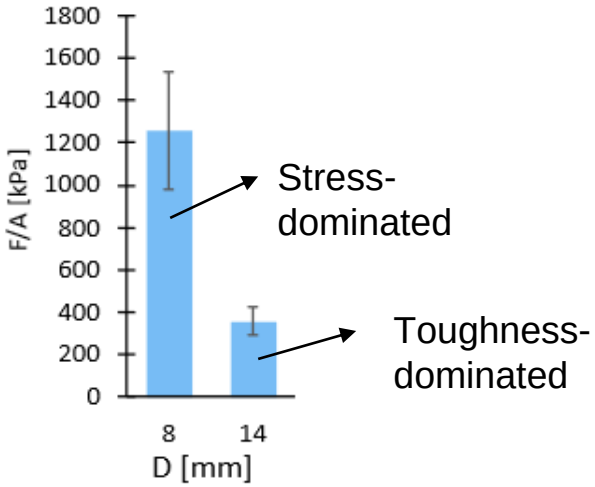


Toughness-dominated



$$-\frac{\partial W_P}{\partial A} = G \geq G_c$$

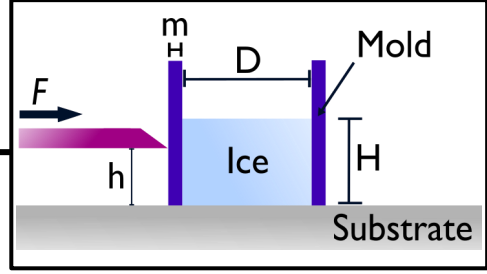
Energy release rate — Toughness

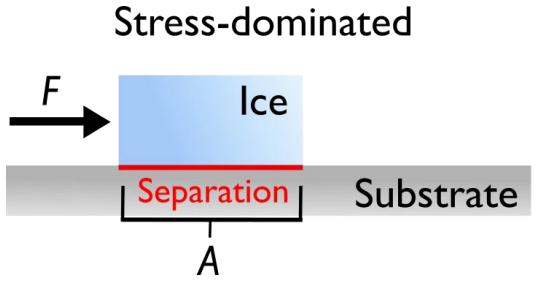


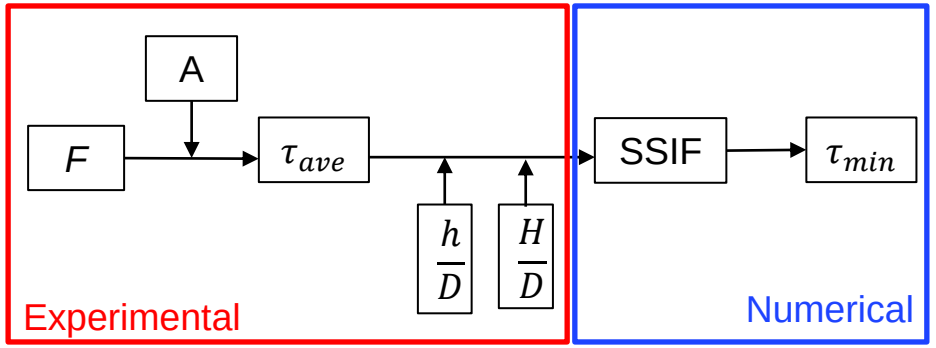
τ_{avg} (F/A) becomes meaningless when the detachment is determined by energy release rate.

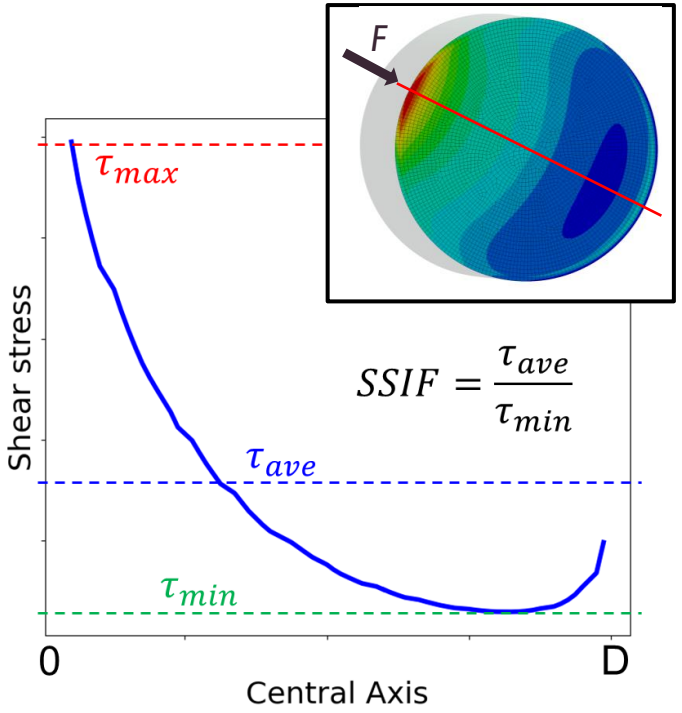
1) Stendardo, L., Gastaldo, G., Budinger, M., Pommier-Budinger, V., Tagliaro, I., Ibáñez-Ibáñez, P. F., & Antonini, C. (2023). Reframing ice adhesion mechanisms on a solid surface. *Appl. Sur. Sci.*, *641*, 158462
2) D. Leguillon, "Strength or toughness? A criterion for crack onset at a notch," Eur. J. Mech. - ASolids, vol. 21, no. 1, pp. 61–72, Jan. 2002
3) E. Martin, T. Vandellos, D. Leguillon, and N. Carrère, "Initiation of edge debonding:coupled criterion versus cohesive zone model," Int. J. Fract., vol. 199, no. 2, pp. 157–168, Jun. 2016

Dimensional Analysis: Shear Stress



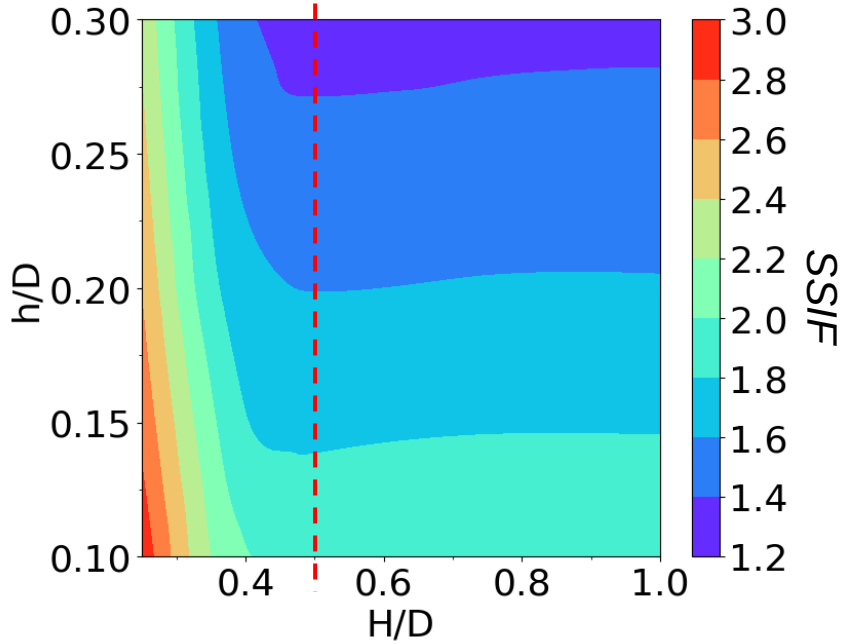






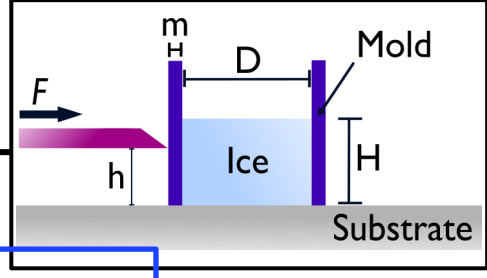
Buckingham Π-Theorem
+ FEM Analysis

$$\frac{\tau_{ave}}{\tau_{min}} = f\left(\frac{h}{D}, \frac{H}{D}\right)$$

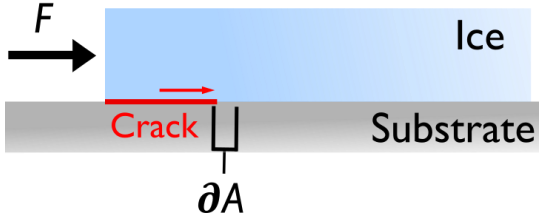


SSIF: **S**hear **S**tress **I**ntensity **F**actor

Dimensional Analysis: Toughness



Toughness-dominated



Buckingham Π-Theorem
+ FEM Analysis

$$\frac{G_c D^3}{F^2} E_{ice} = g\left(\frac{h}{D}, \frac{H}{D}, \frac{m}{D}, \frac{E_{ice}}{E_{mold}}\right)$$

