Adhesive Shear Strength of Impact Ice

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A quasistatic experimental technique was developed to determine the adhesive shear strength of impact ices formed inside an icing wind tunnel. Parametric studies were carried out to determine the dependence of the adhesive shear strength with various factors: 1) tunnel air temperature, 2) wind speed, 3) water drop size, 4) substrate material, 5) substrate surface roughness, and 6) substrate/impact ice interface temperature. The adhesive shear strength property was found to be statistical in nature, and on the average the mean varies between 17 and 60 psi (0.12–0.41 MPa) for rime and glaze ice, respectively. The property is also found to be strongly dependent on substrate surface roughness and substrate/impact ice interface temperature above 25°F (−3.9°C). There is a weak statistical linear correlation between wind speed and droplet size (momentum), but the shear strength appears to be independent of tunnel air temperature, accreted thickness, and substrate material used. Comparison is made with values obtained by other investigators and differences are discussed.

Introduction

THE formation of ice on engines and wings of fixed-wing aircraft and helicopter blades can seriously degrade the safety of an aircraft. On fixed-wing aircraft, ice deposits can adversely affect the aerodynamic characteristics of engines and airfoils. Ice accumulation on helicopter rotor blades is an especially serious problem. In addition to losing the aerodynamic lift, the rotor blade can become severely unbalanced if the ice sheds unevenly, causing dangerous vibration.

In general, there are three basic categories of deicing systems commonly used to deice aircraft or other structures: 1) mechanical systems, 2) thermal systems, and 3) chemical systems.

Mechanical systems can be further subdivided as 1) pneumatic boots, 2) electroimpulse (EIDI), 3) piezoelectric devices, and 4) vibratory devices. In these mechanical systems, the mechanics of deicing a surface can be divided into two distinct phases, breaking the adhesive bond and shedding the ice. At times, the ice will also crack from bending stresses. However, research has shown the dominant factor is the breaking of the adhesive bond by peeling or shear forces.[1] Aerodynamic forces and/or inertia forces acting on the ice are usually the main forces that cause shedding.

Because of all of these variables, a basic understanding of the mechanics of adhesion and fracture of impact ice is needed in order to model and design mechanical deicing systems effectively. Because of the importance of the adhesive bond between impact ice and substrate, this research effort is directed to this particular problem.

Literature Survey

There are numerous investigators who have investigated the adhesion of natural and artificial ice on various substances using a variety of surface roughnesses, treatments, and coatings. One of the earliest works on the adhesion of ice to various surfaces was done by Loughborough and Hass.[2] The shear strength of refrigerated ice was found to reach 250 psi (1.72 MPa). Adhesion of artificial ice to metals and polymers was also studied. He found the adhesive shear strengths varied from 220 psi (1.52 MPa) (aluminum) to 124 psi (0.85 (MPa) (copper). Druez et al.,[3] Phan et al.,[4] and Laforte et al.[5] have studied the adhesive strength of natural rime and glaze impact ice on aluminum electrical power conductors cables. In this work, the adhesive shear strength was shown to vary from 10 psi (67 KPa) to 58 psi (400 KPa), and appeared to increase with both velocity and surface roughness; the greatest variation occurred with roughness. The adhesive shear strength was found also to increase with wind velocity. Beams et al.[6] used the first rotating rotor centrifugal force technique to measure adhesive and tensile strength of thin films of ice on metal. The technique was used by Raraty and Tabor[7] to measure the adhesive shear strength of ice, on polished-cleaned stainless steel. The measured shear strength is 284 psi (1.96 MPa) at 50°F (10°C). Jellinek[8,9] studied the adhesive and cohesive strength of a snow-ice sandwiched between polished circular 304 SS plates approximately 1/8 in. (0.3 cm) apart. Shear stresses were developed from torsional loads. Using the "sandwich" technique he found the adhesive shear strength of ice on stainless steel to be quite high, ranging from 0 psi at 32°F (0°C) to 236 psi (1.65 MPa) at 6.8°F (−14°C). Bascom et al.[10] and Ford and Nichols[11] measured somewhat lower values of 135 psia (1.63 MPa) and 108 psia (0.24 MPa), respectively, for polished stainless steel. Kuroiwa[12] attempted to measure the adhesive shear strength of natural impact ice from the top of Mt. Nisekoan-nupuri. The calculated strength was quite high, i.e., 290 psia (2 MPa) at 14°F (−10°C) and 435 psia (3 MPa) at 23°F (−5°C). Questions are posed as to the accuracy of the calculation. On the other hand, Stallabrass and Price[13] and more recently Itagaki[14] found the adhesive shear strength of ice to be quite low, ranging from 4 to 10 psia (0.03–0.07 MPa) at 20°F (−6.6°C) and 4 to 23 psia (0.03–0.16 MPa) at a temperature of 30.2–59°F (−1°–15°C). These investigators used the dynamic rotating rod centrifugal force technique. Kozitsokii[15] studied the effect of roughness on 304 SS plates. He considered three types of surfaces: a machined surface, a mat surface finish, and a mirror polish 5–7 μin. (12.7–17.8 μcm). Mean adhesive shear strengths were 87 psi (6.1 kg/cm^2), 38 psi (2.7 kg/cm^2), and 9.7 psi (0.68 kg/cm^2), respectively, for a snow-ice layer 0.04–0.08 in. (0.1–0.2 cm) thick and a cross section of 0.97 in^2 (6.26 cm^2). Thus surface roughness increased the shear stress by a factor of almost 10.

