

AIRA Research Thrust III- Physics of Ice Adhesion for Rotating Surfaces

Myron M. Oleskiw, Ph.D.

AIRA Research Implementation Forum (RIF)
Reno, NV
January 8, 2007



Background

- Ice formation and subsequent uncontrolled shedding from rotary-wing aircraft presents a major problem for safe mission performance in challenging environmental conditions
- The relationships between ice accretion, adhesion, shedding and shed particle trajectories are complex and presently poorly understood
- Shedding of large pieces of ice can result in aft airframe or tail rotor impacts with potentially hazardous consequences

NRC-IAR / DND Research Objectives

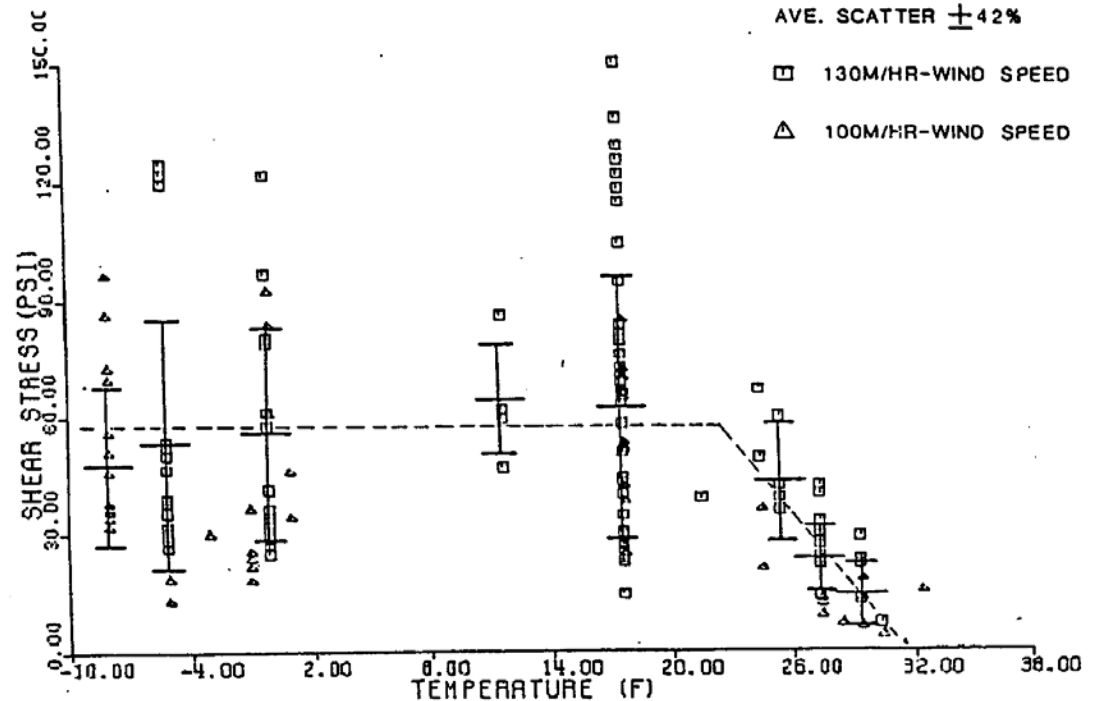
- The National Research Council's Institute for Aerospace Research (NRC-IAR) has recently begun a research program with funding from Canada's Department of National Defence (DND) to:
 - Extend the capabilities of the morphogenetic ice accretion model (Szilder, 2006)
 - Develop an empirical model of ice adhesion strength
 - Develop a computer model for predicting the probability of ice shedding from a helicopter fuselage or rotor as well as the probability of impact
 - Perform validation experiments on full-scale tail rotor
 - Prepare for testing of low adhesion coatings



What are some of the problems with available data?

- Few published results
- Available data exhibits substantial scatter
- Need to understand the relationship between adhesion and ice formation conditions (e.g. airspeed, air temperature, droplet size, liquid water content)
- Need data for larger ice samples

Adhesive shear strength of rime/glaze ice



(From Reich, Scavuzzo & Chu, 1994)

Ice Physics – What do we know?