- E_{ice}/E_{mold} is a test system constant.
- For each m/D, a different graph is plotted.

$$\frac{G_c D^3}{F^2} E_{ice} = g\left(\frac{h}{D}, \frac{H}{D}\right)$$

F required for full crack propagation

- h/D
- H/D
- m/D

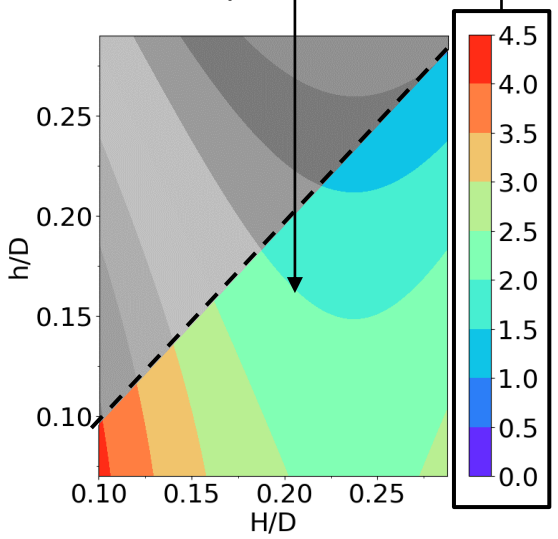
Experimental

$$\underbrace{\frac{G_c D^3}{F^2} E_{ice}}_{} = g\left(\frac{h}{D}, \frac{H}{D}\right)$$

