Loss of de-icing boot and fuselage damage, Aurigny Air Services, Fairey Britten Norman BN2A Mk III-2 'Trislander', G-BEVT

Micro-summary: **A de-icing boot separated from this Fairey Britten Norman BN2A Mk III-2 'Trislander, damaging a window and injuring passengers.**

Event Date: **2004-07-23 at 0637 UTC**

Investigative Body: **Aircraft Accident Investigation Board (AAIB), United Kingdom**

Investigative Body's Web Site: **http://www.aaib.dft.gov/uk/**

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Contents

APPENDIX

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	Air Accidents Investigation Branch
agl	above ground level
BCAR	British Civil Airworthiness Requirements
CAA	Civil Aviation Authority
ft	feet
hrs	hours
JAR	Joint Airworthiness Requirement
kg	Kilogram(s)
KIAS	knots indicated airspeed
km	Kilometre(s)
kt	knot(s)
MRO	Maintenance and Repair Organisation
rpm	revolutions per minute
UK	United Kingdom
UTC	Universal Time Co-ordinated
ºC	Degrees Celsius

Air Accidents Investigation Branch

Aircraft Accident Report No: 1/2006 (EW/C2004/07/06)

Registered Owner and Operator:	Aurigny Air Services
Aircraft Type:	Fairey Britten Norman BN2A Mk III-2 'Trislander'
Nationality:	British
Registration:	G-BEVT
Place of Accident:	Guernsey Airport
Date and Time:	23 July 2004 at 0637 hrs
	(All times in this report are UTC)

Synopsis

Guernsey Air Traffic Control notified the accident to the Air Accidents Investigation Branch (AAIB) at 0715 hrs on 23 July 2004 and the investigation began that same day. The following Inspectors participated in the investigation:

Mr J J Barnett (Investigator in Charge)
Mr K Conradi (Operations)
Mr A P Simmons (Engineering)

Shortly after takeoff from Guernsey Airport, a loud crack or bang was heard in the aircraft's cabin. The aircraft commander was told by a colleague in the cabin that one or more passengers had been injured and that a cabin window was broken. He decided to return to Guernsey Airport having been airborne for approximately four minutes. After the passengers disembarked the pilot noticed that a de-icer boot had separated from the left hand propeller and was now on the seat inside the cabin, adjacent to the broken window.

The investigation identified the following causal factors:

(i) The accident was caused by the separation of a de-icer boot from the left propeller during takeoff.

(ii) The de-icer boot separated due to peel stresses generated by forces on the propeller. The peel stresses arose because of physical or contamination damage to the adhesive bond which occurred because the required filler material was not used at the root of the de-icer boot.

Two Safety Recommendations were made during the course of the investigation.

1 Factual Information

1.1 History of the flight

The aircraft was operated by a single pilot who reported for duty at 0600 hrs. During his external inspection of the aircraft he ran his hand across the propeller blades but felt nothing abnormal. After a normal engine start, he taxied the aircraft to a remote area and completed the engine run-up checks which included running the propellers at 2,100 rpm for a short period. The aircraft was then taxied to the Terminal and the engines shut down whilst the 11 passengers embarked.

After another normal start, the aircraft taxied to the holding point for Runway 27 and was cleared to take off at 0637 hrs. Takeoff was achieved using 10º flap and full power giving a propeller speed of approximately 2,650 rpm. Whilst climbing through 500 ft agl at 95 KIAS a loud crack was heard from an indeterminate source. There were no unusual indications from the airframe, engines or instrumentation but there were signs of agitation from the passengers. A positioning pilot from the same operator seated immediately behind the commander indicated that injuries had been sustained to several passengers and suggested returning to Guernsey Airport.

The commander transmitted to Guernsey Tower 'WE'VE GOT A PROBLEM WE'D LIKE TO DO IMMEDIATE LEFT TURN TO LAND AGAIN' and positioned on the downwind leg for Runway 27. The positioning pilot told him that a cabin window had broken and the commander requested from ATC that the emergency services meet the aircraft on landing. A normal landing was made at 0641 hrs and the aircraft taxied clear of the runway before the engines were shut down. The Airfield Fire and Rescue Service met the aircraft and assisted the passengers. Two minutes later an ambulance arrived and two passengers were taken to hospital.