- At low strain rates, ice demonstrates ductile and viscoelastic behaviour whereas at high strain rates it is brittle and failure may be adhesive, cohesive or a combination of these
- Ice is stronger in compression than in tension or in shear
- Real-world adhesive joints contain flaws (micro-cracks) and these defects (cracks and other stress concentrations) at the interface play a vital role in ice fracture and release whether the far-field load is purely shear, tension or a combination
- A liquid-like layer appears to exist at the interface between ice and other materials
- The thickness of this liquid layer (perhaps a couple of hundred molecules thick near 0°C) decreases as the temperature decreases down to approximately -30°C

What leads to stronger ice adhesion?

- Meteorological Conditions:
 - Lower rates of freezing (lower liquid water content [LWC])
 - Higher humidity on coated surfaces
 - Lower air temperature (Druez et al., 1976; Jellinek, 1957) or higher air temperature (Lack et al., 1957; Archer & Gupta, 1988; Nickolayev & Petrenko, 1995)
 - Increased ice thickness
 - Increased droplet momentum (product of median volume diameter [MVD] and flight velocity)
 - Amount of ice (or contact area)

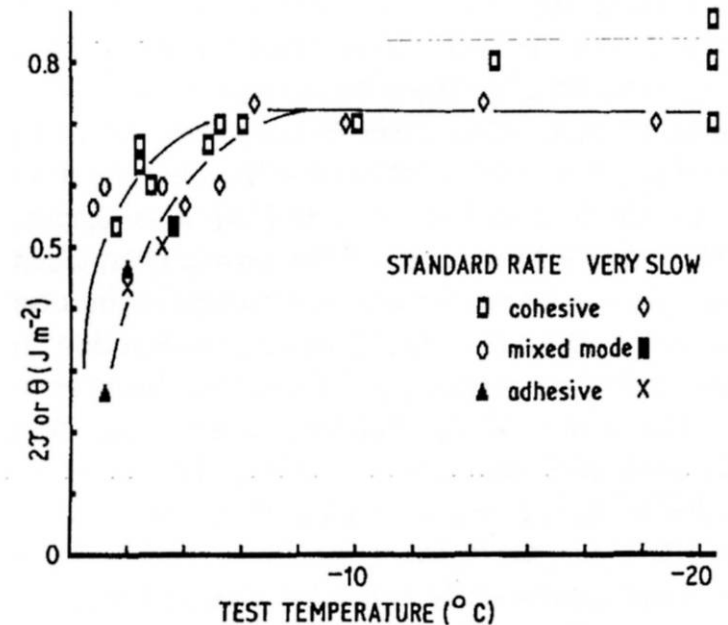


Figure 6 Variation of failure energy with test temperature for titanium substrates at two different pressurization rates as shown. Ice made at -20°C .

From Andrews & Lockington (1983)

What leads to stronger ice adhesion?

- Substrate Properties:
 - Increased matching of the solid lattice with the ice lattice
 - Surface roughness (mechanical interlocking)
 - Surface wettability (decreased water contact angle)
- Experimental Method:
 - Higher shear rate

What impact ice adhesion data is available?

- Stallabrass & Price (1962) [centrifugal]: 0.03 to 0.07 MPa at -6°C; 0.03 to 0.16 MPa at -1 to -15°C
- Laforte, Phan & Druetz (UQAC) (1976-1983) [collar]: 0.12 to 0.075 MPa for hard rime on aluminum; maximum of 0.42 MPa at 23 m/s
- Itagaki (1983) [centrifugal]
- Chu & Scavuzzo (1991) [inner & outer cylinder]: 0.12 MPa for rime; 0.41 MPa for glaze
- Miller & Bond (1989) [centrifugal – model helicopter]

What ice adhesion measurement techniques have been used?

- Shear modes:
 - Horizontal
 - Lap
 - Charpy impact
 - Bending
 - Torque
- Tensile
- Peel
- Laser spallation
- Scratch
- Atomic Force Microscope (AFM)
- Electromagnetic tensile
- Centrifugal
- Direct, using embedded piezoelectric film sensors

Why use the centrifugal method?