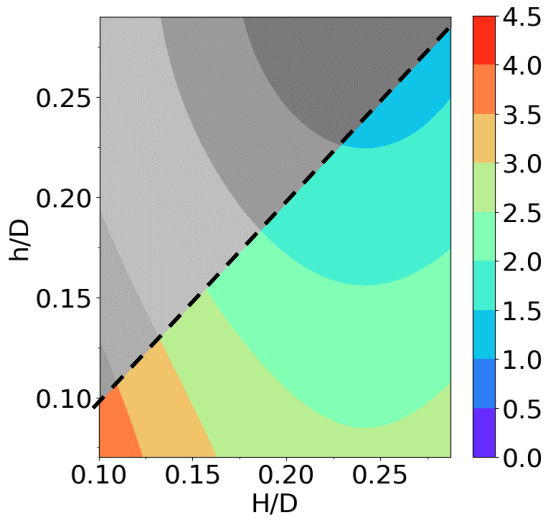
E_{ice}, D → G_c

Numerical

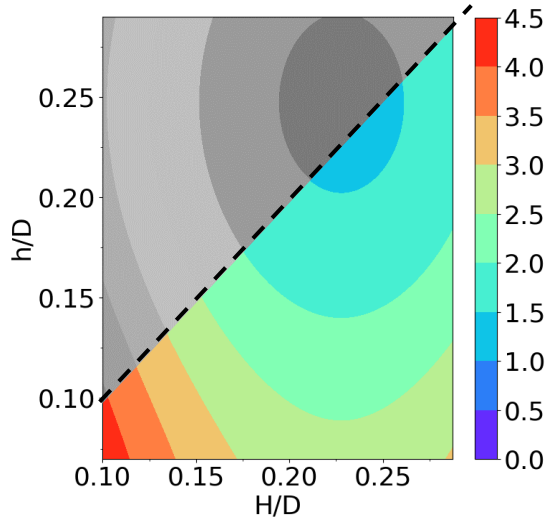
m/D = 0.2



m/D = 0.167

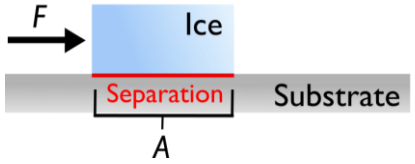


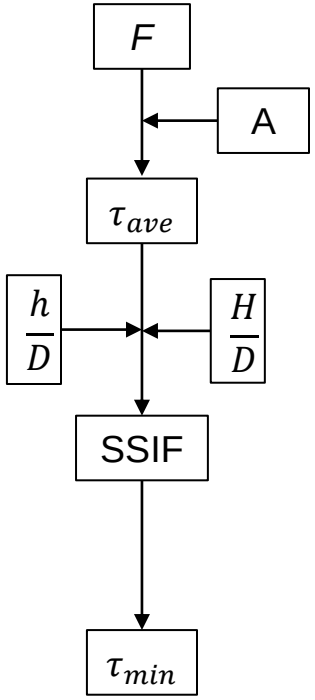
m/D = 0.143

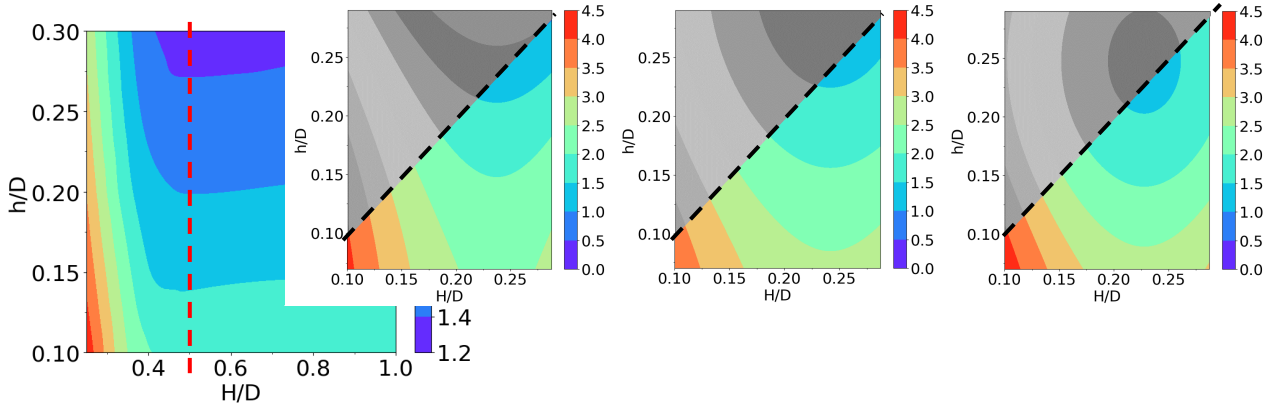


Recap

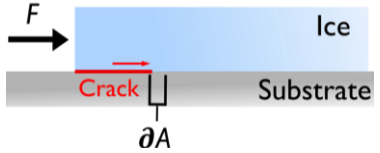
Stress-dominated fracture

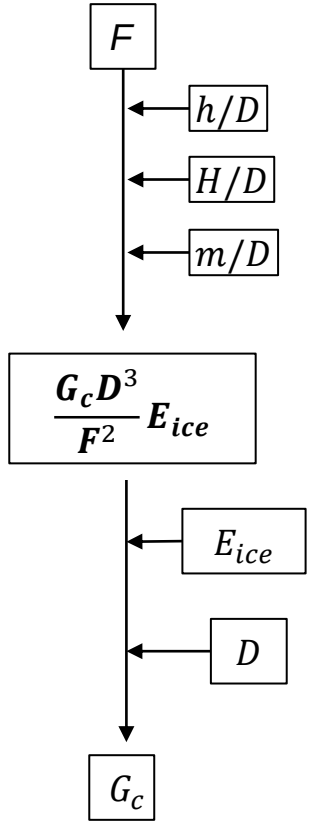






Toughness-dominated fracture





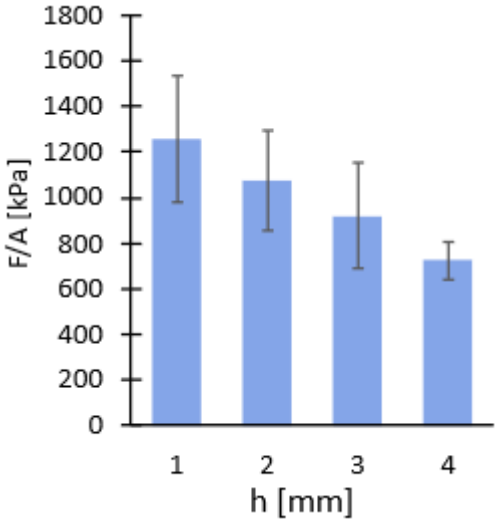
Conclusions

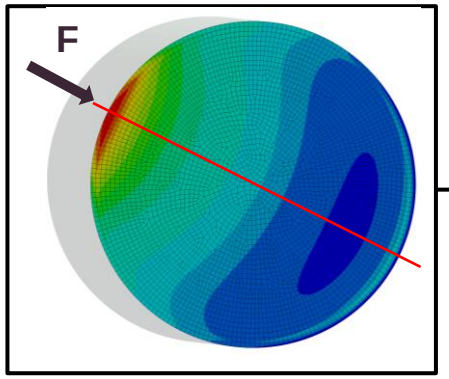
- The average shear stress is **not a sufficient measure** of ice adhesion.
- For larger interfaces, where **crack propagation** is controlled by toughness, the adhesion strength becomes meaningless.
- With the **SSIF**s, the true adhesion strength can be calculated, possibly reducing the discrepancies of shear strength values reported in literature.
- The total toughness can be calculated from the toughness parameters by knowing the **test system parameters** (h/D, H/D, and m/D) and **the force** necessary to propagate the crack.

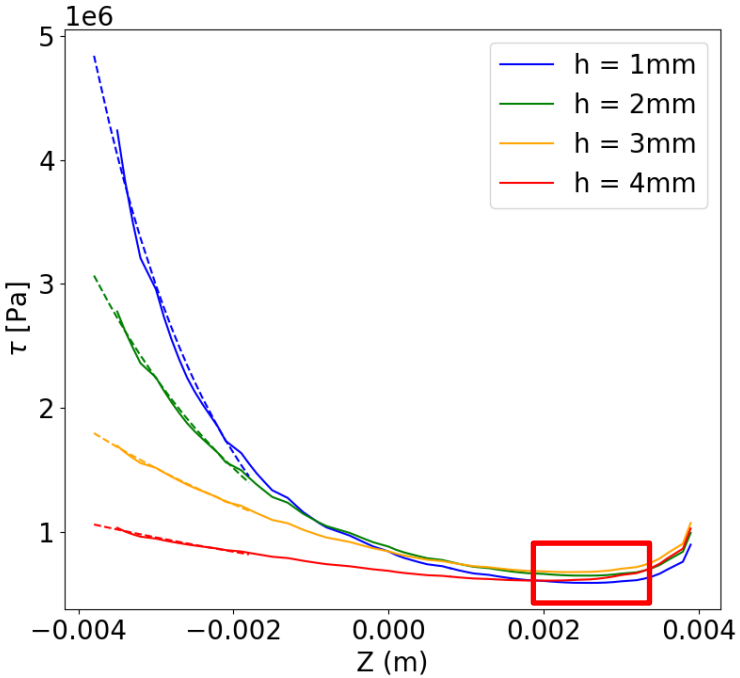
- The novel methodology is developed for a specific set of experimental cases (i.e., cylindrical ice columns and fixed mold material), and it does not differentiate between normal (G_I) and shear opening (G_{II}).
- It represents, however, a step towards more complete characterization of icephobic surfaces.

Backup

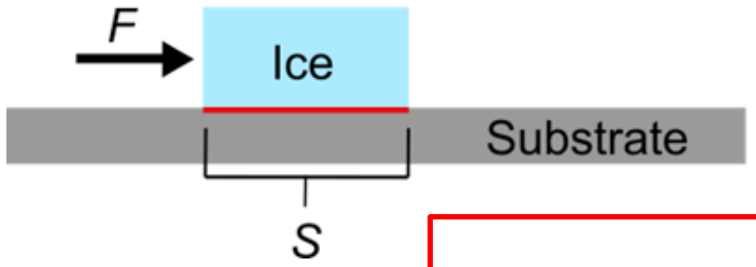
Shear Stress Analysis







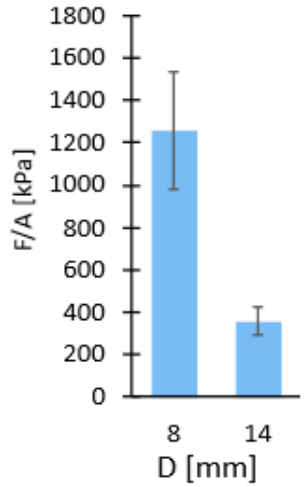
(a) Stress-dominated

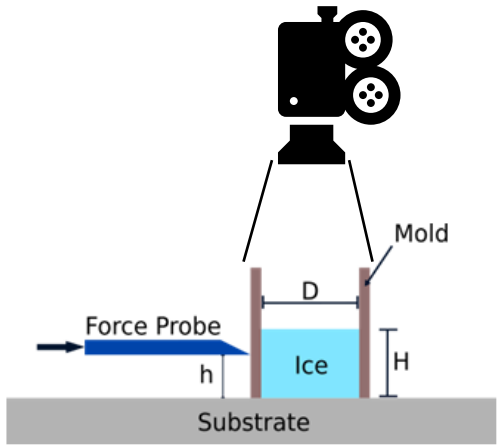


$\tau_{min} > \tau_c, \forall\, x \in S$

h [mm]	τ_{max} [kPa]	τ_{min} [kPa]	τ_{ave} [kPa]	SSIF $[\tau_{ave}/\tau_{min}]$
1	5460	588	1120	1,91
2	3317	646	1013	1,57
3	1874	675	883	1,31
4	1086	606	694	1,14
$\Delta\tau/\tau$	401%	14%	61%	

