Impact Ice Adhesion at NASA Glenn: Current Experimental Methods and Supporting Measurements

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Abstract

When examining the literature on the adhesion strength of impact ice, there have been a wide range of methodologies tried to measure the required stresses to induce interfacial delamination. Utilizing the Icing Research Tunnel at the NASA Glenn Research Center to generate the impact ice required for this work, several different mechanical tests have been used to conduct ice adhesion studies through a wide sweep of icing conditions. To conduct in situ ice adhesion measurements inside of the Icing Research Tunnel, several new experiments are currently being developed to make ice adhesion measurements during and immediately after ice accretion. In addition to these experimental methods, several supporting measurement techniques have been developed to allow for a better understanding on the influence of icing cloud conditions on the mechanical behavior of impact ice. Digital image correlation has been successfully implemented to augment the data generated by the modified lap joint test with full field surface displacement and strain measurements which allow for insight into the deformation processes present during a test. Both optical microscopy of impact ice samples along with ice replication techniques have been used to study the grain structure of the impact ice. This has led to a deeper understanding of the results from the modified lap joint method and how the structure of impact ice changes as it is accreted during an icing spray. The freezing process of impact ice generated by supercooled liquid water is not a volume conserving process, which leads to the presence of residual strains along the interface between ice and substrate. These strains have been observed using both a simplified flat geometry and a representative airfoil. The data gathered by these experimental adhesion methods and supporting measurements allows for a comprehensive understanding on the behavior of impact ice which will be critical to the development of future ice shedding models.

Introduction

The accretion of impact ice due to supercooled liquid water on aircraft in flight poses a significant safety concern. The geometric change to the lifting surfaces leads to a decrease in flight performance and aircraft efficiency. As each new design and concept of aircraft has been developed, the effects of in-flight icing must be analyzed and considered during vehicle certification. This can come in the form of ice protection systems designed to remove accreted ice as well as pilot procedures should icing conditions be encountered.

An emerging sector of the aerospace market is known as Advanced Air Mobility (AAM), which focuses on air transit for both people and cargo using new aircraft designs. A subcomponent of this work includes a significant interest in the field of Urban Air Mobility (UAM) which focuses on the routine transportation of both passengers and cargo over densely populated areas. Both of these areas are of significant interest to the NASA Aeronautics Research Mission Directorate as well as aircraft manufactures. As AAM and UAM aircraft move out of the conceptual design phase towards initial prototypes, the effects of aircraft icing must be considered. Not only is the performance degradation due to ice accretion of concern, but the risks due to ice shedding events. The uncontrolled or unexpected shedding of impact ice can pose a significant risk to the vehicle, infrastructure, and the people who inhabit the areas the vehicles will operate.

With the risk presented by ice shedding to these new aviation markets, the study of ice adhesive strength has emerged as an active area of research. Due to the difficulties associated with testing ice, this has led to the development of new test methods all designed to measure the strength of the bond between ice and a given substrate. However, the influx of new test methods has introduced significant spread in the adhesion strengths being reported [1]. Conducting interlaboratory comparison of adhesion results is made exceedingly difficult due to differences in testing method, ice formation process, surface preparation, or data processing [2]. Additionally, there are significant costs associated with developing each new type of adhesion test, which typically limits each facility to a single type of test.

In this work, we present the approaches used at NASA Glenn Research Center (GRC) to conduct both measurement of the adhesive strength of impact ice as well as supporting measurements that are being used to develop a better mechanistic understanding of the results. The first section of this paper is a discussion about the mechanical testing methods that have been developed to measure the interfacial adhesive strength. This includes the technically mature modified lap joint test method, the novel deformed skin adhesion test, and an upcoming instrumented centrifuge capability. The second section of the paper focuses on the variety of measurement techniques that are being used to better interpret the results from the adhesion measurements. This includes studying the microstructure of the ice to understanding the role of cloud condition on material...
properties which can have a direct influence on the adhesive strength. An augmentation of the modified lap joint test using digital image correlation is presented which gives new insight into the strain fields that occur near the interface, as well as measurement of residual strains that are produced due to the dynamic nature of impact ice formation.