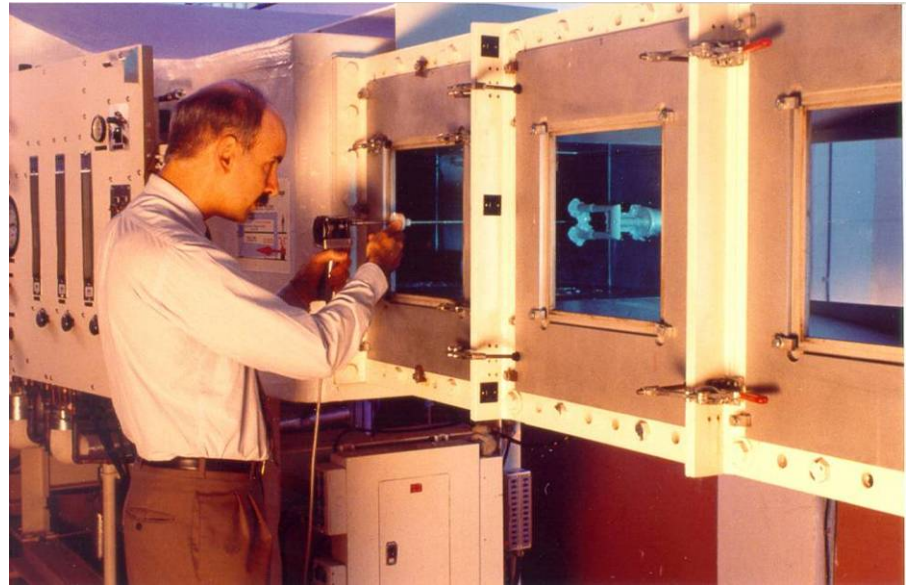
- An improved reproducibility of adhesive shear measurements should be achieved if:
 - The force is applied uniformly to the sample
 - The sample attachment area is not too small
 - The strain rate is constant and probably of intermediate value
- Previously used by:
 - Loughborough and Hass (1946 to 1956)
 - Beams (1955)
 - Rarety & Tabor (1958)
 - Itagaki (1983)
 - Miller & Bond (1989)
- Kellackey & Chu (1991) suggest that non-zero angles of attack provide significant loading on helicopter rotor blades

Can ice shedding be predicted?

- Kellackey, Chu & Scavuzzo (1991) performed statistical predictions of impact ice failure and shedding on rotating systems
- Concluded that “the discrepancy between theory and experiment could be largely attributed to an inadequate number of experimental data points for statistical analysis”.
- Papadakis et al. (2007) predict the trajectories of shed ice particles

Small-scale experiments:

- Impact ice accretion in the Altitude Icing Wind Tunnel (AIWT)
 - Test section: 57 cm [22.5 in] square (30 cm [12 in] with insert)
 - Maximum airspeed: 100 m/s [195 kt] or 185 m/s [360 kt] with insert
 - Liquid Water Content (LWC) from 0.1 to 3.0 g·m⁻³ at maximum airspeed
 - Spray droplet Median Volume Diameter (MVD) from 8 to 120 μm
 - Altitude from Sea Level to 7 km [23,000 ft]
- Initial shedding experiments to be performed using a small spin rig in a nearby cold room



Large-scale confirmatory experiments:



- Once sufficient data are available to characterize relationships between ice adhesion and the meteorological conditions and substrate properties, confirmatory shedding experiments will be performed using a tail rotor in the Propulsion Icing Wind Tunnel (PWT)

PWT Icing Characteristics:

Advantages:

- Large test section (3 m [10 ft] wide; 6 m [20 ft] high; 12 m [40 ft] long)
- Airspeeds up to 125 kt [55 m/s]
- Coverage of most of FAA Appendix C icing requirements:
 - Ottawa winter temperatures typically between 4°C and -25°C
 - Liquid Water Content (LWC) from 0.1 to 2.5 g·m⁻³ at maximum airspeed
 - Spray droplet Median Volume Diameter (MVD) from 15 to 50 µm
- Currently investigating supercooled large drop (SLD) icing simulation capabilities



Seeking Partners:

- NRC-IAR is seeking additional partners for this research project
- Possible contributions:
 - Statistical analysis techniques of shedding data
 - Computer code for prediction of shed ice particle trajectories
 - Provision of a powered tail rotor assembly for large-scale tests
 - Nanostructural studies of ice adhesion to various substrates