There are numerous other studies made on the adhesive shear strength of ice both artificial and natural and under various conditions. Due to space limitations the above papers were selected as the most relevant to this study.

Test Facilities

The NASA Lewis Research Center Icing Research Tunnel (IRT) is a closed-return low-speed refrigerated wind tunnel. Its test section is 6 ft (1.83 m) high and 9 ft (2.74 m) wide.

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The airspeed in the test section can be varied from 20 miles/h (30 km/h) to 300 miles/h (480 km/h), and the tunnel temperature can be varied from above 32°F (0°C) down to about −22°F (−30°C). According to the present calibration, the icing cloud issuing from 77 air atomizing nozzles can produce a drop size range of from below 10 μ to about 40 μ (volume median diameter, DVM). The liquid water content (LWC) in the test section can be varied from about 0.3 to 3.0 g/m^3. Not all combinations of DVM and LWC are possible at every airspeed. The DVM and LWC are set according to the present calibration by adjusting the air and water pressures to the spray nozzles. For details about the spray cloud calibration and a discussion of possible error sources, refer to Ref. 16.

Shear Strength Test Apparatus

Figure 1 shows a schematic diagram of the test apparatus used to determine the adhesive shear strength of impact ices. As shown, the equipment has two main sections: 1) the ice-forming section where impact ices are accreted on the test specimens, and 2) the test section where the adhesive shear force is measured. Instrumentation of the test section is above the IRT; samples are placed in a holder in the wind tunnel for measurement. The test specimen (see Fig. 2) consists of a thin outer cylinder with a window and end flanges and a hollow inner rod (to which the impact ice is accreted through the window). The inner hollow rods of the shear test specimens were fabricated from 304 stainless steel, and aluminum. The roughness of the metal specimens is 10–30 μin. rms (25.4–76.2 μcm rms). Prior to each test the metal inner cylinders were dipped in acetone and allowed to dry. The specimens were assembled with metal tongs so that the surfaces were free of hand oils. The inner hollow rod was also assembled in the same manner. The objective of this procedure was to reduce data scatter. The fit between the outer cylinder and hollow inner rod is a sliding fit so that it will slide freely without vibration. Five of the cylinder pairs are stacked (Fig. 1) on top of each other on a common shaft which is mounted vertically inside the IRT. The assembly is rotated in the wind tunnel at a rate of approximately 20 rpm. When the stack is rotated, an almost uniform coating of impact ice is deposited onto the cylinders. Two types of windows were used (Fig. 2): a square 1³⁄₁₆ × 1¹⁄₁₆ in. (3 × 2.7 cm) window and rectangular window 1³⁄₁₆ × 2⁹⁄₁₆ in. (3 × 6.5 cm).