**Impact Ice Adhesion Methods**

The Revolutionary Icing Materials Evaluation Laboratory (RIMELab), located at NASA GRC, conducts the mechanical experiments and data analysis required to understand the adhesive strength of impact ice to various substrates. Samples are generated using the Icing Research Tunnel (IRT) located at GRC which produces a wide range of icing conditions. The highly calibrated icing cloud generated in the IRT allows for the study in how various cloud conditions and wind tunnel parameters influence the adhesive strength. Adhesion experiments can be conducted either in-situ in the IRT using test methods such as the deformed skin adhesion test or samples can be transported to external facilities for testing using the modified lap joint test. The RIMELab is equipped with multiple freezers which allows for the long-term storage of samples at various conditions for the duration between accretion and testing.

Over the course of several experimental test campaigns the coupon design has been refined to reduce the influence of sharp edges which act as stress concentrators and testing procedures have been refined to limit operator error. Initial efforts were focused on the modified lap joint test method which requires significant sample handling and transportation, the capabilities of the lab have now grown to include in-situ adhesion testing using the IRT with the deformed skin adhesion test. As the need for both inter and intra facility adhesion test comparisons has increased, the RIMELab is adding a centrifugal testing as a method. By having several different methods available to measure ice adhesion, the RIMELab is poised to begin work on the direct comparison of adhesion results from the same facility using different methodologies.

**Modified Lap Joint Test**

The modified lap joint test [3] is the most technically mature ice adhesion testing method in the RIMELab’s portfolio. This methodology has undergone significant advancement since its initial round of tests in 2018 [4], including coupon geometry changes and improvements to the data reporting. This high throughput test enables the generation of data sets large enough to undergo statistical analysis to determine the influence of various icing and testing parameters [5].

The impact ice samples for this test are generated by placing an array of coupons mounted to a supporting framework inside of the test section of the IRT. The coupons are mounted in rows, an example of which is shown in Figure 1 with ice accreted onto the coupon. The current iteration of the supporting framework is capable of holding 46 coupons that can be removed after exposure to an icing cloud for later testing. Two coupons instrumented with thermocouples were used to ensure the substrates were at the desired temperature before the spray began. After removal from their individual mounting brackets, the samples are placed into individual bags packed with snow to prevent sublimation, allowing samples to be tested months after formation to study the effect of annealing time. The samples were stored and tested at the total temperature of the IRT during the spray, and this was accomplished using storage freezers and a custom climate-controlled testing chamber that surrounds the testing frame. Both the testing fixture and climate control chamber are shown in Figure 2.

The testing procedure has remained constant along with the data reporting methodology since it was reported in [5].

![Figure 1. Modified lap joint test coupons with ice accreted onto them inside of the IRT. The mounting bracket used to secure the coupon is dark grey, the coupon is light grey.](image1)

![Figure 2. Climate control chamber and testing frame used to conduct ice adhesion testing using the modified lap joint test inside of the RIMELab.](image2)

In addition to the experimental campaigns conducted using bare test coupons [3-5], a series of test was conducted with coupons covered with various icephobic coatings designed to reduce the interfacial adhesive strength. A total of 6 different coatings were tested, as listed in Table 1 along with the corresponding coupon IDs which were used to track individual results. Due to the ongoing nature of this work, the exact composition of each coating is not reported in this paper. Prior to testing in the IRT, the coatings underwent material characterization with impact testing conducted in accordance with ASTM D2794 and wear resistance following the guidance of ASTM D406013. Impact testing was conducted using an Elcometer 1615 and the tabor abrasion resistance evaluations were conducted using an H18 well spinning at 60 rpm for 1200 cycles. All coatings passed impact testing requirements and had acceptable wear index values. A visual comparison of the 6 coatings is given in Figure 3.
Table 1. Icephobic Coating Composition.

<table>
<thead>
<tr>
<th>Composition</th>
<th>IRT Coupon ID #</th>
<th>V (kts)</th>
<th>LWC (g/m²)</th>
<th>MVD (µm)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Coating</td>
<td>K1 - K15</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
<tr>
<td>Epoxy 1</td>
<td>K16 - K30</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
<tr>
<td>Epoxy Urea 1</td>
<td>K31 - K45</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
<tr>
<td>Epoxy 1 + Additive</td>
<td>L1 - L15</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
<tr>
<td>Epoxy Urea 2</td>
<td>L16 - L130</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
<tr>
<td>Epoxy Urea 1 + Additive</td>
<td>L31 - L45</td>
<td>100</td>
<td>0.91</td>
<td>79.7</td>
<td>264</td>
</tr>
</tbody>
</table>

Figure 3. Adhesion Test coupons coated with the proposed icephobic coatings given in Table 1. Starting left most coupon and moving right: Commercial Coating, Epoxy 1, Epoxy Urea 1, Epoxy 1 + Additive, Epoxy Urea 2, Epoxy Urea 1 + Additive.