1.2 Injuries to persons

Injuries	*Crew*	*Passengers*	*Others*
Fatal	-	-	-
Serious	-	1	-
Minor/None	1	10	

1.3 Damage to aircraft

The damage to the aircraft was confined to the detached de-icer boot from the left-hand propeller and a broken window on the left-hand side of the cabin immediately adjacent to the propeller. Two pieces, making up most of the detached de-icer boot, were subsequently found inside the passenger cabin.

1.4 Other damage

There was no other damage.

1.5 Personnel Information

1.5.1	Commander:	Male, aged 34 years	
	Licence:	Commercial Pilot's Licence	
	Instrument Rating:	Valid to 31 March 2005	
	Licence Proficiency Check:	Valid to 31 March 2005	
	Operators Line Check:	Valid to 31 August 2004	
	Medical certificate:	Class 1, valid to 31 May 2005 with no limitations	
	Flying Experience:	Total all types:	3,228 hours
		Total on type:	642 hours
		Total last 28 days:	39 hours
		Total last 24 hours:	1 hour
	Previous rest period:	Off duty:	2000 hrs on 22 June
		On duty:	0700 hrs on 23 July

1.6 Aircraft information

The aircraft was a Fairey Britten Norman BN2A Mk III-2 'Trislander', built in 1977. It carried the manufacturer's serial number 1057 and was operated by a company registered in the Channel Islands. At the time of the accident, it had accumulated 19,017 hours and 60,507 landings since new. The aircraft was fitted with three Lycoming 0-500-E4C5 piston engines. When the new aircraft was delivered the engines were equipped with two-bladed constant-speed Hartzell propellers, designated HC-C2YK-2CUF. In 2002, the UK CAA issued Additional Airworthiness Note No 24016, which allowed Hartzell

HC-C3YR-2CUF three-bladed propellers to be fitted to the wing-mounted engines. The reason for this modification was to reduce noise levels. For technical reasons, such a propeller could not be fitted to the centre engine, so this was not included in the modification.

A further modification was introduced in 2003, when the UK CAA issued a further Additional Airworthiness Note No 24665, which installed the de-icing system, including the de-icer boots, on the three-bladed propellers.

The following engine and propeller hours and cycles were as recorded on 14 July 2004 immediately prior to a combined Check 1 and Check 2 maintenance input. Subsequently the aircraft accumulated a further 72 landings and 11.55 hours before the accident flight. Both the daily inspections and the Check 1 and Check 2 inspections include checks for security of the propeller de-icer boots.

Engines

Position	*Left*	*Centre*	*Right*
Serial No	L24377-40A	L18739-40A	RL23501-40A
Hrs TSO[1]	2,708.19	5,638.43	2,854.44
Cycles	60,435	60,435	60,435

Propellers

Position	*Left*	*Centre*	*Right*
Type	HC-C3YR-2CUF	HC-C2YK-2CUF	HC-C3YR-2CUF
Serial No	CK3678A	AU9014B	CK3634A
Hrs TSO	460.32	1,753.41	1,557.27

The aircraft was first registered on 5 August 1983. On 16 November 2003, its Certificate of Airworthiness, Certificate No 004093/008 was renewed by the UK CAA, and this was valid until 15 November 2006. A Certificate of Maintenance Review was issued by the operator's JAR 145 approved Maintenance and Repair Organisation (MRO), valid until 8 September 2004.

[1] Time Since Overhaul

1.7 Meteorological information

A weak cold front moved eastwards through the Channel Islands several hours prior to this accident with fine weather moving in behind it. At the time of the accident the surface wind was reported as 350°/7 kt, the visibility was greater than 10 km and there was no cloud below 5,000 ft. The air temperature was 15ºC and the dew point was 13ºC.

1.8 Aids to Navigation

The performance of navigational aids was not relevant to this accident.

1.9 Communications

There were no communication issues relevant to this accident.

1.10 Aerodrome information

Aerodrome information was not relevant to this accident.

1.11 Flight recorders

Flight recorders were not fitted or required to be fitted to this class of aircraft.

