Design of an Experimental Set-up Concerning Interfacial Stress to Promote Measurement Accuracy of Adhesive Shear Strength Between Ice and Substrate

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Abstract: Accumulation of ice on airfoils and engines seriously endangers the safety of the fight. The accurate measurement of adhesion strength at the ice-substrate interface plays a vital role in the design of anti/de-icing systems. In this pursuit, the present study envisages the evaluation of the stress at the icesubstrate interface to guide the design of experimental set-ups and improve the measurement accuracy of shear strength using the finite element analysis (FEA) method. By considering such factors as the peeling stress, maximum von-mises stress and uniformity of stress, the height and radius of ice and the loading height are investigated. Based on the simulation results, appropriate parameters are selected for the experimental validation. Simulation results show that the peeling stress is decreased by reducing the loading height and increasing the height of ice. Higher ice, increasing loading height and smaller ice radius are found to be beneficial for the uniformity of stress. To avoid cracks or ice-breaking, it is imperative that the ice should be of a small radius and greater height. Parameters including the ice height of 25 mm, radius of 20 mm, and loading height of 9 mm are adopted in the experiment. The results of FEA and the experimental validation can significantly enhance the measurement accuracy of shear strength.

Key words: aircraft de-icing; adhesive shear strength; finite element analysis (FEA); experimental set-up; interfacial stress

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0 Introduction

When an aircraft encounters a cold cloud condition during the flight, the icing on craft surface can occur. Aircraft icing causes overall lift falling and an increase in the drag, and can lead to a serious threat to flight safety. The research of effective anti/de-icing systems needs a significant attention in the aircraft design. Currently, there are several well-established anti/de-icing systems, including the electrothermal system, electro impulse system, and hot-air system. Meanwhile, some new technologies, such as superhydrophobic surfaces, plasma jet, and hybrid systems have been developed remarkably[1-2].

The core of ice shedding is to break the adhesion between the ice and the skin. Only if the adhesion is broken will the ice fall off the surface of aircraft due to its own gravity or aerodynamic forces. Thus, regardless of the anti/de-icing technology used, it is of great significance to understand the adhesion between the ice and skin, especially for the design of the anti/de-icing system. Many researchers have studied the adhesion force between ice and substrates. The anti-icing materials international laboratory (AMIL) introduced the centrifuge adhesion test (CAT) to investigate the adhesion force in

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2005, which utilized the centrifugal force to shed the ice[3]. According to the archetype of the AMIL's test, improved centrifugal tests were later developed. Itagaki[4] calculated the adhesion strength based on the dimension of the dislodged ice. Comparing with the CAT, this test was not ex situ icing and thus avoided some extra stress. This method was also called the calculated CAT(CCAT). Brouwers et al.[5] used the instrumented CAT (ICAT) to study the ice adhesion, which involved an airfoil and impact ice in the test. Besides the centrifugal tests, other more direct methods have also been used. In these methods, the interface between the ice and the substrate was separated by the force applied on the ice sample. A push test was used to investigate the relationship between the water wettability and ice adhesion by Meuler et al[6]. Ge et al.[7] pushed the ice using a needle to evaluate the anti-icing property of the superhydrophobic surface. Scavuzzo et al.[8] and Druez et al.[9-10] used a test apparatus that pushed the accreted ice around a metallic cylinder. Recently, Pervier et al.[11] designed a new setup to measure the adhesive shear strength of impact ice on alloy, in which the ice was pushed by high-pressure nitrogen through a pressurization system. In comparison with the centrifugal method, the direct-force test had merits of low cost, high efficiency, and validity. Thus, while the centrifugal tests, in general, have more reasonable scatter. So most scholars adopted the direct-force methods.

Although numerous experimental studies have been conducted in this arena, data from literatures has a serious lack of consistency. One of the main factors behind this is the complexity of the stress contribution at the interface. However, most of the research only paid attention to the experimental data and ignored the finite element analysis (FEA) for the stress at the interface. According to a review of Ref.[12], more than 100 papers reported experimental data, but only eight used FEA and just five of these papers were published after 2009. Koivuluoto et al.[13] demonstrated the stress concentration at the interface for CAT throughout FEA. Makkonen's FEA results indicated that the thermal stress was induced at the interface during the frozen process, which affected the adhesion strength to a certain degree[14]. In 2015, Schulz et al.[15] analyzed the interface stresses created by various methods, including shear, bending and centrifugal test, showing that peel stress also contributed along with the shear stress in the detachment of the ice. Pervier et al.[11] used FEA to assess the controlling shear stress in the most highly stressed zone of the ice-substrate interface. As a result, the shear strength was defined by the critical stress intensity. Thus, it can be inferred that the inaccuracy of experimental results was mainly caused by the stress concentration, normal stress (not pure shear stress), and possible ice-breaking at the ice-substrate interface.

