CHARACTERIZATION OF ICE ADHESION: MODES OF LOADING AND MICROSTRUCTURE

Bishoy Dawood[1], Denizhan Yavas[1], Christopher Giuffre[1], Ashraf Bastawros[1]*

[1]*Iowa State University, Ames, IA, USA*
** Presenting Author email: bastaw@iastate.edu*

Abstract
We present fracture mechanics-based approaches to characterize interfacial fracture parameters for the tensile and shear behavior of a typical ice/aluminum interface. An experimental framework employing single cantilever beam, direct shear, and push-out shear tests were developed to achieve near mode-I and near mode-II fracture conditions at the interface. Both analytical (beam bending and shear-lag analysis), and numerical (finite element analysis incorporating cohesive zone method) models were used to extract mode-I and II interfacial fracture parameters. The combined experimental and numerical results, as well as surveying published results for the direct shear and push-out shear tests, showed that mode-II interfacial strength and toughness could be significantly affected by the test method due to geometrically induced interfacial residual stress. As a result, the apparent toughness of the zero-angle push-out test could reach an order of magnitude higher than those derived from direct shear tests. Moreover, it was found that the interfacial ice adhesion is fracture mode insensitive and roughness insensitive for tensile and shear modes, for the observed modes of failures in this study.

1. Introduction
Ice adhesion strength has been studied over the past 70 years through different types of mechanical testing configurations, including push-out, direct shear, cylindrical twist of normal interface, and centrifuge configuration. With diverse testing configurations and experimental testing environment, a wide range of ice adhesion shear strength on typical metallic surfaces was reported with more than an order of magnitude of variance of 70-2,500 kPa, for a typical ice-aluminum interface. These tests are considered a strength-based measurement where the bonding strength of ice/substrate was characterized by measuring the interfacial shear strength, and very little work has utilized the fracture mechanics approach to accurately understand the mechanics of ice shedding. Such limit load interpretation of the ice-solid interface ignores the role of micro-structural and interfacial defects, as well as the geometrical constraints arising from different testing methodologies. This study embraces a fracture mechanics approach to delineate the difference between direct-shear and push-out tests. It also highlights the response of near mode-I or a tensile fracture of the interface utilizing a specially designed single cantilever beam with those derived under mode-II shear fracture. Summary of testing configurations, finite element calibration of cohesive parameters for each of the failure modes, and summary of the critical results are given.

2. Results
A generalized testing frame is designed and built inside an environmental chamber, with different sample holders for a single cantilever beam (SCB) to test the ice-substrate interface at near mode-I tensile fracture, for a direct shear testing configuration to test the ice-substrate interface at near mode-II loading, and for push-out shear testing configuration with also a near mode-II fracture loading. A parametric finite element simulations study was carried out, incorporating cohesive surface approach to extract the cohesive fracture parameters. First, the experimentally derived mode-I and mode-II toughness values were used as the initial values for mode-dependent cohesive fracture energy. Then, the corresponding mode-dependent strength were varied in a particular range to match the maximum force of the load-displacement curves of the experimentally measured values for each testing configuration. Each mode was calibrated separately without enforcing a mixed mode constitutive relation for fracture energy. The main findings are:

a. The work of adhesion is insensitive to the applied mode of loading, of whether being tensile or shear fracture.
b. The interfacial adhesion energy is almost independent of the surface roughness.

c. The direct shear results revealed much smaller variability compared to those form repeat tensile SCB tests, which might arise from statistical entrapment of interfacial defects in SCB.
d. The push-out test interfacial fracture toughness is about eight-times the direct shear results. A direct outcome from the residual stress generated during the freezing process, arising from the axisymmetric constrains on the volumetric expansion within the plane of the ice.
e. The failure mode changes from shear strength dominated to crack-nucleation and propagation dominated failure with increasing sample length. The transition between the modes sets the critical ice length scale, wherein a stable crack propagation could be observed for larger samples.
f. While the experimental measurements showed similar interfacial fracture energy for both tensile and shear mode loading, however, each mode have very different traction-separation relation with different cohesive strength and critical cohesion length. This difference arises from the difference of the interface stiffness under the normal and shear-loading mode, implying that the bridging length scale in shear is much bigger (at least three times as big) compared to tensile fracture.

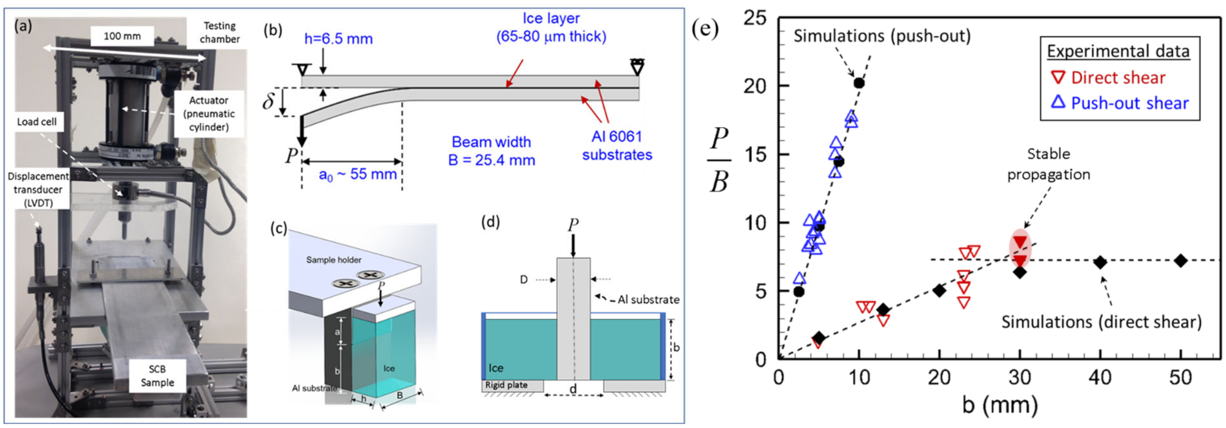

Fig.1 – Experiment: (a) Developed universal testing setup. (b) Single cantilever beam testing configuration. (c) Direct shear-testing configuration. (d) Push-out testing configuration. Results: (e) Summary of the experimental and numerical results for the interfacial normalized decohesion force (by the sample width) vs. the shear ice length for both the direct shear and push-out shear tests. The initial slope of the curve is the interfacial shear strength of the ice-solid interface.

3. Conclusions

A fracture mechanics based approach is utilized to understand the role of testing configuration geometry on the adhesion of ice-solid interface. Three different geometric configurations were studied, including a near mode-I single cantilever beam configuration, and a near mode-II and a direct shear and push-out configurations. The experimental results showed that the effective work of adhesion is both insensitive to the mode of loading and the roughness of the solid interface for the range of performed experimental measurements and for the observed cohesive interfacial failure. The role of surface roughness induced asperity locking was completely absent for the observed cohesive interfacial failure. Moreover, the experimental results showed almost an order of magnitude increase in both the work of adhesion and the critical shear strength of the interface for the push-out test, compared to the direct shear test. Such significant enhancement arises of the axisymmetric geometric constraints on the lateral expansion within the plan of the ice, leading to increase compressive stresses on the interface. The FEA cohesive surface analysis has highlighted the relative scale of the critical cohesive displacement at the interface under normal and shear loading, which could be utilized in the design of icephobic surface.

Acknowledgements
This work was supported by NASA grant number NNX16AN21A, with Mr. Richard Kreeger as the technical officer, and by Iowa State University through the T.W. Wilson Professorship.