1.12 Engineering investigation

1.12.1 Certification

The aircraft was type certificated in accordance with British Civil Airworthiness Requirements (BCAR) Section 'K', which is applicable to smaller public transport aircraft with a maximum weight of less than 5,700 kg. Paragraph K.4-8 2.2.2.(d) states:

> *'The primary flight controls shall be so located with respect to the propellers that no portion of the flight crew or the controls, excluding cables and control rods, lies in the region between the plane of rotation of any inboard propeller and the surfaces generated by a line passing through the centre of the propeller hub and making an angle of 5 degrees forward and aft of the plane of rotation of the propeller.'*

Historically, ice shed from propeller blades had resulted in cosmetic damage to Trislander and the similar Islander types. A modification, NB-M-1237, had been issued to introduce an ice protection panel for the right hand door but the incidence of ice impact was much lower on the left side for which no similar modification existed. The ice protection panel was not intended to withstand impact from aircraft parts shed from the propeller.

1.12.2 De-icing requirement

The operator's fleet of Trislander aircraft were mainly, but not exclusively, equipped with airframe and propeller de-icing systems. When the three-bladed propellers were fitted to G-BEVT, they were not de-iced and in order to fit de-icing equipment, a further approval was required. The propellers in question were identical to those certificated by the FAA with BF Goodrich de-icing equipment for use on the Piper Navajo Chieftain. On that basis, in 2003 the UK CAA issued a further Additional Airworthiness Note, No 24665, which approved installation of the BF Goodrich de-icing system, including the de-icer boots, on the Trislander's three-bladed propellers in accordance with BF Goodrich technical report No 59-728.

Installation of the FAA approved de-icing equipment was based on the use of the appropriate procedures contained in Hartzell Aluminium Blade Manual 133C. This required the use of BF Goodrich de-icer boots, materials and procedures. An approved alternative was the use of De-Icers (MHG) Limited de-icer boots, materials and procedures.

1.12.3 Materials and processes used by the propeller overhaul agency

The propeller overhaul agency was familiar with the Hartzell propeller and its de-icing system, and with the use of the alternative De-Icers (MHG) Limited. boots, materials and procedures. The agency entered into a commercial contract with the operator, in which they offered the alternative boots. The work was certified on the appropriate JAA Form One as being completed in accordance with the appropriate Hartzell manuals, including Manual 133C.

Manual 133C requires the use of an approved filler material around the root end of the de-icer boot (this is required on all de-icer boots with a long lead strap, such as on this installation). The purpose of this filler is to help prevent the de-icer boot from peeling. No such filler had been applied.

1.12.4 Technical log entries and maintenance on subject propeller

The propeller logbooks and other technical records showed that the propeller had been received from the overhaul agency on 10 July 2003 with a recorded usage of 2,118 hours. It was fitted to G-BEVT on 9 September 2003 with zero time since overhaul. On 4 October it received a Check 1 inspection, and on

3 November it received a Check 2 inspection. On 26 November it received a further Check 1 inspection. On 5 December 2003, with approximately 243 hours since overhaul, it was removed for rectification of a cracked harness guard on one of the blades. This work was certified complete on the MRO shop order on 18 December 2003; however, the propeller logbook shows that the propeller was not then used until it was fitted again to G-BEVT on 11 May 2004. On 1 June 2004 another Check 2 was completed and on 24 June another Check 1 was completed. The last check was a Check 2 carried out on 14 July 2004, nine days before the accident.

The work pack which covered the replacement of the defective harness guard showed that at the same time, the restrainer strap (a plastic cable tie) at the root of the boot was renewed. The reason for this is not recorded, and the work pack gives only the propeller serial number. Blade serial numbers are not visible with the propeller assembled; however, blade numbers are stamped on the counterweights of each blade and these numbers could have been recorded within the work pack. It is possible that some damage had occurred to the adhesive bond of the de-icer boot at this time but because the blade number was not recorded, it is not possible to confirm that this was the blade which subsequently shed the de-icer boot.