In the present study, an experimental validation based on the push approach is performed to measure the adhesive shear strength and analyze the three factors (mentioned above) obtained from a prior FEA study. Depending on the results of FEA, the parameters are selected to enhance the measurement precision. By including the comprehensive FEA for deciphering the interfacial stress during the set-up design stage, we adopt a more rational equipment and achieve highly accurate tests, thereby leading to more even stress distribution, less peeling stress, and a lower possibility of ice breaking.

1 Computation Scheme

1.1 Finite element method

The finite element method is an approximate numerical analysis method, in which the structure is divided into finite elements, and then the displacement mode is constructed on the elements. Subsequently, the stress of each element can be solved through constitutive equations. In the present study, we acquire the stress distribution at the ice-substrate interface using the finite element analysis.

1.2 Simulation model

Direct-force test typified by using the push method is one of the most reliable approaches in determining the adhesive strength between ice and substrate. By using this principle, an experimental set-up is devised as shown in Fig.1.

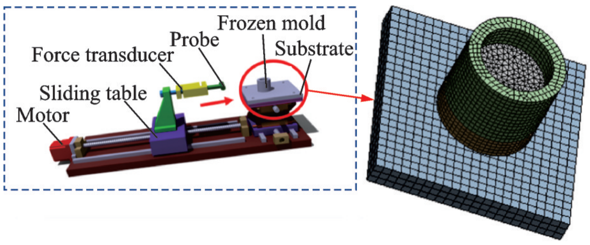

Fig.1 Design of experimental set-up and simulation model

Normally, ice gets frozen in a mold on the aluminum plate first. Then the sliding table is driven by the motor move towards the ice. Naturally, the force transducer and the probe also move to push the mold and ice to slide. At the moment of ice detachment from the substrate, the sensor indication is the adhesion shear force. By dividing the adhesion force by the contact area between ice and the aluminum plate, the shear strength can be calculated by

$$\tau = \frac{F}{A} \tag{1}$$

where τ is the adhesion shear strength, F the adhesion shear force, and A the contact area between ice and the aluminum plate.

The zone in which the ice is in contact with the substrate, is the part that concerns us most. Hence, FEA in this study mainly focuses on the aluminum plate, frozen mold, and ice, as indicated in the rightmost part of Fig.1. The external push force is directly applied to the set point on the mold. The contact of mold-substrate and ice-substrate is frictionless and bonded respectively and the aluminum plate is fixed. Based on this model, we investigate the effect of three parameters including the radius of ice r, the loading height of push force h, and the height of ice H on the interface stress, as shown in Fig.2.

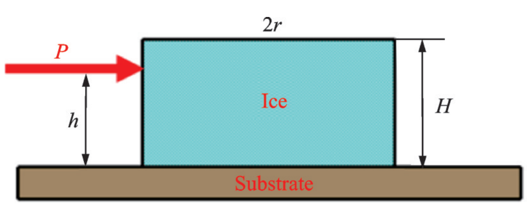

Fig.2 Schematic diagram of parameters

It is worth noting that this FEA model ignores the surface topography, so the real shear strength between the ice and aluminum substrate cannot be achieved from the FEA results. The aim of FEA in this study is to explore the interface stress at various parameters in order to reduce experimental errors at the source.

1.3 Stress at ice-substrate interface

1.3.1 Peeling stress

Owing to the distance from the ice-substrate interface to the loading point, the applied push force produces a bending moment at the interface, resulting in tensile stress and compression stress. The tensile stress promotes the peeling of the accumulated ice layer to some extent, so it is also called peeling stress. The presence of the peeling stress causes the mixed failure of shear and normal direction, which degrades the accuracy of adhesion shear strength measurement.

As shown in Fig.2, the bending moment at the interface can be calculated by

$$M = Ph \tag{2}$$

where M is the bending moment and P the applied push force.