Samples were generated in the IRT at three different total temperatures (−15°C, −20°C, and −25°C) and tested using the modified shear lap joint configuration using the same procedures as previously reported data [5]. The samples were left to anneal at the total temperature of the IRT during their accretion prior to mechanical testing. The adhesion strength for each sample tested is given in Figure 4 and Figure 5. All 6 of the coatings that were tested exhibited a much lower adhesion stress than a bare metal coupon with most of the results falling below 200 kPa adhesion strength. The adhesion data combined with the results from wear and impact testing indicate all compositions are potential candidates for future icephobic coatings. The results are also significant since the samples were left to anneal for a month prior to testing, which has been shown to drastically increase the adhesive strength of the interface.

Figure 4. Results of adhesion testing the K ID coupons with the modified lap joint test.
The results given in Figure 4 and Figure 5 highlight both the advantages and disadvantages of using the modified lap joint test. At both $-15^\circ\text{C}$ and $-25^\circ\text{C}$, the test was able to generate reproducible results within a reasonable threshold. Measuring the adhesion of impact ice at these low adhesion strengths is a significant challenge as small touches by the researcher during handling can lead to accidental sample failure. As previously mentioned, the samples require extensive researcher handling to remove them from the mounting brackets inside the IRT and transport them to long term storage. In addition, the testing procedure is manually intensive. Any of these steps could have introduced anomalies to the sample that would cause the large spread shown for the $-20^\circ\text{C}$ samples for 4 out of the 6 coatings. The only coatings which do not see a significant increase in the spread of the measured adhesion strengths were Epoxy 1 and Epoxy 1 + Additive. At this time, it is not known if this is due to the chemical composition of Epoxy 1 or additional testing factors. To develop this understanding, significant experimental efforts would need to be put forth to generate a comprehensive data set to study.

**Deformed Skin Adhesion Test**

While the modified lap joint test is an effective test for producing large data sets for statistical analysis, there remains a need for developing new methods to determine the adhesive strength of impact ice. The current methodology for conducting mechanical shear testing methods require significant handling of the samples between generation in the IRT and testing which leads to the loss of samples and can cause unintended interfacial damage. To overcome these issues, a new adhesion method is being developed at NASA GRC called the deformed skin adhesion test (DSAT) [6]. This test is designed to be conducted completely hands free and will enable in-situ measurement of the force-displacement response of the test coupon before and after ice accretion. To capture the mechanical response to loading, an Omega LD1-619-6.4-A010s linear variable inductance transducer (LVIT) and an Omega LCCD-100 IP67 rated load cell are attached to the testing frame. To apply the necessary displacement to generate load on the skin of the coupon, an L-239 High Load Motorized Linear Actuator was attached to the testing frame which allows for sub-micron displacement control. The coupon has the same outer profile as the hybrid model of the 65% midspan station NASA Common Research Model. A comparison between the CAD model and actual test article are shown in Figure 6.

![Figure 5. Results of adhesion testing the L1D coupons with the modified lap joint test](image1)

![Figure 6. DSAT Test Coupon CAD model and full completed test frame with coupon](image2)
stresses is primarily the out of plane displacements along the coupon surface in the x direction as shown in Figure 7. The displacement and stress fields are inversely related, as the negative displacement regions mean there will be positive surface traction, and the positive displacements indicating the coupon crushing into the ice. This is shown in Figure 8, with the stresses quickly diffusing compared to the displacement fields.

![Figure 7. DSAT finite element model deformation undergoing a 1 mm displacement in the z direction. The bottom displacement map shows the displacement in the x direction along the surface of the coupon, which is the deformation responsible for forming the necessary surface tractions to induce delamination.](image)

![Figure 8. Normal Surface stresses in MPA that will induce delamination of the ice from the underlying coupon. Stresses observed on the ice layer, which is the reason for the flipping of the y axis.](image)

A major factor in selecting icing cloud conditions is the sensitivity of the coupon to the overall thickness of the ice layer. To study the role of ice thickness, the best metric for capturing the change in coupon behavior is the overall stiffness of the system which can be expressed as the required force to move the rod 1 mm. The length and width of the ice layer were sufficient as to not impact the results from this series of simulations [6]. Results from this study are shown in Figure 9, with the simulations reaching a near steady-state response after 10mm of ice bonded to the coupon. Since the interface between ice and a metallic substrate is assumed to be extremely brittle, and ice is often assumed to be linear elastic; there will be no change in the force-displacement relationship measured for any ice layer exceeding 10 mm in thickness. This will be critical as accurate simulation of the experiment will be required to determine the adhesion stress as no analytical model for this test currently exists.