1.12.5 Laboratory analysis of failure

The AAIB commissioned QinetiQ, a UK research agency (formerly the Defence Research Agency) to carry out a series of tests on the failed parts and the adhesive bond. Relevant extracts from their technical report are attached at Appendix ‘A’. Briefly, the report concluded that the bond had evidence of both adhesive (cement to boot or blade) and cohesive (separation of the cement itself) failures. There was no evidence of incorrect or inadequate surface preparation, or of incorrectly prepared materials. However, the specified filler at the root of the boot had not been applied. The report suggests that there was probably a small region of the lead strap, underneath the restrainer strap and extending a few millimetres outboard, which did not have adhesive applied. This could, the report stated, lead to the generation of peel stresses which would cause further damage to the adhesive bond.

Although there was no evidence of any difference in the chemical or physical properties of the adhesive on the three blades, the laboratory determined that the adhesive of the failed boot was a darker colour than that of the other two boots, and that this colouration was caused by exposure to the atmosphere. In subsequent discussions with the laboratory, the possibility that the failed boot may have had significant disbonding damage when the harness guard was replaced was discussed, as was the possibility of deterioration of the bond due to contamination ingress. However, the adhesive discolouration is not progressive with time, and it was not possible to determine relative time periods of exposure because, although the adhesive was generally darker, it was not noticeably different in the region of the lead strap.

The report shows that a brittle fracture of the de-icer lead strap occurred at the root near the restrainer strap. Moreover, the fracture in the middle of the boot was also brittle. Both of these fractures indicated a high strain rate, typical of impact. A third fracture near the electrical termination was ductile indicating a lower rate of strain onset. Also, a substantial section of the lead strap was missing. These findings are consistent with the sudden release of the boot and its impact with the window. They imply that the lead strap failed first and the boot was then pulled through the restrainer strap and released. Evidence of rubber on the restrainer strap itself supported this explanation.

1.12.6 Propeller manufacturer's advice

The propeller manufacturer advised that the small unbonded area underneath and adjacent to the tie-wrap would not be large enough to generate damaging peel stresses, unless the bond failed further. However such a void would create a natural chamber for moisture and other contaminants to enter and be trapped. Without the environmentally protective properties of the filler, these contaminants could progressively degrade the bond over an increasing area.

The manufacturer proposed a rectification process for affected propellers. Any propellers which had been in service without the required filler were to be inspected for disbonding. If no such disbonding existed, the filler material was to be applied and the propeller could then continue in service. In the event that disbonding was detected, the affected de-icer boot was to be removed and a new one fitted. At the time of writing, it is not known how many blades will be found to have defective adhesive bonds.

1.13 Medical and pathological information

Two passengers sustained injuries caused by flying debris within the cabin and were treated in hospital. One was released shortly afterwards with minor injuries and one was detained with a serious hand injury.

1.14 Fire

There was no fire.

1.15 Tests and Research

1.15.1 Availability of materials

The AAIB attempted to determine the reasons why the filler material required by Hartzell Manual 133C had not been used on the de-icer boot installation. UK suppliers were contacted and the specified materials, or alternatives, were available. However, it was noted that the filler was classified as hazardous material for freight purposes and it appears that there was a period when the filler material and suitable alternatives were unavailable. These materials became available again in mid 2003 but because they have a short shelf-life, difficulties may have been created in the meantime for maintenance and repair organisations outside the USA.

1.15.2 CAA actions

The UK CAA identified approximately 100 propellers which had been overhauled without using the required filler. The propellers had all been overhauled by the same organisation within a six year period, which is the calendar overhaul period for these propellers. The UK CAA has also been working with the propeller manufacturer to establish an inspection and rectification regime for the affected propellers.

1.16 Organisational and management information

The propeller overhaul company's business was the maintenance of aircraft and the overhaul of propellers. The UK CAA entered into discussions with the organisation to establish the extent of the problem and to oversee the inspection and rectification programme. Some months after this accident, the company sold its propeller business to another organisation but the CAA has continued working with the new organisation.

1.17 Additional information

1.17.1 Previous incidents

During this investigation, another propeller fitted to the operator's fleet exhibited evidence of de-icer boot disbonding. It was withdrawn from service. It had been overhauled by the same agency in January 2003 and did not have the required filler material at the root of the de-icer boot.

On 9 March 1997 another of the operator's Trislander fleet, G-RBSI, shed a de-icer boot. The propeller had been overhauled by a different agency. There was no secondary damage or injury to persons but some vibration was felt. On 14 March 1997 the same aircraft shed another de-icer boot, again without damage or injury. The propeller, which had been overhauled by a different agency, had completed 50 hours since overhaul when the first boot was shed and 70 hours when the second boot detached.