The section modulus in bending W is

$$W = \frac{\pi r^3}{4} \tag{3}$$

Thus, by Eqs.(2, 3), the maximum peeling stress $\sigma_{\max}$ can be solved as

$$\sigma_{\max} = \frac{M}{W} = \frac{4Ph}{\pi r^3} \tag{4}$$

1.3.2 Von-mises stress

The von-mises stress is an equivalent stress based on shear strain energy, which is a combination of three principal stress. It reflects the comprehensive force on the object. In addition, it is more reasonable to use von-mises stress to evaluate the stresses in ice because ice shows different elasticity and plasticity under different loading conditions. It is given by

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \tag{5}$$

where σ_{eq} is the von-mises stress; σ_1, σ_2 and σ_3 are the first, second and third principal stress, respectively. In this study, σ_{eq} is used to evaluate the uniformity of the stress and whether the ice is broken at the interface.

2 Presentation of FEA Results

2.1 Peeling stress

As described in Section 1.3.1, the peeling stress is unfavorable for the measurement of shear strength, so it is expected to select a set of parameters with the lowest peeling stress. Fig.3 shows the effect of the height of loading point h and the height of ice H on the maximum peeling stress. It is obvious that the maximum peeling stress increases with the height of the loading point, which is in accordance with Eq.(4).

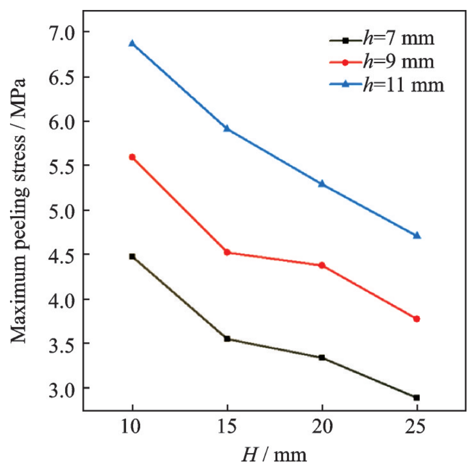

Fig.3 Effect of loading location and ice height on peeling stress

Besides the effect of loading height, the rise in height of the ice also leads to a decline in the maximum peeling stress. However, H is not included in Eq.(4). In other words, the height of ice theoretically exhibits no impact on the peeling stress. In fact, the frozen mold could be neglected when deducing Eq.(4). To survey the influence of the frozen mold on the FEA results, a path is defined along the direction of the height of ice as drawn in Fig.4 and the stress along this path is plotted, in which the area enclosed by the curve and the two coordinate axes is defined as stress moment T. The subgraph in the upper right corner of Fig.4 depicts the change of stress moment at different heights of ice. It can be seen that the stress moment diminishes with an increase in the height of ice, as shown in Fig.3. Apparently, the frozen mold transfers the applied concentration load to various distributed stress. Although the high ice had a longer path under stress, the magnitude of stress is lower than that of the short ice, leading to the minimization of stress moment.

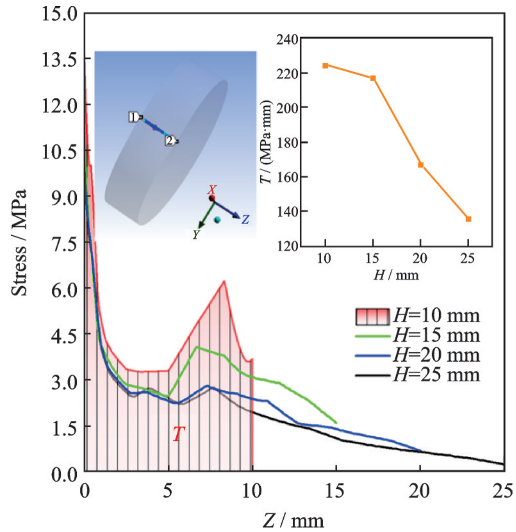

Fig.4 Effect of frozen mold on peeling stress

As for the radius of ice r, the FEA results are demonstrated in the blue curve in Fig.5. With an increase in the radius, there is a corresponding decrease in the peeling stress, agreeing with Eq.(4). However, it must be noted that the applied push force is constant when there is a change in the radius. In reality, as Eq.(1) shows, when the shear strength remains constant, the shear force should increase proportionally with the radius of ice. Therefore, it is essential to study the difference of the maximum peeling stress when the applied force also rises proportionally to balance the increasing adhesion shear force. Here, the constant value of shear strength is 1 MPa[12]. As the red line illustrates, the