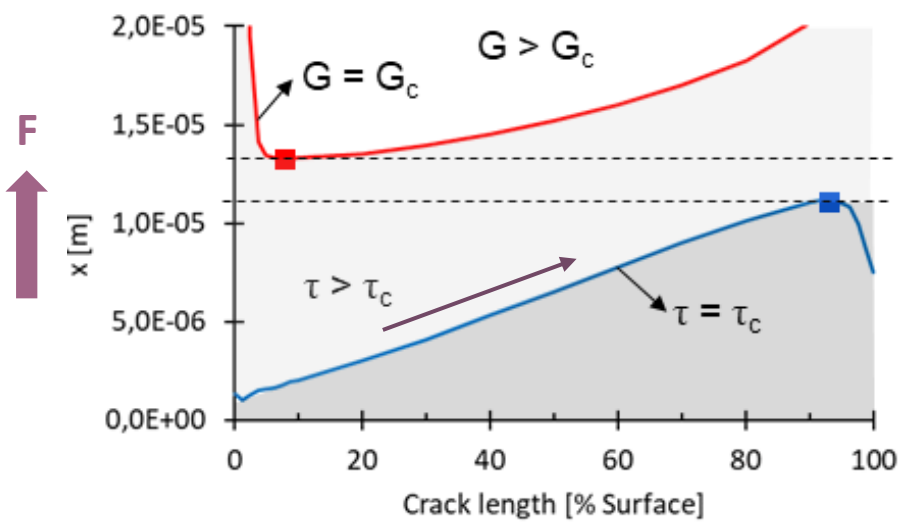
Strain Energy Analysis

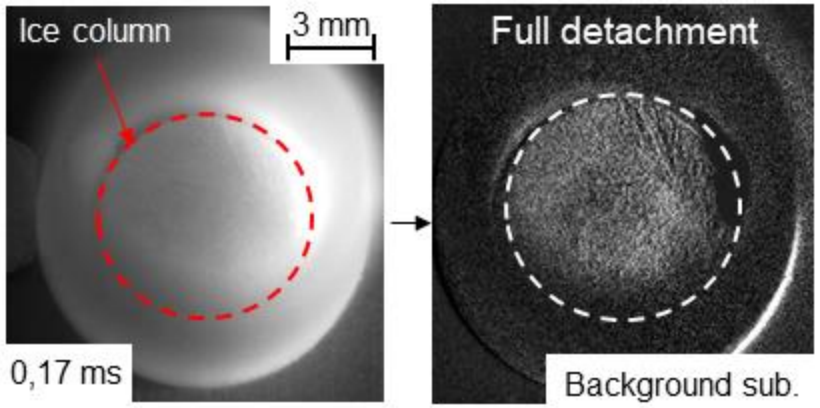




Stress-dominated

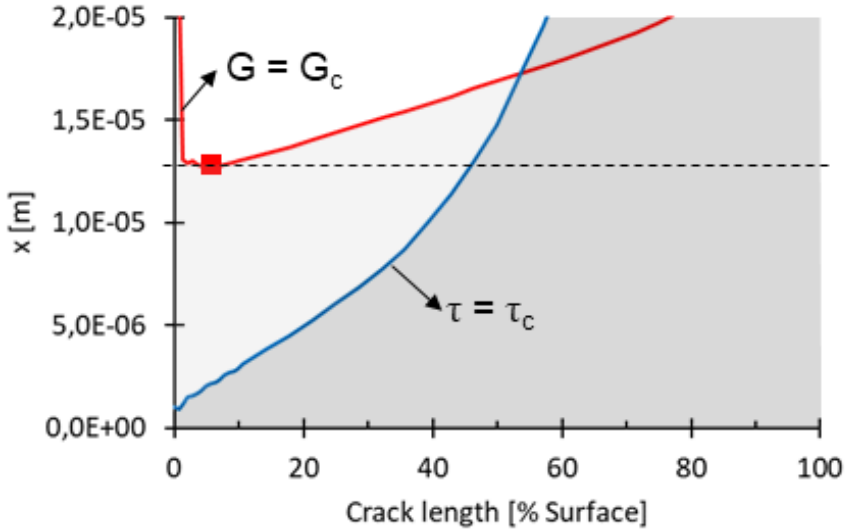
D = 8 mm

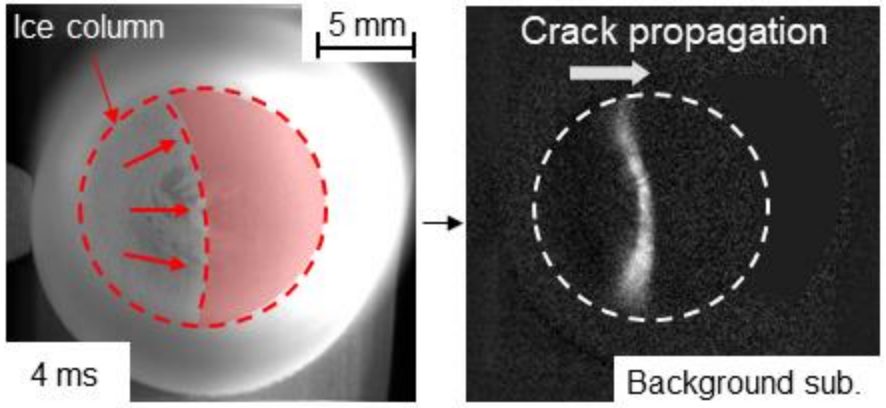


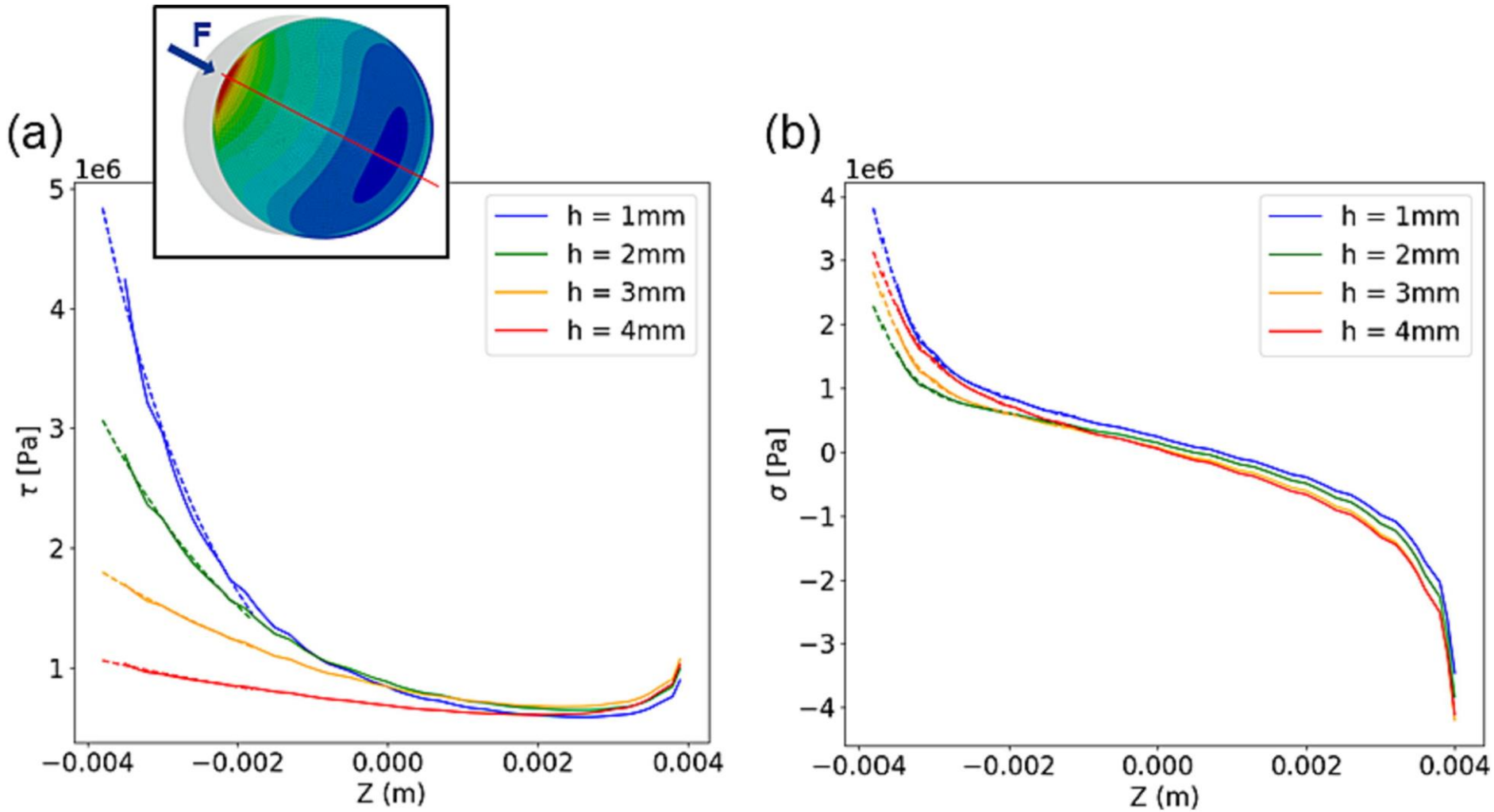


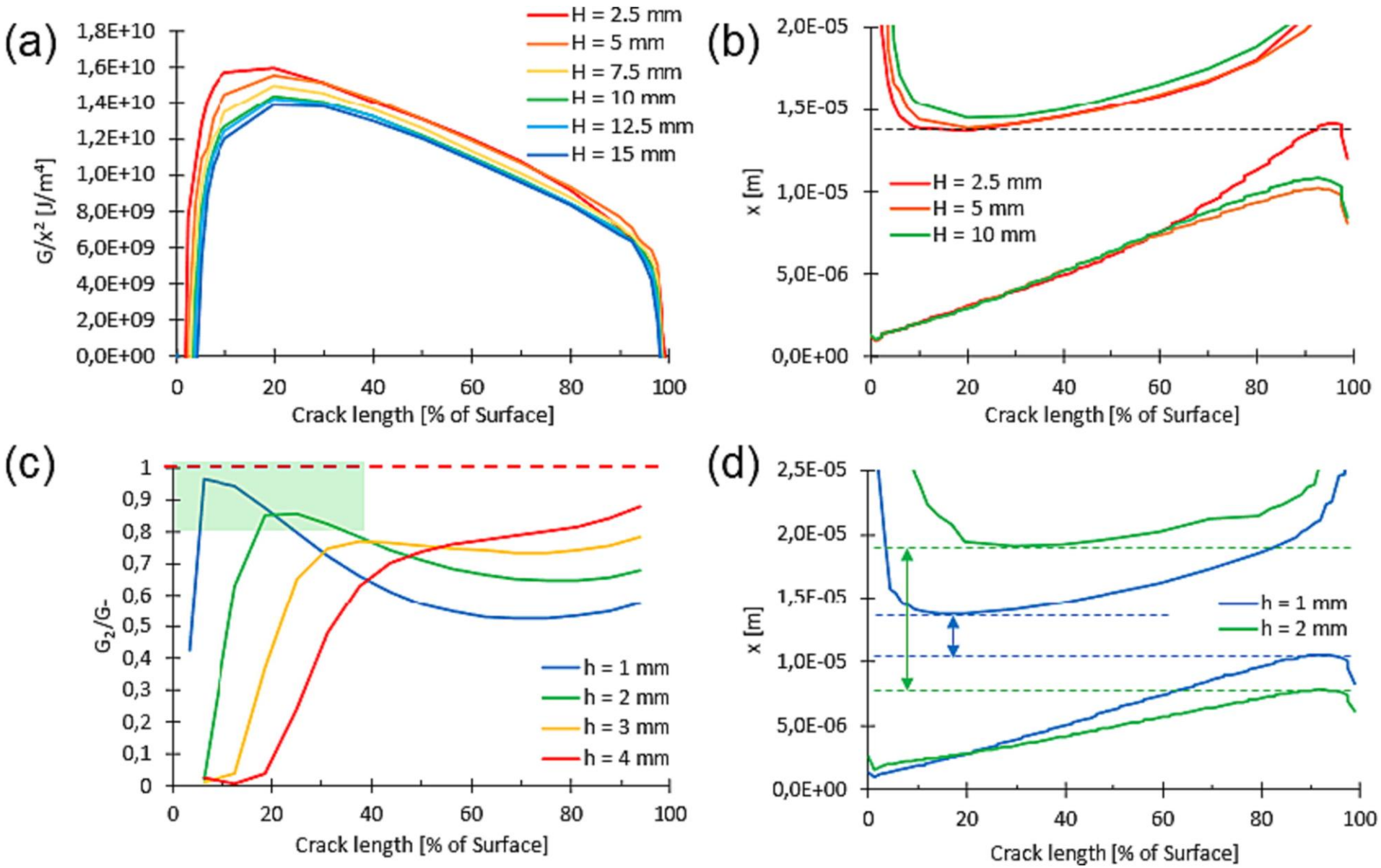
Toughness-dominated

D = 14 mm






(a)
F
1e6
5
4
3
2
1
τ [Pa]
h = 1mm
h = 2mm
h = 3mm
h = 4mm
−0.004
−0.002
0.000
0.002
0.004
Z (m)
(b)
1e6
4
3
2
1
0
−1
−2
−3
−4
σ [Pa]
h = 1mm
h = 2mm
h = 3mm
h = 4mm
−0.004
−0.002
0.000
0.002
0.004
Z (m)


(a)
G/x² [J/m⁴]
1,8E+10
1,6E+10
1,4E+10
1,2E+10
1,0E+10
8,0E+09
6,0E+09
4,0E+09
2,0E+09
0,0E+00
0
20
40
60
80
100
Crack length [% of Surface]
H = 2.5 mm
H = 5 mm
H = 7.5 mm
H = 10 mm
H = 12.5 mm
H = 15 mm
(b)
x [m]
2,0E-05
1,5E-05
1,0E-05
5,0E-06
0,0E+00
Crack length [% of Surface]
H = 2.5 mm
H = 5 mm
H = 10 mm
(c)
G2/G-
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Crack length [% of Surface]
h = 1 mm
h = 2 mm
h = 3 mm
h = 4 mm
(d)
x [m]
2,5E-05
2,0E-05
1,5E-05
1,0E-05
5,0E-06
0,0E+00
Crack length [% of Surface]
h = 1 mm
h = 2 mm