Time of exposure to the ice cloud was varied so that the thickness of ice deposit was approximately 1/4 in. (0.64 cm) to 3/8 in. (0.95 cm) thick. It was found that if the ice was too thin, cohesive failure would occur in the window section. As expected, this type of failure occurred more often with rime ice than with glaze ice. The rime is accreted with small water drops (15 μm) appeared to be weaker than the ones accreted with larger drops (20–27 μm). On the other hand, if the ice was too thick, the stack assembly could not be taken apart without significant force, which often disturbed the adhesive bond between the inner rod and ice. Thus, by trial and error it was found that the optimum thickness for these tests was about 1/4 in. (0.64 cm) for glaze ice and about 3/8 in. (0.95 cm) for rime ice.

One other aspect about testing rime ice should be pointed out. Bumps and depression in the surface of the specimen affected the shape of the ice deposit. Thus, the lip at the window edge of the outer cylinder could be easily distinguished in a 3/8-in. (0.95 cm) ice deposit even though the lip was filed to a sharp edge. This problem was worse with small drops (15 μm) at low temperatures −8°F (−22°C). This weakness in rime ice often leads to a cohesive failure along the window edges rather than an adhesive failure on the sur-

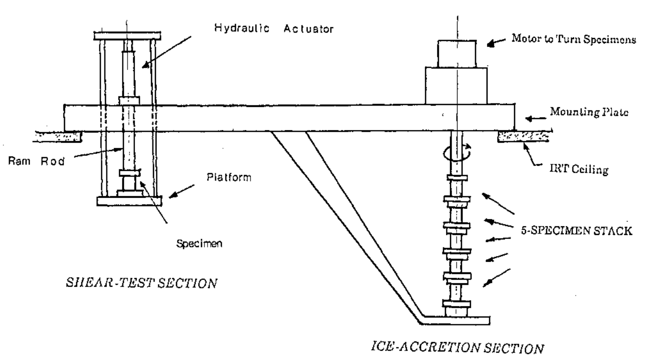

Fig. 1 Schematic of test apparatus.

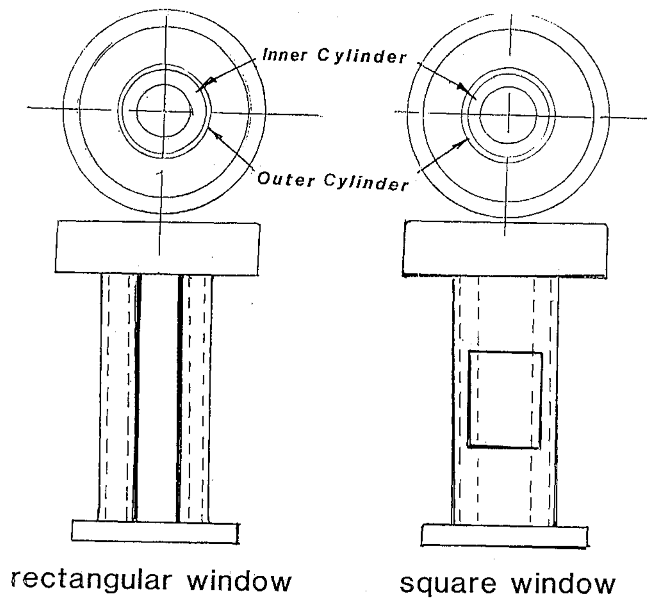

Fig. 2 Schematic of test specimen.

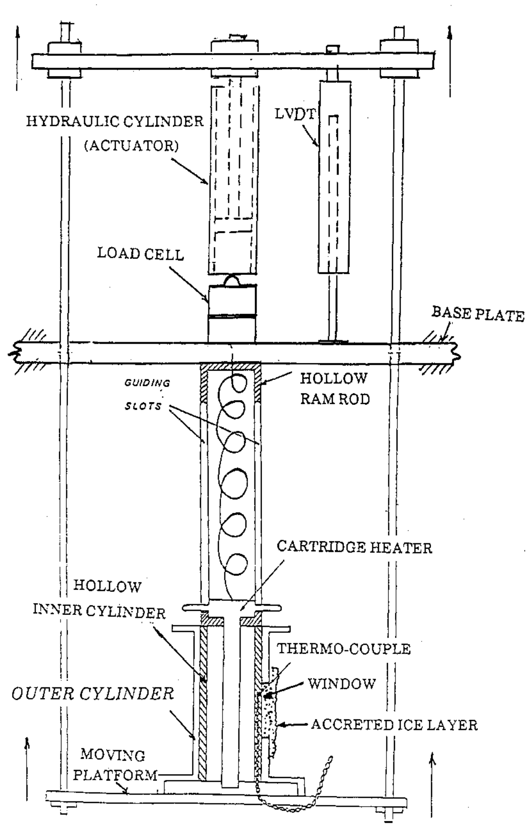

Fig. 3 Schematic of test section.

face of the inner cylinder. None of these cohesive failure data were used in this report.