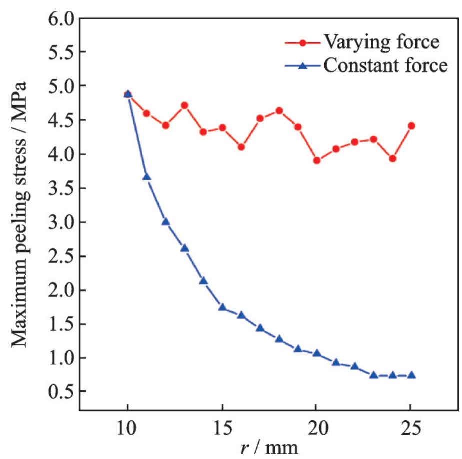

Fig.5 Effect of ice radius on peeling stress

trend of the curve does not show a monotonous change and no obvious law could be concluded. In the current range of options, a radius of 20 mm is the best choice.

2.2 Uniformity of stress

Eq.(1) is used to calculate the shear stress, when the data of shear force is obtained from experiments. However, this equation is based on the assumption that the stress distribution at the interface is entirely even. In reality, the stress concentration is inevitable, so we have to evaluate the uniformity of stress to get a result with less error.

A path is defined along the direction of diameter at the ice-substrate interface, as drawn in Fig.6. The von-mises stress is extracted along this path and the result is depicted in the figure. It can be observed that the stress at the ice edge, especially in the direction close to the loading, is distinctly higher than that of the central zone due to stress concentration.

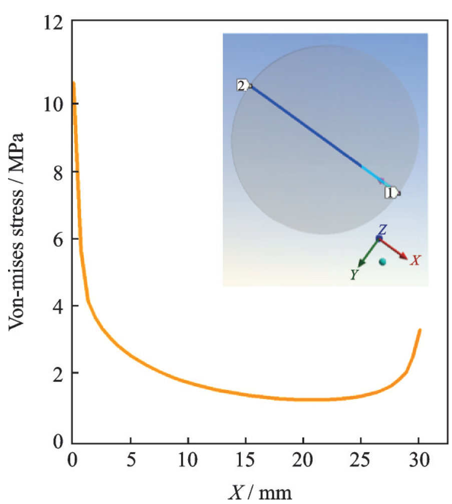

Fig.6 Von-mises stress distribution at interface along diameter direction

The standard deviation of the stresses at all points on the path is used as a criterion for judging the uniformity of the stresses. From Fig.7, it can be observed that the standard deviation descended with the increase in the height of ice H and the loading height h and a decrease in the radius of ice r. This shows that a more homogeneous stress distribution exists at the interface. Here, the loading force also changes with the radius.

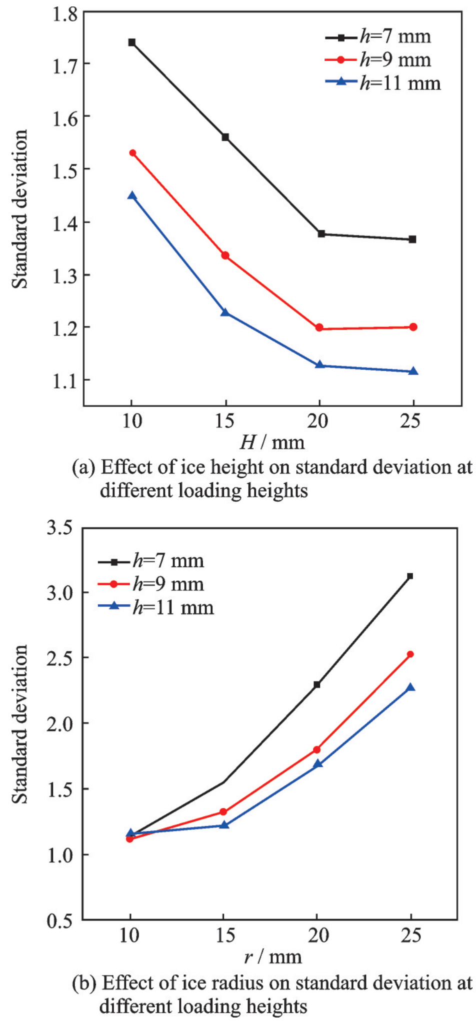

Fig.7 Effect of loading location, ice height and radius on standard deviation

In addition, the effect of the change in the applied force from push to pull is studied on the uniformity of the stress. Fig.8 demonstrates that there is no significant difference between pushing and pulling.