On 15 March 1997, G-XTOR, another of the operator's Trislander fleet shed a de-icer boot from the left propeller during takeoff. This propeller had also been overhauled by a different agency. The boot struck the fuselage and dislodged a window which struck a passenger, albeit without injury.

The CAA investigation into these three events found that the de-icer boots had all been bonded using the same defective batch of adhesive. The batch of adhesive had already been withdrawn at the time of this last incident, and the operators of other affected aircraft were alerted.

A further case of which AAIB became aware occurred to an Islander in September 2001. A de-icer boot was shed from a left propeller during flight and it struck the top of the fuselage. The operator raised a Mandatory Occurrence Report but no further action or information concerning the cause has been traced.

1.17.2 Subsequent incident

On 25 April 2005 G-BEVT suffered a further incident when, during takeoff from Alderney, a de-icer boot separated from the right-hand propeller. The boot was subsequently found on the runway, and there was no secondary damage or personal injury as a result of the incident. The propeller had been overhauled and the de-icer boots fitted after the accident which is the subject of this report. It had accumulated a total of 175 flying hours since overhaul. Revised overhaul procedures were already in place and applied to this propeller during the overhaul process. They included use of the correct filler material and a change of adhesive cement to an alternative recommended by the propeller manufacturer. Initial investigation of this event by the AAIB indicated that the cause of separation was not the same. This subsequent incident was due to inadequate adhesion between the de-icer boot and the adhesive cement. Accordingly, the AAIB will investigate this later event separately.

1.17.3 Frequency of de-icer boot separation

Industry wide, the frequency of de-icer boots becoming completely detached is low. Partial disbonding is sometimes detected during inspections and there are various reasons why the adhesive bond may become damaged or otherwise fail.

A search of the UK CAA database for the previous 15 years found only six cases of complete separation, four of which involved Trislanders or Islanders. The Islander and Trislander fleets have accumulated approximately 10 million flying hours, and during that period only a small number of cases of de-icer boots being released have been recorded. However, it has not been possible to gather conclusive data concerning this type of event. The CAA Mandatory Occurrence Reporting scheme began in 1976, so events before that date were not recorded by the CAA. Events occurring outside the UK are probably not included, and may not have been subject to any form of reporting at all. When events such as de-icer boot separations occur without causing injury or damage, it is still commonplace around the world for such events to be unreported.

For the same reason, records held by the airframe manufacturer regarding de-icer boot incidents are very limited. Also the hours flown by the fleet, with and without de-icer boots, are not known. Therefore it is not possible to draw conclusions about the acceptability of the rate of occurrence of such events, albeit the frequency over certain short periods of time may seem higher than desirable.

Release of ice from the propeller has been a sufficiently frequent occurrence to warrant modification action, however this was mainly for cosmetic purposes, the consequences of ice impact being minor and predominantly on the right hand side of the cabin.

1.18 New investigation techniques

None.

2 Analysis

2.1 Flight crew action

When a de-icer boot separated from the left-hand propeller and penetrated the adjacent cabin window, injuring two passengers, the commander was confronted by an incident that was awkward to diagnose at a critical stage of flight. He was fortunate in having the assistance of a positioning company pilot sat behind him but nevertheless, he took the prompt and correct decision to return to Guernsey Airport. His aircraft handling, decision making and communication skills allowed the injured passengers to receive medical attention with the minimum of delay.

2.2 Separation of the de-icer boot

The laboratory report (Appendix 'A') attributed separation of the de-icer boot to peel stresses generated outboard of the restrainer strap in an area where the adhesive bond was damaged. The propeller manufacturer considered that the initial, very small unbonded area was insufficient to generate damaging peel stresses, but that the area had grown due to ingress of contaminants because the required filler material had not been applied. Whatever the initial reason for the disbond, once the disbonded area became large enough to generate a peel force equal to the peel strength of the adhesive, the disbonded area would have started to grow very rapidly. Most adhesives have poor strength in peel; therefore the installation was designed such that the de-icer boot would be relieved of peel stresses. This was partly achieved by the installation of the restrainer strap at the root of the de-icer boot. It is likely that the location of the initiation close to the hub and the outboard direction of propagation of the damage were the reasons why this boot completely separated from its blade.