As shown in Fig. 3, the test section consists of a (vertically) moving platform, a hollow ram rod, a hydraulic cylinder, a load cell, and a linear variable displacement transducer (LVDT). The load cell underneath the hydraulic cylinder measures the adhesive shear force and the LVDT measures the vertical displacement of the platform. Measurement procedure is described in more detail later in this paper.

Also shown in Fig. 3, a thermocouple is embedded at the center of the window of the test specimen through the periphery of the inner hollow rod. The thermocouple measures the interface temperature between the substrate (inner rod) and the impact ice accreted to it through the window opening. Also shown is the heater cartridge right at the center of the hollow inner rod. This is used to vary the impact ice/substrate interface temperature.

Test Procedure

The cylindrical test specimens (Fig. 2), stacked up five high in each (column) test set, are shown in Fig. 1 and rotated inside the IRT. After the impact ice has been accreted uniformly around the specimen to a certain thickness, the stack is removed from the ice accretion section and the test cylinders are very carefully separated from one another. Each test cylinder is then mounted on the platform of the test section as shown in Fig. 3. As shown, the hollow ram rod is positioned concentrically with the inner hollow rod of the cylinder specimen. The operator then commenced the testing by activating the hydraulic cylinder. The hydraulic cylinder upon extension lifts up the platform, and the stationary ram rod pushes the inner rod down the test cylinder. The ramming force of separation is measured by a load cell underneath the hydraulic cylinder (see Fig. 3). The measured force is the adhesive shear strength between the impact ice accreted through the window of the outer cylinder and the inner rod of the test cylinder.

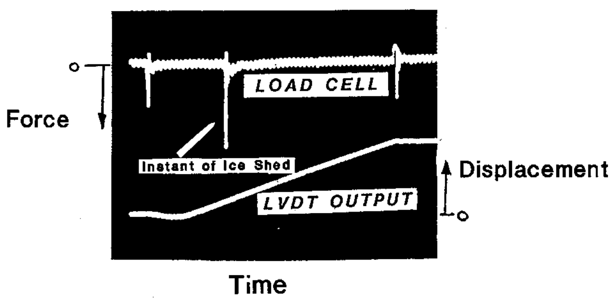

Fig. 4 Typical force vs displacement graph.

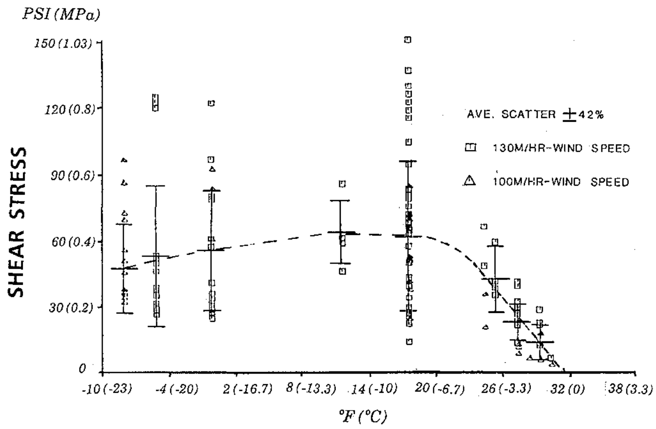

Fig. 5 Shear stress vs ice/substrate interface temperature.

In order to determine the instant of shedding (maximum force) during the spatial ramming period, a LVDT (see Fig. 3) is attached longitudinally across the cylinder body and piston rod of the hydraulic cylinder. The output of the load cell (ordinate) and the LVDT (abscissa) is displayed on a calibrated storage scope. A typical force vs displacement experimental test curve is shown in Fig. 4.