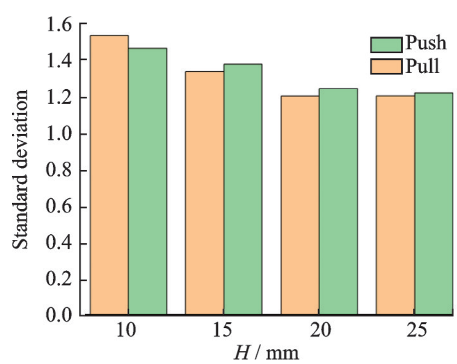

Fig.8 Effect of push and pull on standard deviation

2.3 Analysis of strength

Before the ice is pushed off the substrate, the stress at the interface exceeds the strength limit, which causes cracks and even breakage of the ice. This phenomenon occurs due to the stress concentration and it affects the measurement results seriously. To avoid this problem, the maximum von-mises stress is compared with the allowable stress of ice, which is determined to be 20 MPa from Ref.[16].

It can be seen from Fig.9 that r is high and H is low (about 25 mm and 10 mm, respectively), when the maximum von-mises stress surpasses the allowable stress. This is applicable to any case, no matter what h is. Therefore, it is advisable to avoid the simultaneous existence of ice with a large radius and low height.

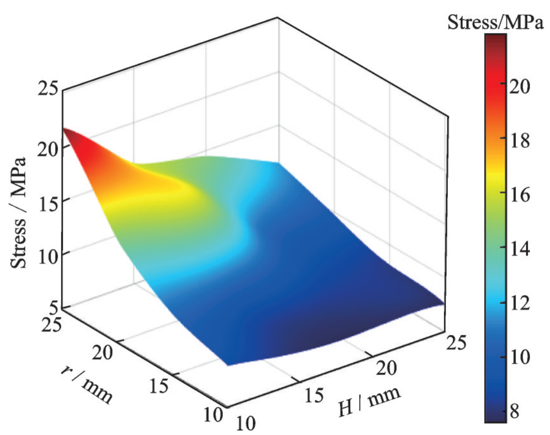

Fig.9 Effect of ice height and radius on the maximum von-mises stress

3 Experiments

The test platform shown in Fig.1 is built in a cold chamber. The radius and height of ice and the loading location are chosen according to the comprehensive results, taking all three factors in Section 3 into consideration. The specific values are listed in Table 1.

Table 1 Selected parameters for experimental validation

Radius of ice/mm	Height of ice/mm	Loading height/mm
20	25	9

The adhesive shear strength at different substrate temperatures is investigated by experiments. In this investigation, the ice is frozen by pouring water into the mold instead of the accumulation of the supercooled water droplets. The reason is that frozen ice is more regular and better for exploring the effect of different factors on adhesion. Although there are differences in physical properties of frozen ice and impact ice themselves, the experimental results for frozen ice are meaningful because their adhesion behavior is similar under the same substrate and environment. Fig.10 demonstrates the change in the force sensor during the experiment. Before the contact of the probe and the mold, the reading is zero. When the probe starts to push the mold and ice, a rise is noted. At the moment of the detachment of ice, the indication decreases to near zero at once. The maximum value in this process is the adhesion force, which is substituted in Eq.(1) to calculate the shear strength. After the ice is shed off, it is observed that the bottom of the ice is totally flat without any crack.

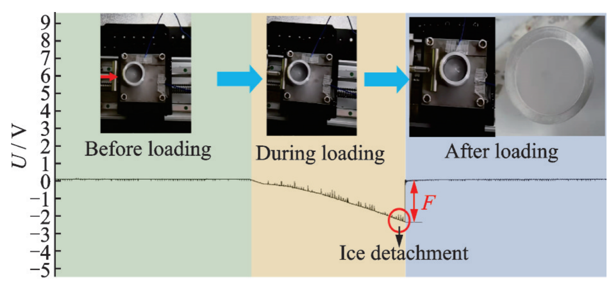

Fig.10 Indication of force transducer during experiments

The results of shear strength are shown in Fig.11. With a decrease in the substrate temperature, the shear strength correspondingly declines. There is enough time for the water to penetrate the micro-structures of the surface, when the substrate temperature is high. However, the water immediately freezes, as the aluminum plate becomes colder. When the substrate temperature gradually decreases, the interface transites from Wenzel-state to Cassie-state[17]. The former means that the surfaces are filled with water or ice and the shear strength increases at the same time. In contrast, the adhesion strength is expected to decrease due to the reduced contact area between the ice and the substrate under the Cassie-state.