The way in which this damage progressed was, therefore, not typical of the more usual disbonding of de-icer boots, where damage usually starts at an edge some way outboard on the blade. In these cases, the forces acting on the propeller do not tend to impose additional stresses on the lead strap of the boot itself. In such cases the damage progresses relatively slowly and can be detected during daily inspections.

There was no evidence to confirm or refute the suggestion that ingress of moisture or other contaminants was the mechanism which caused the bond to deteriorate. While it is entirely plausible that this was the case, work was carried out on this propeller by the operator which involved fitting a new harness guard and restrainer strap to one of the blades. When the restrainer strap was removed, and whilst it was absent from the blade, it would have been very easy to damage the adhesive bond if any movement of the de-icer boot lead strap had taken place. The risk of such damage would have been reduced if the de-icer boot had been installed with the required fillet of filler material because this would have relieved any peel stress on the adhesive. Unfortunately, it was not recorded which of the three blades was reworked so it is not possible to say whether this maintenance by the operator could have been a causal factor. Apart from routine inspections no other maintenance was carried out by the operator.

From the above considerations it is likely that because of the rapidity with which the damage progressed, the disbond was not detected either on the maintenance checks or during the daily inspections.

The propeller overhaul agency had overhauled approximately 100 propellers without using the required filler. This investigation has not determined the reason why filler was not applied, other than that it was probably related to a real or perceived supply difficulty. The importance of the filler may not have been realised fully, since some de-icer boots with short lead straps are installed without the filler. Whatever the reasons, the subsequent CAA involvement has ensured that the non-compliant practice has been corrected and the affected propellers identified.

2.3 Human Factors

Periodically the AAIB has cause to investigate cases of non-compliance with maintenance procedures, and has observed that there is sometimes a lack of awareness regarding the requirement for an approved organisation or a licensed engineer to comply with the prescribed maintenance practices. These practices are as much a part of the design approval as is the use of approved parts, and to work around them is to usurp the role of the Design Authority. Since it is likely that only the Design Authority has access to all the relevant data, any non-compliance is inherently risky and could be unsafe; it also invalidates the Form One and/or the Certificate of Release to Service.

While recklessness or carelessness cannot be condoned, the AAIB has also observed that often these unapproved practices are carried out by hard working, competent and well-intended individuals who are attempting to resolve a problem in the best interests of the organisation and the customer. Furthermore, there is an increasing realisation that many so-called human errors in aircraft maintenance are in fact deliberate violations carried out to circumvent problems. Put differently, whilst it is the individual who carries out the unsafe action, in most cases it is the regulatory, financial, commercial and managerial system within which the individual works that provokes the non-compliant action.

The AAIB considers that the solution to this problem lies primarily in awareness and education, not in blame. The UK CAA has put considerable effort into the area of human error in maintenance, as have some other regulators around the world, and the culture of the industry in some regions is changing as a result. However, these efforts need to be continued and enhanced within a pan-European context, and this will require both effort and funding. Therefore the AAIB made the following Safety Recommendation:

> The UK Civil Aviation Authority and the European Aviation Safety Agency should work closely together to develop further the valuable progress already made in human factors in aircraft maintenance, focusing on the underlying reasons for both errors and violations, with a view to reducing the potential for system-induced errors and violations, and therefore the risk of maintenance related accidents. (Safety Recommendation 2005-078)

2.4 Penetration of the window

The aircraft was certificated to BCAR Section 'K', which was the appropriate airworthiness code for this size and weight of aircraft. It therefore did not need to meet the more demanding requirements for occupant protection which are mandatory for large turbine powered aircraft, such as the then current BCAR Section 'D' requirements or the more modern JAR /FAR Part 25 requirements. This is because it is not practical in smaller, simpler aircraft to provide the same level of passenger protection as is found in larger aircraft, nor is it necessary to the same extent. As such, provision of protection for the passengers from debris such as engine or propeller parts was not a requirement.