The numerical model has been verified by performing a series of experimental measures of the ice removal force on aluminum and comparing the obtained toughness value with the literature. The obtained interfacial toughness of Al-6060 aluminum alloy based on our numerical model and experimental data was $G_c = 0.57 \pm 0.26\, J/m^2$.

Reference	Test Method	G_I vs. G_{II}	Value [J/m^2]
Yeong et al. [31]	Pressurized air ice fracture test	G_I	0.72 ± 0.11
Palanque et al. [14]	Electro-mechanical de-icing	G_I	0.38 ± 0.09
Pervier and Hammond [32]	Pressurized air ice fracture test	G_I	0.95 ± 0.45

Stress-dominated detachment: full detachment of the ice in less than 0.17 ms.

200x slow-motion

Mold diameter D = 8 mm
Pushing height h = 1 mm
Ice height H = 5 mm

"Reframing Ice Adhesion Mechanisms on a Solid Surface"

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Toughness-dominated detachment: visible crack propagation and full detachment in 4 ms.

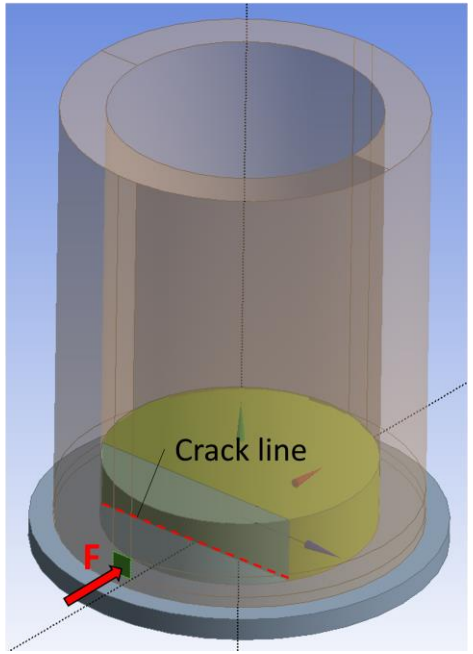
200x slow-motion

Mold diameter D = 14 mm
Pushing height h = 1 mm
Ice height H = 3 mm

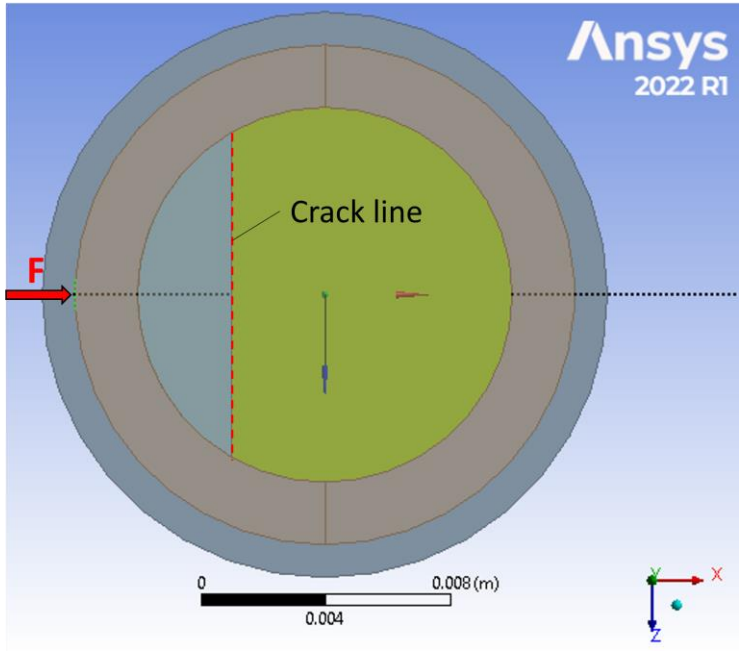
"Reframing Ice Adhesion Mechanisms on a Solid Surface"

Luca Stendardo, Giulia Gastaldo, Marc Budinger, Valérie Pommier-Budinger, Irene Tagliaro,
Pablo F. Ibáñez-Ibáñez, Carlo Antonini