![Figure 9. Stiffness response as a function of ice thickness](image)

**Centrifugal Methods**

With the emergence of new rotorcraft technologies that are being designed for use in urban airspace, ice adhesion methods utilizing centrifugal forces to induce delamination have become necessary. Rotorcraft icing presents a unique series of challenges to understanding the interfacial strength and the mechanics of ice...
shedding. In 2013, a series of tests were conducted in the IRT utilizing a full-scale heated tail rotor to study the trajectories of ice after it had been shed from the test article [7]. Results from these studies is shown in Figure 10, with the predicted shedding trajectories overlayed with images captured during the experiment. However, this test was not able to produce data regarding the strength of the bond between ice and rotor prior to shedding. While the ability to identify and track ice post shedding will be critical to ensuring safe operation of rotorcraft vehicles in densely packed urban environments, there remains significant work to understand stress states which promote ice shedding.

![Figure 10. Comparison of actual and predicted trajectories of ice shed from a rotating component in the IRT. From [7]](image1)

To begin the rigorous study on the shedding of impact ice from rotating machinery, NASA GRC procured an instrumented centrifuge which will be capable of operation in both the IRT and in a cold chamber containing a spray nozzle. Known as AERTS Jr. II (AJ2), this equipment is a refinement of the AERTS Jr. centrifuge currently at NASA Langley Research Center. Both pieces of test equipment were developed at Penn State University Adverse Environment Rotor Test Stand facility. AJ2 includes several upgrades over previous facilities including the ability to conduct completely hands-free testing, and controllable strain rates. Figure 11 shows the AJ2 fully installed into one of the walk-in freezers located in the RIMELab. The rotor head is incased in shielding to protect the facility as AJ2 has a maximum recommended operating speed of 5000 rpm. Ice is accreted on two 1” in diameter stainless steel discs with shedding events being recorded via strain gages bonded to the coupon attachment arms. A view of the rotor head with the coupons removed is shown in Figure 12. During a test, the rotor head will rotate in the counterclockwise direction until there is sufficient ice accretion on the coupon for shedding to occur. A significant improvement with AJ2 over previous centrifuges is the angle of the coupon holders to promote pure shear delamination. Full details regarding the design of AJ2 can be found in several published papers including comparisons to other centrifuge facilities [8,9,10].

![Figure 11. AERTS Jr II. Instrumented centrifuge adhesion test stand installed in a cold chamber located in the RIMELab.](image2)

![Figure 12. AERTS Jr II. Rotor head with the test coupons removed.](image3)

Perhaps more important than the addition of AJ2 to GRC’s portfolio of ice adhesion experiments, AJ2 represents a testing method that will be used to conduct inter-laboratory comparison of ice adhesive strength. Both the AERTS facility at Penn State University and AJ1 at NASA Langley Research Center are similar facilities but differ in terms of capabilities such as cloud formation. All three facility operate using the same test principles, but in very different operating conditions.
conditions. Both the AERTS test stand and AJ1 are tested enclosed in cold chambers with nozzles mounted in the ceiling to produce the icing cloud. AJ2 is unique in its capability to operate in both a similar cold chamber as well as the IRT. By testing in the IRT, AJ2 will be capable of gathering in-situ adhesion data from an icing research tunnel during an icing spray. The results from this test will also be compared to results from the modified shear lap joint test and the DSAT.

Supporting Measurements

In addition to the direct measurement of adhesion strength at NASA Glenn, there has been significant work done to develop additional supporting measurements to better understand the connection between the adhesive strength and icing cloud conditions. The purpose of these measurements is to acquire data that can provide a more detailed analysis and develop a deeper mechanistic understanding of the adhesion results. This will allow for a better explanation of trends in the data such as the role of icing cloud condition on sample failure mode and impact ice microstructure. The role of these measurements is to augment the adhesion experiments and provide the necessary information that will be used in the design and planning of future experiments.