The lack of reports of de-icer boot separation is due either to this being an infrequent event, or possibly due to it having a low probability of causing damage or injury, which would make proper reporting less likely. In either case there is no evidence that the overall frequency and severity of this type of event is not acceptable.

2.5 Corrective actions

The UK CAA has acted to contain the problem and to address the issues of non-compliance within the relevant organisation. The affected propellers have been identified and subjected to an inspection and rectification programme. Therefore the necessary actions to reduce the risk of recurrence, and to meet the intended level of safety, have been taken.

2.6 Inspection of de-icer boots

Disbonding of de-icer boots normally begins at the edges of the boot and can be detected by the pilot during the daily inspection, or by the more detailed inspection carried out periodically by the MRO. If, however, the disbond is not apparent at the edge, it is very difficult to detect. During this investigation the laboratory used various advanced ultrasonic techniques to try to determine the condition of the adhesive bonds, but these were unsatisfactory for a variety of reasons. One technique which the laboratory suggested was the use of a thermal imaging camera once electrical power had been applied. This would identify hot spots in poorly bonded regions. The laboratory report recommended that this method should be investigated further (see Appendix 'A'). Therefore the AAIB made the following Safety Recommendation:

> Hartzell Propeller Incorporated should investigate the feasibility and potential benefits of using thermal imaging techniques to inspect de-icer boots for disbonded areas. (Safety Recommendation 2005-079)

3 Conclusions

(a) Findings

1. During takeoff, while the engines were at high power, a de-icer boot from a blade of the left hand propeller separated and struck an adjacent cabin window, penetrating the window and injuring two passengers.

2. The left hand propeller was fitted with a BF Goodrich de-icing system including the de-icer boots on the propellers, in accordance with BF Goodrich technical report No 59-728.

3. The aircraft was type certificated in accordance with British Civil Airworthiness Requirements (BCAR) Section 'K'. This airworthiness code contained no requirement to protect passengers from piston engine or propeller parts.

4. Installation of the de-icer boots was certified on the appropriate JAA Form One as having being completed in accordance with the appropriate Hartzell Manual 133C. However, the filler material required by that Manual had not been applied.

5. Work was carried out on the propeller to replace a defective harness guard and restrainer strap. It is possible that some damage had occurred to the adhesive bond of the de-icer boot at this time but because the blade number was not recorded, it was not possible to confirm that this was the blade which subsequently shed the de-icer boot.

6. The laboratory report concluded that there was probably a small region of the lead strap of the de-icer boot, outboard of the restrainer strap, which was unbonded.

7. The small unbonded area of the lead strap created a natural chamber for moisture and other contaminants to enter and be trapped, further degrading the adhesive bond

8. Growth of the disbonded area caused increasing peel stresses which led to final failure of the remainder of the adhesive bond, and separation of the de-icer boot.

9 There was a period when the filler material and suitable alternatives were commercially unavailable in the UK. These materials became available again in mid 2003. However the short shelf life of the materials may have created difficulties in the meantime for maintenance and repair organisations outside the USA.

10 The UK CAA identified approximately 100 propellers which had been overhauled without using the required filler.

11 The manufacturer and the UK CAA have proposed a rectification process for affected propellers.

12 Industry wide, the incidence of de-icer boots becoming completely detached is low, even though disbonding is sometimes detected during inspections.

13 Efforts to control human factors in maintenance need to be continued and enhanced within a pan- European context.

14 There is potential in the use of a thermal imaging to identify hot spots in poorly bonded regions of electrical de-icer boots.

(b) Causal factors

1 The accident was caused by the separation of a de-icer boot from the left propeller during takeoff.

2 The de-icer boot separated due to peel stresses generated by forces on the propeller. The peel stresses arose because of physical or contamination damage to the adhesive bond which occurred because the required filler material was not used at the root of the de-icer boot.

4 Safety Recommendations

The following safety recommendations have been made:

4.1 **Safety Recommendation 2005-078**: The UK Civil Aviation Authority and the European Aviation Safety Agency should work closely together to develop further the valuable progress already made in human factors in aircraft maintenance, focusing on the underlying reasons for both errors and violations, with a view to reducing the potential for system-induced errors and violations, and therefore the risk of maintenance related accidents.