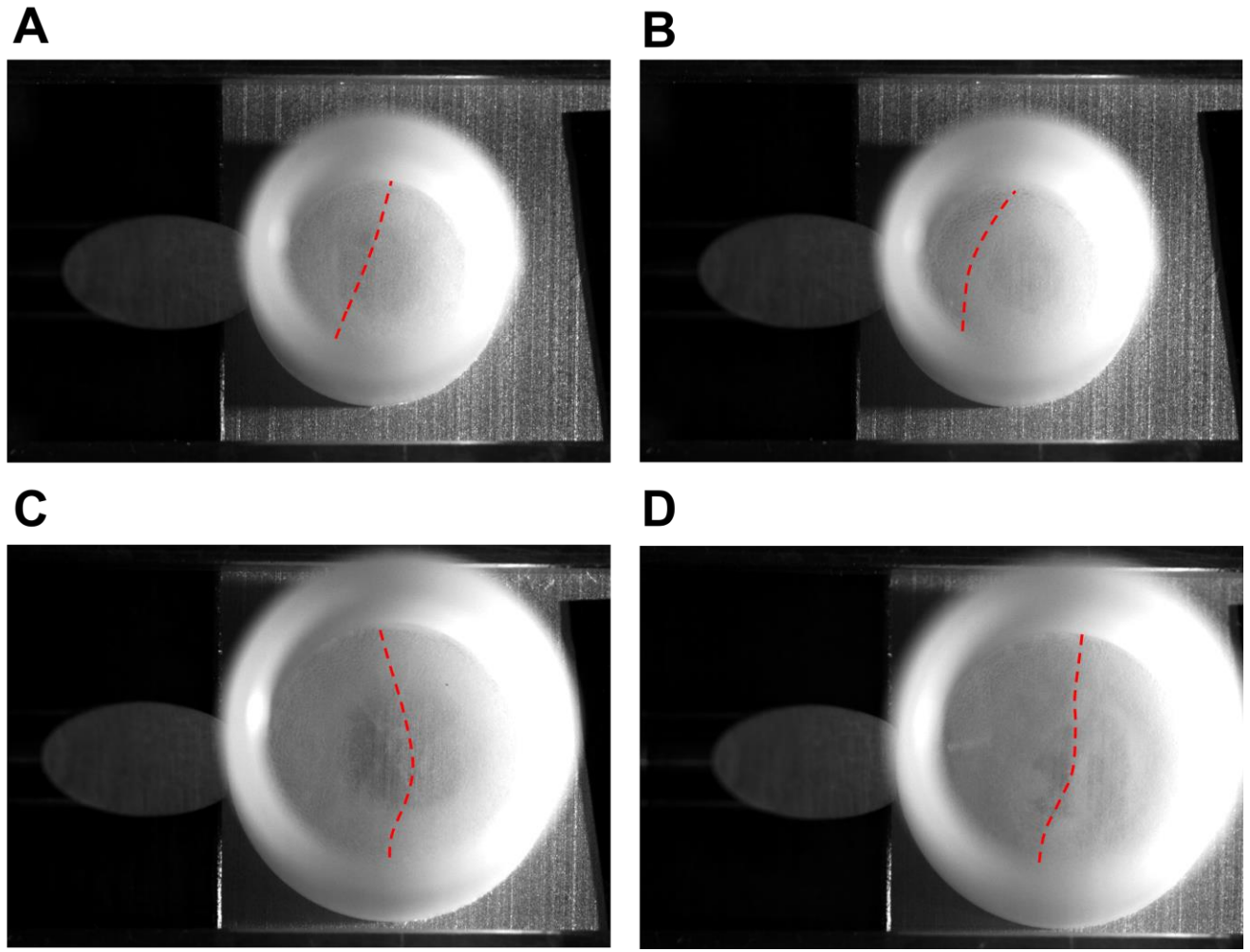
A

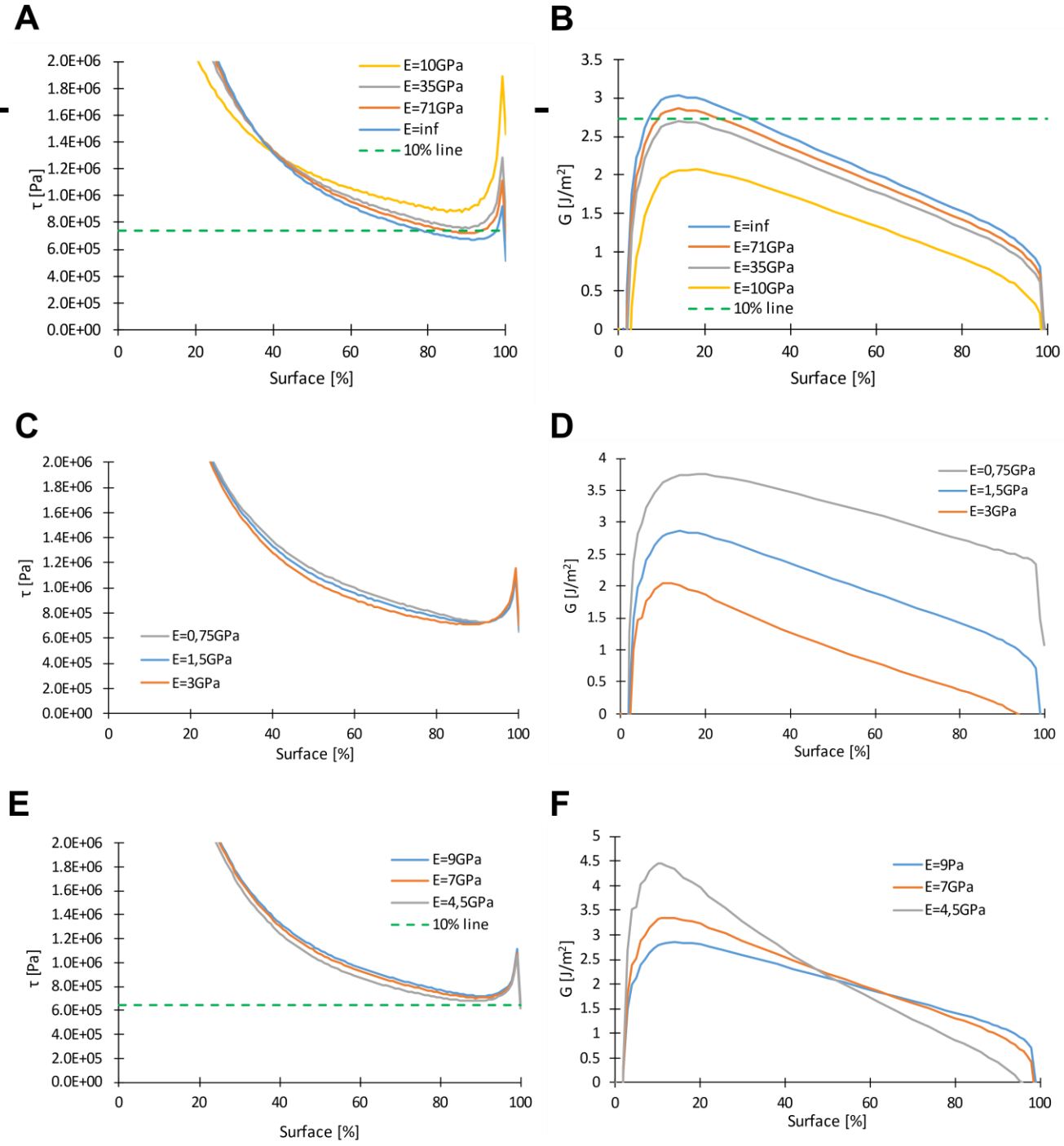


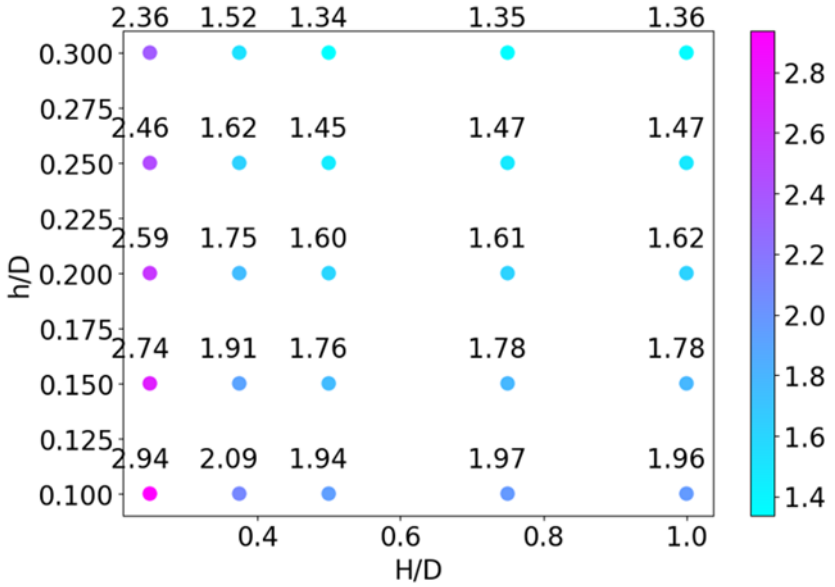
B



Material	ρ (kg/m^3)	E (GPa)	v
Aluminum	2700	68	0.36
Nylon	1140	1.5	0.39
Ice	897	9	0.31