Figure 3 shows a thermocouple that is embedded in the periphery of the inner (hollow) rod wall at the center of the rectangular window. This thermocouple was used to measure impact ice/substrate interface temperature. The power of the heating element at the center of the hollow rod is turned on from 5 to 10 min to gradually heat the ice/substrate interface at a rate of approximately 2°F/min. The instant a predetermined temperature is attained, the hydraulic cylinder is actuated by the operator to shear the specimen. In this manner, shear stress as a function of the interface temperature was determined.

Discussion of Results

There was significant effort made to perform the test consistently. In spite of all precautions observed, there is significant data scatter in all shear test results. Previous investigators experienced the same scatter of ice data.

Due to the inherent scatter of the data obtained, the result is presented in a statistical format. Mean values and standard deviations are shown in the figures.

The discussion is divided into three main parts: 1) shear strength as function of tunnel and impact ice/substrate interface temperature, 2) shear strength as a function of wind velocity and momentum, and 3) other parametric studies. A total of 242 data points were collected.

Shear Strength vs Impact Ice/Substrate Interface Temperature

Figure 5 shows a scatter plot of all data collected from this experimental series. As can be seen, there appears to be a strong correlation between the ice/substrate interface temperature and the adhesive shear strength, at an interface temperature above 25°F (−4°C). The shear strength on the average tends to decrease above 25°F (−4°C) and approaches zero at the melting point temperature of 32°F (0°C). Also shown superimposed is the statistical plot of the data. In this case, only statistical mean shear strength at selected interface temperatures with adequate data sample for a statistical mean analysis are shown. As can be seen there is a gap of missing data between temperatures of 2°F (−17°C) and 8°F (13°C); nevertheless there appears to be a sharp decrease of the adhesive shear strength at temperature above 25°F (4°C). The average data scatter (standard deviation) is ±20% of the average reading and a maximum of ±42% at 18°F (−8°C). This scatter is believed to be inherent, because tunnel conditions are quite repeatable and the test specimens were carefully cleaned and prepared in every test.

Shear Strength vs Tunnel Wind Velocity

Figures 6 and 7 show both a scatter plot and statistical averages of data points obtained from these test series. Figure 6 shows the variation of adhesive shear strength with wind velocity for hard glaze and rime ice deposits at temperatures above 3°F (−16°C) and Fig. 7 shows for temperatures below 3°F (−16°C). As can be seen in Fig. 6, for hard rime-glaze ice, the adhesive shear strength appears to increase very slightly as the wind velocity increases as shown by the statistical curve. Similarly, for powdery rime ice −8°F to 3°F (−22°C to −16°C) in Fig. 7, there appears a slight increasing trend. Also in the test samples with these particular conditions, the ice deposits at the window shattered during the shearing test, and because of this, somewhat fewer samples were left that gave reliable test values. In both conditions, the correlations, if any, appear to be weak.

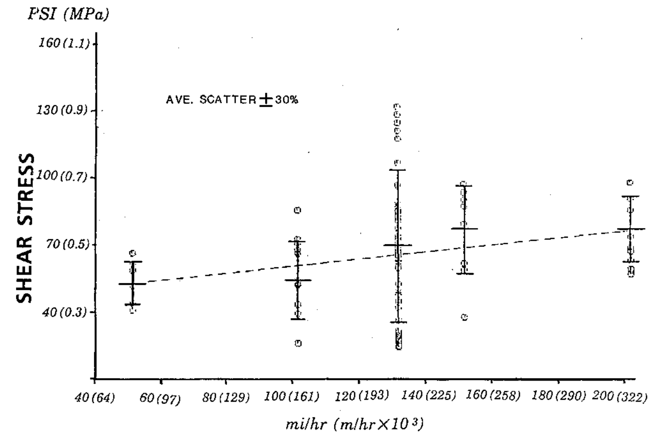

Fig. 6 Shear stress vs wind velocity, $T > 3°F$ ($-16°C$).