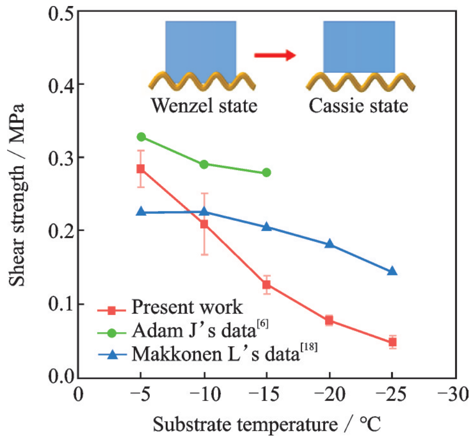

Fig.11 Effect of substrate temperature on shear strength and comparison with literatures

In this test, the relative standard deviation of the measured ice shear strength is 2% in average, suggesting that the method and experimental equipment provide results with good repeatability and precision for the ice adhesion measurements. Comparing the data obtained in this study with Refs. [6, 18], it can be found that the trend is similar, but the absolute value consists a certain error. The existence of the error is mainly because the icing conditions and substrates are not exactly the same. It is impossible to make a perfect comparison, while matching all the important variables across the earlier studies, since many of critical variables are not reported. Nonetheless, the similar tendency and repeatability prove that the experiment results in this investigation are credible.

4 Conclusions

The present study envisages the evaluation of the stress at the ice-substrate interface to guide the design of experimental set-ups and improve the measurement accuracy of shear strength using the finite element analysis method followed by an experimental validation of the simulated results. The conclusions of the study are as follows:

(1) In order to reduce the peeling stress at the ice-substrate interface, it is necessary to decrease the loading height and increase the height of ice. The ice radius of about 20 mm is found to be most appropriate from the FEA setup.

(2) Increased loading height and ice height and smaller ice radius enhance the stress uniformity at the interface.

(3) Simultaneous existence of the ice with an increased radius and low height of more than 25 mm and less than 10 mm, respectively, results in cracking and even breakage of the ice.

(4) Ice with a height of 25 mm and a radius of 20 mm, and a loading height of 9 mm is adopted in experimental setup to achieve an accurate measurement. Experimental results show that the adhesion shear strength decreases with a reduction in the temperature of the aluminum substrate. A good agreement of the results with the previous reports and high repeatability demonstrate that the FEA of stress at the ice-substrate and the experimental setup in this investigation can contribute in the correct measurement of the shear strength.

References

[1] MORITA K, KIMURA S, SAKAUE H. Hybrid system combining ice-phobic coating and electrothermal heating for wing ice protection[J]. Aerospace, 2020, 7(8): 102.

[2] GAO T X, LUO Z B, Zhou Y, et al. A novel de-icing strategy combining electric-heating with plasma synthetic jet actuator[J]. Proceedings of the Institution of Mechanical Engineers. Part G: Journal of Aerospace Engineering, 2021, 235(4): 513-522.

[3] LAFORTE C, BEISSWENGER A. Icephobic material centrifuge adhesion test[C]//Proceedings of the 11th International Workshop on Atmospheric Icing of Structures (IWAIS). Montreal, Canada: [s.n.], 2005: 12-16.

[4] ITAGAKI K. Mechanical ice release processes: I. Self-shedding from high-speed rotors[M]. Hanover, NH: Cold Regions Research and Engineering Laboratory, 1983.

[5] BROUWERS E W, PETERSON A A, PALACIOS J, et al. Ice adhesion strength measurements for rotor blade leading edge materials[C]//Proceedings of the 67th American Helicopter Society International Annual Forum 2011. Virginia Beach, VA, United States: Elsevier, 2011: 3011-3023.