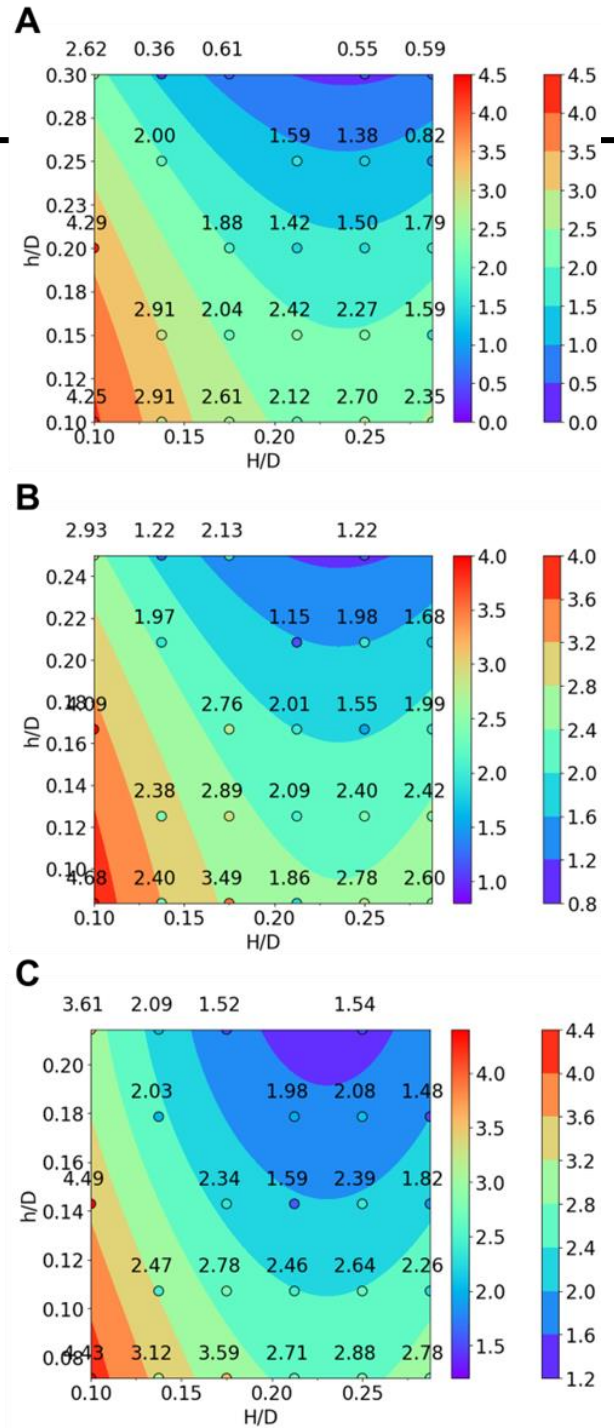

A
B
C
D


A
τ [Pa]
Surface [%]
E=10GPa
E=35GPa
E=71GPa
E=inf
10% line
B
G [J/m²]
Surface [%]
E=inf
E=71GPa
E=35GPa
E=10GPa
10% line
C
τ [Pa]
Surface [%]
E=0,75GPa
E=1,5GPa
E=3GPa
D
G [J/m²]
Surface [%]
E=0,75GPa
E=1,5GPa
E=3GPa
E
τ [Pa]
Surface [%]
E=9GPa
E=7GPa
E=4,5GPa
10% line
F
G [J/m²]
Surface [%]
E=9Pa
E=7GPa
E=4,5GPa



$$f = a\sin\left(b\frac{H}{D}\right) + c\cos\left(d\frac{h}{D}\right) + e$$

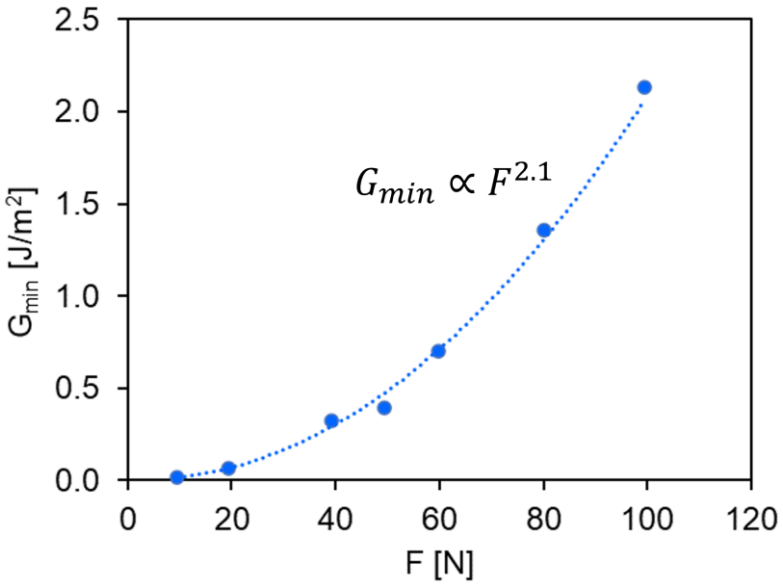
m/D aspect ratio	a	b	c	d	e
m/D = 0.2	-4.59E+0	6.62E+0	5.71E+3	8.78E-2	-5.71E+3
m/D = 0.167	3.28E+0	-6.49E+0	7.92E-1	9.82E+0	5.24E+0
m/D = 0.143	4.60E+0	-6.90E+0	7.89E-1	1.27E+1	6.77E+0

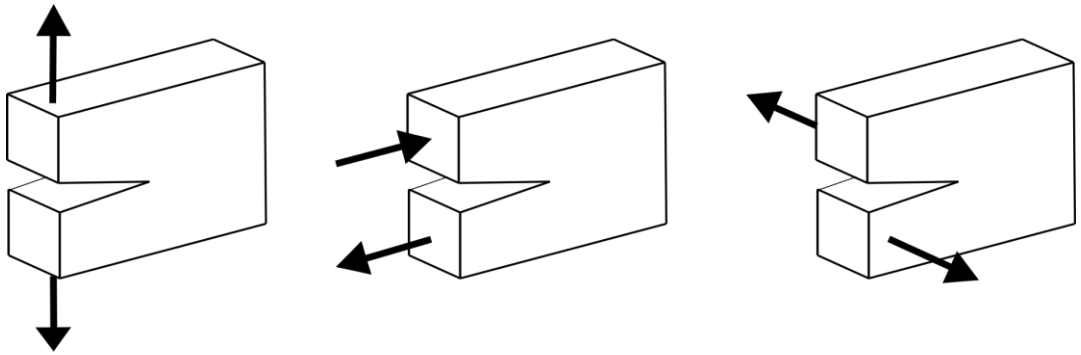


G_c [J/m^2]	F [N]	E_{ice} [GPa]	A	B
0.40	50	9	2.51	5.50
0.49	50	8	3.27	5.52
0.69	50	7	3.53	5.53
0.01	10	9	2.57	5.26
0.07	20	9	2.80	5.27
0.32	40	9	3.26	5.41
0.40	50	9	2.46	5.50
0.70	60	9	3.06	5.56
1.36	80	9	3.30	5.69
2.13	100	9	3.35	5.78

A: $\frac{G_c D^3}{F^2} E_{ice} = g\left(\frac{h}{D}; \frac{H}{D}\right)$

B: $\frac{\tau_{ave}}{\tau_{min}} = f\left(\frac{h}{D}; \frac{H}{D}\right)$





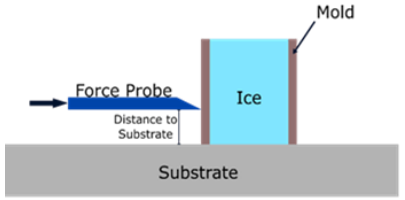
Mode I
(normal)