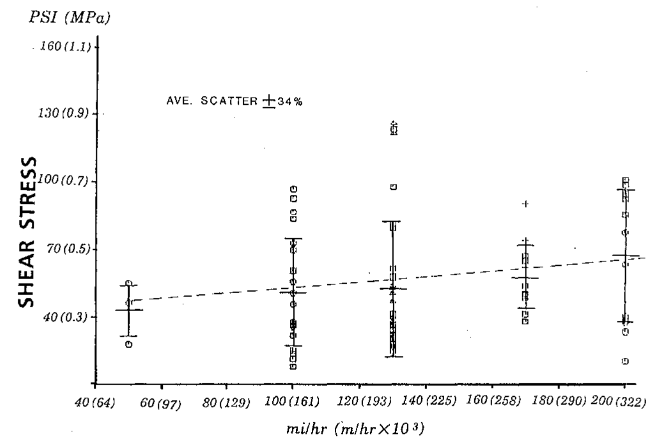

Fig. 7 Shear stress vs wind velocity, $T < 3°F$ ($-16°C$).

Adhesive Shear Strength vs Droplet Momentum

Figure 8 shows a statistical plot of shear strength vs wind velocity (V) multiplied by droplet diameter (D) cube (i.e., VD^3 which is proportional to the droplet momentum, if the mass density of ice is assumed constant), for hard glaze-rime ice conditions above 0°F (−18°C) tunnel temperature. As can be seen, the same trend is observed: the shear strength increased slightly with increasing droplet momentum.

Other Parametric Studies

The following are "by-product" results and not the main thrust of the study. These are results of exploratory preliminary studies conducted to obtain optimum parameters to be used in the study presented above.

Shear Strength vs Ice Thickness

In order to determine the optimum impact ice thickness to be used in the study, a parameter study was conducted at glaze ice conditions. The thickness of the accreted ice was varied from 1/4 in. to 1/2 in. (0.64–1.27 cm). Figure 9 shows the results. The statistical mean suggests that the adhesive property is independent of ice thickness.

Shear Strength vs Material Substrates

In order to determine the optimum material to be used in the study, preliminary studies were conducted between aluminum and stainless steel specimens. The two materials are of the same surface roughness, about 30 μin. rms (76 μcm

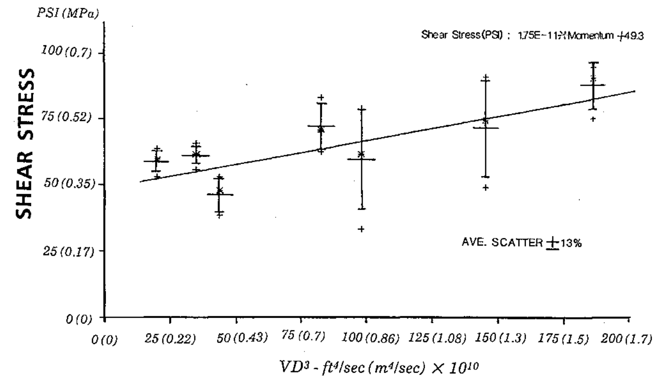

Fig. 8 Shear stress vs droplet momentum.

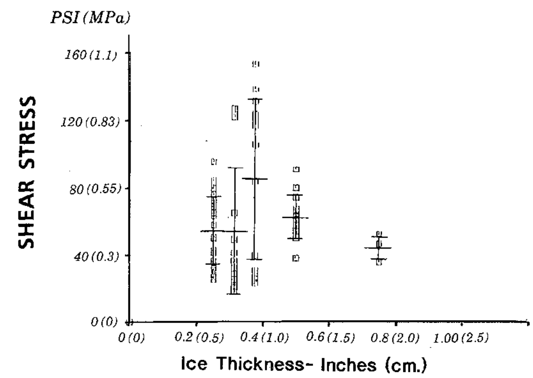

Fig. 9 Shear stress vs ice layer thickness.