Grain Structure of Impact Ice

In any engineering material composed of individual grains, i.e., polycrystalline metals, there is a direct relationship between the grain size and various material properties. This is often viewed through the lens of the Hall-Petch relationship [11], where the grain size is inversely related to material strength. Additionally, the formation of impact ice involves the freezing of droplets being transported by high-speed airflow once they have impacted a coupon, which can lead to air bubbles being captured in the ice. The presence of such defects in a material function as stress concentration points, leading to bulk failure of the sample at stress states far below the expected failure point of the interface.

To better understand the role of cloud conditions, on the microstructure of impact ice, samples from various IRT test campaigns were imaged using an Infinity 3 Lumenera camera mounted to a Leica Microscope containing both x5 and x10 objectives. Prior to imaging, the ice surface was exposed to the atmosphere for a minimum of 40 minutes to promote sublimation of the ice, which improves the visibility of the grain boundaries. Additionally, samples were imaged at different distances away from the interface to understand the changes in microstructure during the ice accretion process. The difference in grain structure is highlighted in Figure 13 and Figure 14 with images taken from the same sample, but at different distances away from the interface. These surfaces were exposed using a Bright Series 8000 microtome kept inside of the temperature-controlled chamber. Each layer was given the same amount of exposure time to the atmosphere prior to imaging to ensure the grain boundaries were easily identifiable. Changes such as the bubble distribution and grain size are noticeable, which can lead to changes in the behavior of the ice during loading. This can have several unintended consequences including undesired sample failure or changes in the constitutive properties of the ice as a function of distance away from the interface.

As the images were taken closer to the interface, the light reflection off the test coupon greatly degraded the quality of the image. This is due to the transparent nature of ice and the reflective nature of the coatings, with an example of the image degradation shown in Figure 15. Due to the magnification used to gather these images, the tool marks on the coupon surface produce an interference pattern that makes accurate distinguishment of the grain boundary difficult. To accurately capture the grain structure at the interface, replicas of the ice was generated using RepliSet two-part silicon rubber produced by Struers. Using the same sublimation procedures to enhance the grain boundaries, the ability of this method to capture the grain structure is shown in Figure 16. Images from the ice replica are gathered using a ZYGO Nexview NX2 optical profiler at x10 magnification, which results in a field of view of 0.86mm by 0.866mm and a lateral resolution of 0.186 micron. By replicating the entire area of the interface, this method will facilitate study of the change in ice grain size as a function of position along the coupon. While Repliset is accepted for work done using ASTM standard E 1351, the error quantification between grain sizing using microscope images and replica images has not been completed for this work.
temperature of the IRT has a significant impact on the mean grain size, where lower temperatures result in much smaller grain sizes, with the tunnel velocity having a minimal role in changing the grain size.

To increase the output of grain size analysis from GRC, both the grain boundary identification and Hilliard’s circular intercept method were automated. Grain boundary identification was accomplished through the training of a deep learning segmentation model known as Micronet. The model was trained using microscope gathered images with the grain boundaries manually identified and traced. The full details regarding the model training process and the post-processing of model identified grain boundaries are given in [14]. Initial study of the model results indicates this new methodology compares favorably with the results from manually identifying grain boundaries. This new grain identification capability will allow for significant investigation into the role wind tunnel conditions play on the ice microstructure and begin a concentrated effort to better understand previous adhesion results. In addition to grain boundary identification, the effort to develop machine learning models capable of measuring the size and distribution of bubbles present in impact ice. These models are still in development, but initial results show great promise in this technology’s ability to have a significant role in understanding the mechanical behavior of impact ice.

**Digital Image Correlation**

While the modified lap joint shear test is well suited to conduct high throughput tests, the data gathered during a normal experiment is limited to the applied load required to induce sample failure and failure mode. While this reduction in data allows for large data sets to be studied using statistical models and regression fitting, a significant amount of data that could inform the study on the mechanical behavior of ice is discarded. To capture this data, digital image correlation (DIC) [15] has been implemented to provide a method for studying the displacement and strain response of the impact ice–coupon interface under shear loading [16].