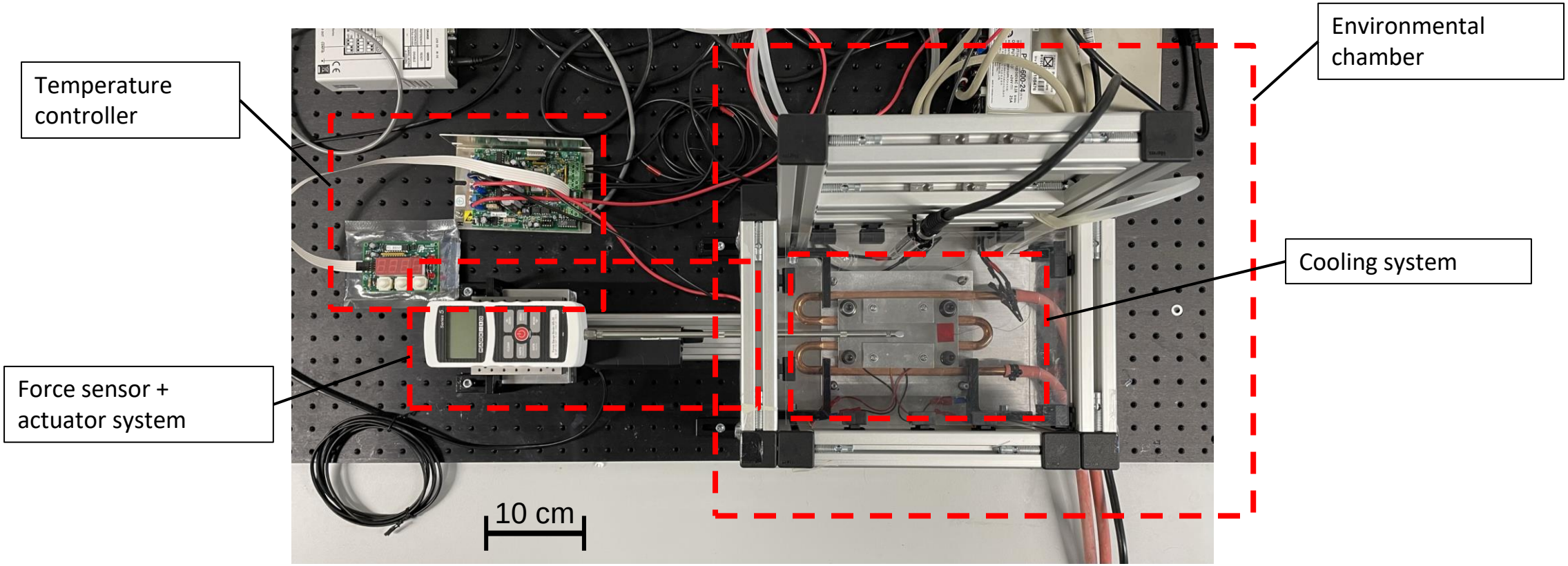
Mode II
(shearing)

Mode III
(tearing)

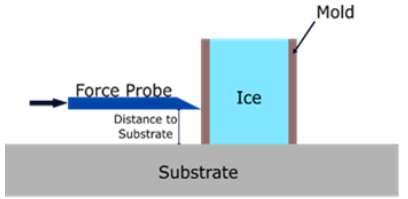
D [mm]	h [mm]	Critical H [mm]	H/D
8	1	-	-
10	1	2.5	0.25
12	1	3	0.25
14	1	3.3	0.24

Ice Adhesion Test System

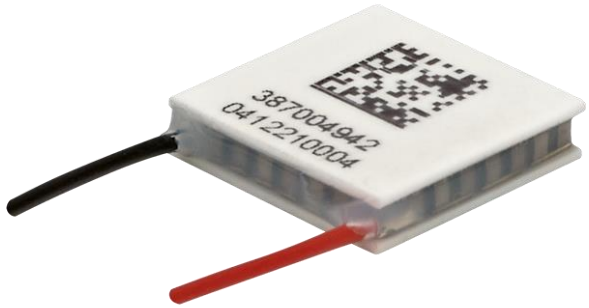


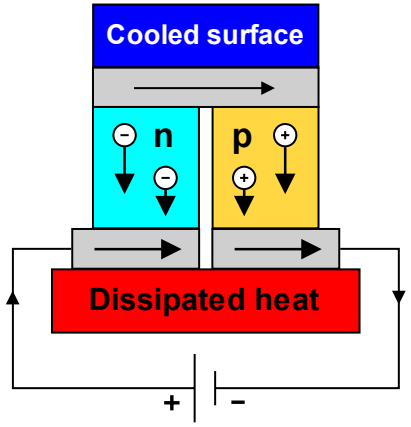


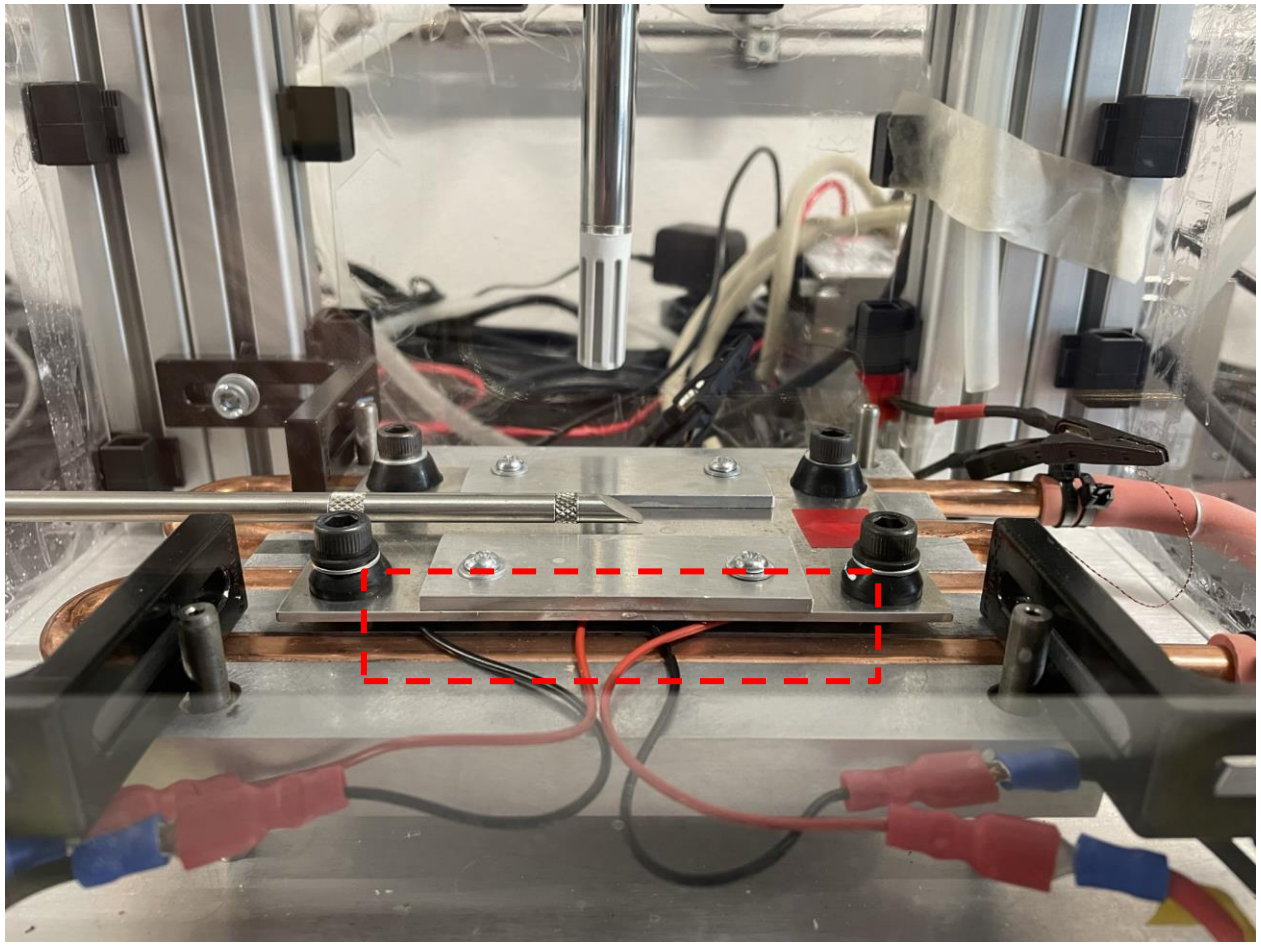
Ice Adhesion Test System



Thermoelectric Cell







Ice Adhesion Test System