[6] MEULER A J, SMITH J D, VARANASI K K, et al. Relationships between water wettability and ice adhesion[J]. ACS Applied Materials & Interfaces, 2010, 2(11): 3100-3110.

[7] GE L, DING J, WANG H, et al. Anti-icing property of superhydrophobic octadecyltrichlorosilane film and its ice adhesion strength[J]. Journal of Nanomaterials, 2013. DOI: 10.1155/2013/278936.

[8] SCAVUZZO R J, CHU M L. Structural properties of impact ices accreted on aircraft structures[M]. [S.l.]: National Aeronautics and Space Administration, 1987.
[9] DRUEZ J, NGUYEN D, LAVOIE Y. Mechanical properties of atmospheric ice[J]. Cold Regions Science and Technology, 1986, 13(1): 67-74.
[10] DRUEZ J, PHAN C L, LAFORTE J L, et al. The adhesion of glaze and rime on aluminum electrical conductors[J]. Transactions of the Canadian Society for Mechanical Engineering, 1978, 5(4): 215-220.
[11] PERVIER M L A, GURRUTXAGA LERMA B, PILES MONCHOLI E, et al. A new test apparatus to measure the adhesive shear strength of impact ice on titanium 6Al-4V alloy[J]. Engineering Fracture Mechanics, 2019, 214: 212-222.
[12] WORK A, LIAN Y. A critical review of the measurement of ice adhesion to solid substrates[J]. Progress in Aerospace Sciences, 2018, 98: 1-26.
[13] KOIVULUOTO H, STENROOS C, RUOHOMAA R, et al. Research on icing behavior and ice adhesion testing of icephobic surfaces[C]//Proceedings of the 16th International Workshop on Atmospheric Icing of Structures(IWAIS).Uppsala, Sweden:[s.n.], 2015.
[14] MAKKONEN L. Ice adhesion—Theory, measurements and countermeasures[J]. Journal of Adhesion Science and Technology, 2012, 26(4/5): 413-445.
[15] SCHULZ M, SINAPIUS M. Evaluation of different ice adhesion tests for mechanical deicing systems: 2015-01-2135[C]//Proceedings of SAE 2015 International Conference on Icing of Aircraft, Engines and Structures.[S.l.]:[s.n.], 2015.
[16] PETROVIC J. Review mechanical properties of ice and snow[J]. Journal of Materials Science, 2003, 38(1): 1-6.
[17] KOISHI T, YASUOKA K, FUJIKAWA S, et al. Coexistence and transition between Cassie and Wenzel state on pillared hydrophobic surface[J]. Proceedings of the National Academy of Sciences, 2009, 106(21): 8435-8440.
[18] MAKKONEN L. Adhesion of pure ice and saline ice at temperatures −1 to −60°[C]//Proceedings of the 12th Annual Meeting of the Adhesion Society. [S.l.]: [s.n.], 1989.

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Author contributions Mr. **WANG Yusong** designed the study, complied the models, conducted the analysis and experiments, interpreted the results and wrote the manuscript. Mr. **HAN Liang** and Mr. **LIU Zhenguo** contributed to data and conducted experiments. Prof. **ZHU Chunling** and Dr. **ZHU Chengxiang** contributed to the discussion and background of the study and supervised the work. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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考虑界面应力的高精度冰粘附力测量平台设计

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摘要：机翼和发动机上的积冰会对飞行安全带来严重威胁。准确测量冰-基底界面的粘附强度对防/除冰系统的设计起着至关重要的作用。本文研究通过有限元分析(Finite element analysis，FEA)对冰-基底界面的应力进行评估，以指导实验装置的设计，从而提高剪切粘附强度的测量精度。通过考虑剥离应力、最大冯-诺斯应力和应力均匀性等因素，对冰的高度和半径以及加载高度进行了评估。根据仿真结果，为实验验证选择了适当的参数。仿真结果显示，通过降低加载高度和增加冰的高度，剥离应力有所下降。较高的冰层、增加加载高度和较小的冰层半径有利于提高应力均匀性。同时，为了避免裂纹产生或者冰层破碎，冰样必须满足小半径和大高度的条件。最终实验中采用的参数为冰高25 mm，半径20 mm，加载高度9 mm。有限元分析和实验验证的结果均表明，本研究能显著提高剪切粘附强度的测量精度。

关键词：飞机结冰；剪切粘附强度；有限元分析；实验装置；界面应力