Digital image correlation allows for the study of several different aspects of how the ice deforms during a test using the modified lap joint. For lap joint adhesion tests conducted without this measurement technique, only the total displacement of the sample and the applied load were gathered. However, with DIC there is the ability to capture and reproduce the entire displacement field on the surface of the sample. Using the displacement boundary condition extraction method discussed in previous work [10], the experimental directional displacement fields shown in Figure 17 are very similar to the displacement fields generated using finite element simulations in Figure 18. For the frame shown, there is significant displacement in both directions where \(u_x\) is the displacement in the x direction and \(u_y\) is the displacement in the y direction. The slight differences in the fields are due to the noise levels and spatial resolution which are due to the current limitations of the sample preparation method [16]. Additionally, the finite element simulations used a perfectly rectangular geometry while the experimental samples increased in thickness as the ice grew away from the interface. Since the exact ice shape was not captured at the time of the experiment, these assumptions were deemed acceptable to show the development of this methodology. The total thickness of the finite element simulation is the thickness of the coupon used during the lap joint test, 6.37mm, and the total length was limited to the field of view of the camera used during DIC.

To measure the average grain size, the microscope images were manually analyzed using the methods outlined in ASTM standard ASTM-E112-13. Of the three methods outlined in the standard (Heyn’s linear intercept, Hilliard’s circular intercept, and Jefferie’s procedure) Hilliard’s was used to analyze the bulk of the images gathered, with some data being generated using the Heyn’s and Jefferie’s method. The full results from this work can be found in several NASA technical memorandums [12, 13], where the grain boundaries were manually identified. The results presented in both memorandums are self-consistent, with the grain size increasing as a function of position away from the interface. These results indicate a change in accretion processes of impact ice as the initial droplets to reach the coupon interact with the metal coupon while later drops adhere to the already formed ice layer. Additionally, the total...
Figure 17. Displacement fields generated from digital image correlation during the modified lap joint shear test

Figure 18. Displacement fields generated from finite element simulations using boundary conditions generated from experimental DIC data.

A fully detailed explanation of the strain calculations is given in previous work [16], where the calculations were limited to the interface between the ice and coupon. In that work, the interface was discretized into bins, with only a small percentage of the data near the interface being analyzed. By fitting linear regressions to the displacement data contained with the bin, the required derivatives for the strain calculations were the slope of the line. To expand this methodology to calculate the entire strain field on the surface of the sample, the entire sample was similarly discretized with a user selected number of bins segmenting the y direction. This allowed for the entire displacement field to be discretized into bins and the full strain fields calculated. The same linear progression procedure was used to calculate the displacement derivatives that are required for the strain calculations.

Since the entire surface is now being analyzed, both normal strain fields are computed with

\[
\varepsilon_{xx} = \frac{\partial u_x}{\partial x} \tag{1}
\]

\[
\varepsilon_{yy} = \frac{\partial u_y}{\partial y} \tag{2}
\]

and the shear strain field

\[
\gamma_{xy} = \frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y} \tag{3}
\]

For this work, the small rotation form of the shear strain is used as it was shown to accurately capture the behavior at the interface. To validate the extension of the strain calculation to encompass all three strain fields and the extension from 1D to 2D, the results are compared against the direct output from the finite element simulation that produced the displacement fields shown in Figure 17 and Figure 18. A comparison of \(\varepsilon_{xx}\) calculation is shown in Figure 19, \(\varepsilon_{yy}\) in Figure 20, and \(\gamma_{xy}\) in Figure 21. In the case of all three strain reconstructions, the binning and linear regression fitting does an excellent job of recreating the strain fields. The methodology was able to accurately capture both the pattern of the strain fields along with the magnitudes.

Figure 19. Comparison of \(\varepsilon_{xx}\) fields from finite element output (left) and the calculated using fitting methodology.
One of the most significant observations from examining the full surface strain fields is the significant presence of $\epsilon_{yy}$, especially near the interface. This test is designed to be a near pure shear test, and the presence of strains near the same magnitude as the shear strain along the interface highlights the need to augment adhesion experiments with additional measurement techniques. Further analysis of the strain fields generated from the experimental data and improved finite element modeling is required to understand the impact of these results on the analysis of the modified lap joint test.

**Interfacial Residual Strains**

The formation of impact ice onto a test article inside of the IRT is an extremely dynamic process. This leads to the formation of residual stresses with the ice layer and along the interface due to the non-volume conserving process of freezing super cooled liquid droplets. The effect of these residual strains was first observed when adhesion test samples in the IRT would completely delaminate from the coupon after an icing spray and a region of frost was present around the edges of the coupon. Examples of coupons exhibiting this frost pattern can be seen in Figure 22. The loss of these experimental samples is significant given the time and resources that are required to generate impact ice in a facility such as the IRT.