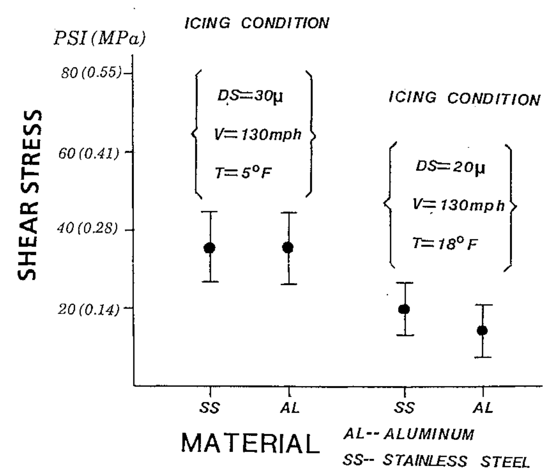

Fig. 10 Shear stress vs substrate material.

rms). Figure 10 shows the statistical result for two icing conditions. The statistical data points represent the average of 10 test specimens each. As can be seen, the mean value for both materials for the two test conditions are practically equal. The adhesive shear strength appears to be independent of the two substrate materials tested.

Shear Strength vs Substrate Material Roughness

As pointed out above, the shear strength property appears to be substrate material independent. To test the effect of surface roughness a number of aluminum specimens were sand blasted. The roughness was increased from 30 to 40 μin.

rms (76–102 μcm rms) to 70–80 μin. rms (178–203 μcm rms). Figure 11 shows statistically that the adhesive force for a roughness of 30–40 μin. rms (76–102 μcm rms) varies between 30 and 40 psi (0.21–0.28 MPa), but for the 70–80 μin. rms (178–203 μcm ms) roughness, the adhesive force is between 50 and 60 psi (0.35–0.41 MPa). For roughness about 80 μin. the test apparatus could not induce adhesive failure; the maximum force reached was 160 lb (711 N) (about 114 psi, 0.79 MPa). These results suggest that roughness is a major parameter affecting the adhesive strength of impact ice.

Shear Strength vs Impact Ice Type

When the data were grouped as to types of ice (i.e., glaze or rime ice), it was found out that majority of the data 132 points were for glaze ice and only 46 data points were for rime ice. As mentioned above, rime ice tends to fail cohesively and the majority of the data were rejected. The mean adhesive shear strength was found to be 58.4 psi (0.4 MPa) and 16.8 psi (0.12 MPa) for glaze and rime ice, respectively.

Comparison of Results with Other Investigators

It is quite impossible to pinpoint exactly the cause of the different values obtained by the various investigators. The first and foremost factor that causes data scatter is the inherent stochastic nature of ice. Most investigators, with very few exceptions, experienced some scatter in their data. In order to determine the statistical average of the ice properties, substantial data points are required; most previous investigators failed to obtain sufficient data points.

Another critical factor is the control and similarity of parameters used by various investigators: such as the kind or type of ice (natural or artificial), and if natural, whether it is glaze, rime, or a mix of both types; the cleanliness and roughness of the substrate surface; wind speed; water drop size; and water content of spray. For other factors that affect the adhesive strength of ice, see Jellinek.[8,9] One other very significant factor is the method of measurement. Both Stallabras and Itagaki as pointed out earlier used the dynamic rotating rotor centifugal force technique. Rotating structures are subject to both vibrations and aerodynamic forces that may not have been accounted for in the measurement. These forces could have prematurely jarred loose the ice particles from the substrate, and thereby contributed to the somewhat lower values measured by both investigators (see Fig. 12). In contrast, both this study and that of Jellinek used a quasistatic measurement technique, and obtained comparably higher ranges of shear strength values. Also Stallabrass's experiment did not pay particular attention to the cleanliness of the substrate surface. It is claimed that this is desirable since actual airfoil/blades do not remain polished in actual situations. However, surface impurities such as "hand" oil has been found by Baker et al.[17] to result in extremely low adhesive shear strength of $7.25/\times 10^{-6}$ psia (0.5×10^{-6} MPa). This may be one of the causes for the relatively low adhesive shear strength measured by Stallabras. Both Jellinek (using benzene) and this study (using acetone) paid particular attention to having consistently "clean" substrate samples. To prevent hand oils, contamination tongs were used to handle the specimens after being dipped cleaned in a bath of acetone. This could be one of the most significant factors for the relatively higher values measured for the adhesive strength by this study.