To better understand and quantify these strains, two separate experimental campaigns took place in the IRT with both instrumented adhesion style coupons [17] and a fully instrumented CRM leading edge [18]. The CRM leading edge contained two different strain sensors: conventional resistive strain gages and a network of Fiber Bragg grating sensors contained within a series of optical fibers. Both sensors can be seen in Figure 23 with the grating sensors located above the array of strain gages. As GRC moves towards conducting more in-situ ice adhesion experiments using the CRM, understanding the residual strains along the interface is critical to predicting the direction of interfacial delamination. As previously reported [18], the direction of the strains changes from tension to compression (or vice versa depending on observation time) as you move away from the stagnation point of the airfoil in the chordwise direction. This will have a significant impact on the direction of crack propagation, as the presence of tensile residual strains potentially weaken the interface, resulting in much lower observed adhesion values. Additionally, the presence of residual strains along the interface between airfoil and impact ice also indicate there is a high likelihood of out of plane residual strains normal to the airfoil. While measuring these strains might be impossible using standard instrumentation, the data gathered from these experiments will be critical to the development of future finite element simulations that will allow for detailed study of the residual stress state. From these simulations, it will be possible to either generate correction factors
for experimental data or provide initial stress fields for experimental efforts, such as the work being done with the DSAT.

does not stop at the reporting of adhesion strength, but also seeks to develop a more fundamental understanding of the mechanical behavior of impact ice through several supporting measurements. The unique ability to capture the microstructure of impact ice generated in the IRT and the grain size measurement capabilities will allow for better understanding of failure modes influenced by grain boundary toughening or air bubbles acting as stress concentration points in the material. The augmentation of the lap joint test with DIC enables the study of how impact ice deforms over a test. Methods developed to measure the strain along the interface have been extended to now enable study of the strains present on the entire surface of the sample. This will allow for a better understanding of the failure modes present in this test along with an understanding of the true stress state of the sample during testing. The modified lap joint test was previously thought to be a near pure shear experiment; however, it is now clear that there are significant normal stresses near the interface. This understanding will guide the next generation of tests and help better understand previously gathered data. The ability to produce surface deformation maps of the impact ice will allow for new study into the constitutive laws and material properties that govern impact ice deformation. After the observation of premature sample failure immediately after sample formation in the IRT, several experimental campaigns showed the presence and significance of residual strains along the interface. With the move towards in-situ testing using coupons mounted into airfoils, understanding the distribution and magnitude of these stresses will be critical to accurately predicting delamination propagation.

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Conclusion

The study of ice adhesion strength at NASA Glenn Research Center cuts a broad swath through both experimental methods for determining the stresses required to delaminate the ice and additional measurements which help improve the relationship between the icing cloud conditions and adhesive strength. High throughput direct measurements of the adhesive strength allow for a large data set to be constructed, while a method using a representative geometry will be the first in-situ adhesion testing done in the IRT. The addition of centrifugal based test methods into the suite of methods available will enable easier comparison of adhesion results between facilities equipped with similar technology. The work done at NASA Glenn

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Definitions/Abbreviations

AAM Advanced Air Mobility
AERTS Adverse Environment Rotor Test Stand
AJ1 AERTS Jr. I
AJ2 AERTS Jr. II
ASTM American Society for Testing and Materials
CAD Computer Aided Drafting
CRM Common Research Model
DIC Digital Image Correlation
DSAT Deformed Skin Adhesion Test
GRC Glenn Research Center
IRT Icing Research Tunnel
LVIT Linear Variable Inductance Transducer
LWC Liquid Water Content
MVD Mean Volumetric Diameter
RIMELab Revolution Icing Materials Evaluation Laboratory
UAM Urban Air Mobility
V Free Stream Velocity
\( \varepsilon_{xx} \) Engineering strain normal to the x axis
\( \varepsilon_{yy} \) Engineering strain normal to the y axis
\( \gamma_{xy} \) Engineering Shear Strain
\( u_x \) Displacement in the direction of the x-axis
\( u_y \) Displacement in the direction of the y-axis
\( u_z \) Displacement in the direction of the z-axis

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