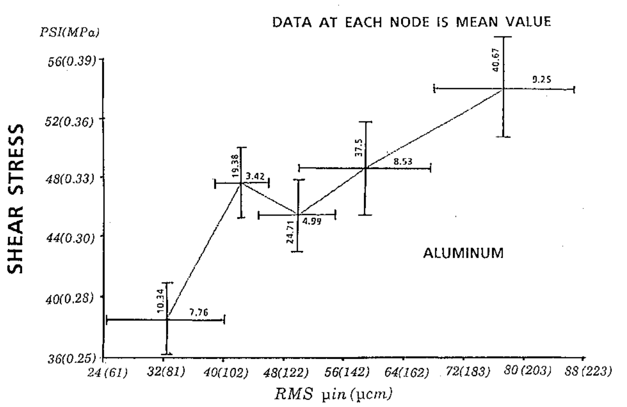

Fig. 11 Shear stress vs substrate material roughness.

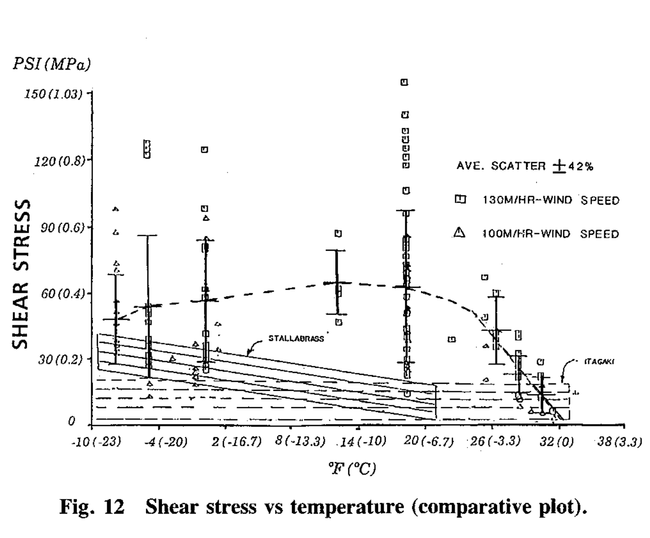

Fig. 12 Shear stress vs temperature (comparative plot).

Conclusions

This study is one of the most extensive (in terms of data points) studies on the adhesive shear strength of wind-tunnel-generated impact ice. More than 200 data points were collected. In general the adhesive shear strength of impact ice is found to be highly stochastic in nature. It is independent of substrate material, tunnel temperature $T \leqq 20°F$ (−7°C), and ice thickness. It has weak linearly increasing correlation with total droplet momentum. On the other hand, it has strong correlations with the following factors: the shear strength linearly decreased with increasing ice/substrate surface temperature at $T > 25°F$ (−3.9°C), and there was a marked linearly increasing correlation with substrate surface roughness. The adhesive shear strength of rime ice (16.8 psi) (0.12 MPa) is 30% lower than glaze ice, 58.4 psi (0.4 MPa). Therefore it can be concluded that the adhesive shear strength of rime ices is much weaker than that of glaze ices. While glaze ice is a homogenous transparent hard continuum solid, rime ice is nonhomogenous, consisting of powdery ice particles, shaped into finger-like structures. As shown above, the rime ice conditions have fewer data points compared to the glaze ice conditions (46 vs 177). This is due to the fact that rime ice often leads to cohesive failure along the window edges rather than an adhesive failure on the surface of the hollow rod substrate. These cohesive failure data were rejected. It should be mentioned that the collection of experimental data in this study is taken under various preselected values of water drop size, water content, and wind speed. Since the adhesive shear strength is somewhat weakly correlated to some of these factors, it may have contributed to the relatively large data scatter.

The differences in values of the adhesive shear strength measured by various investigators (including this study) could be attributed to many factors. The most significant ones are: 1) the types of ices used in the experiment (natural, wind tunnel, refrigerated, rime, glaze, etc.); 2) the conditions of the substrate surfaces (clean, oily, rough, smooth, etc.); 3) the methodology of measurements (static, quasistatic, dynamic, et.); and 4) statistical adequacy of data points collected, which is necessary due to the inherent highly stochastic nature of the properties of ice. This study is still exploratory in nature, although somewhat more extensive (in terms of number of data points taken) when compared to some previous investigators. Further investigation is necessary to collect more extensive data points at rigidly maintained parameters of wind speed, drop size, water content, etc., in order to pinpoint the "true" mean value and narrow down the large deviation to a more statistically acceptable value.

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