4.2 **Safety Recommendation 2005-079**: Hartzell Propeller Incorporated should investigate the feasibility and potential benefits of using thermal imaging techniques to inspect de-icer boots for disbonded areas.

J J Barnett
Deputy Chief Inspector of Air Accidents
Air Accidents Investigation Branch
Department for Transport
December 2005

Extract from QinetiQ Report E3203

'Examination of G-BEVT Trislander De-icing Boot Failure'

This report was commissioned by the Air Accidents Investigation Branch in support of the investigation into the accident to Trislander G-BEVT, on 23 July 2004 at Guernsey.

1 Introduction

1.1 In July 2004, the de-icing boot on Blade 1 of Trislander G-BEVT debonded minutes after take-off and penetrated an adjacent window resulting in damage to the aircraft and injury to a passenger. Prior to take-off the safety check included a visual examination of the bond between the de-icing boot and the blade. No mention of any delamination between the boot and blade was made.

1.2 The remains of the de-icing boot and the Hartzell propeller were delivered to the Applied Materials group at QinetiQ by AAIB, with a request that the de-icing boot be examined to identify the cause of failure and, in particular, that the adhesive bond and fractures in the rubber boot be subjected to fractographic assessment to establish the sequence of failure. It was also requested that non-destructive evaluation (NDE) be used to examine the remaining de-icing boots on blades 2 and 3 followed by the destructive analysis of these two boots for comparison to the failed boot.

1.3 The de-icing boots were bonded to the blades following refurbishment of the propeller at Jade Air. The information received from AAIB indicated that the boots should have been bonded using Bostik 2402 polychloroprene adhesive and Bositikure D curing agent, with Bostik 9252 primer (for Hamilton Sunstrand) applied to the blades prior to application of adhesive. The work sheet supplied by Jade Air covered the basic process, including surface preparation, application of adhesive and fixing of the boots but made no mention of the application of the primer. However, discussions between QinetiQ and both Jade Air and AAIB confirmed that it is policy to apply the primer.

1.4 The bonding procedure recommended by the boot manufacturer is documented in ATA 30-60-07 "Goodrich De-icing and Speciality Systems Installation/Removal Manual Standard & FASTprop^{TM} Propeller De-Icers" and includes the following stages:

- Blade preparation
- Standard de-icer boot preparation
- Cementing
- Finishing: Sealant/filler and restrainer strap installation

1.5 Figure 1 shows the manufacturer's demonstration of a bonded de-icing boot supplied to QinetiQ by AAIB for comparison with the propeller under examination. The image shows the position of the sealant/filler at the root end of the blade and around the edge of the de-icing boot and shows the tie wrap attached over the bonded section of the strap. It was presumed that this sealant is present either to prevent the edge of the boot lifting during rotation of the propeller and/or to reduce the ingress of moisture, which could lead to degradation of the adhesive bond.

1.6 The demonstrator image appears to show a filled/sealed de-icing boot consistent with the instructions in section 5 of the installation manual. However, the instructions supplied were for Dowty, McCauley and Hamilton Sunstrand propellers. For all Hartzell installations, the instructions refer to a separate manual (Hartzell Manual 61-13-33), details of which were not provided to QinetiQ. However, as described within this report, the propeller examined did not appear to have any filler or sealant applied. Furthermore, the position of the tie wrap appeared to be significantly further from the root of the de-icing boot than shown in the demonstrator.

2 Description and Visual Assessment of Fractures

2.1 Figure 2 shows a photograph of the propeller identifying the three blades. Blade 1 had shed the de-icing boot and Blades 2 and 3 appeared well bonded. On arrival at QinetiQ each part of the propeller and the damaged de-icing boot was photographed and visually examined.

Failed de-icing boot

2.2 The failed de-icing boot was supplied in two parts, the separation into the two halves was believed to be a result of the impact with the window, see Figure 3. On the bonded surface of the boot there was a small patch of adhesive near the centre. The remainder of the surface showed no residual adhesive. At the root end of the boot the resin appeared much darker (marked in Figure 3). The boot strap had fractured at the root of the de-icing boot, this failure of the rubber appeared brittle, see Figure 4. Examination of the surface of Blade 1 showed the adhesive to be well bonded in most regions with the exception of the root end as shown in Figure 5.

2.3 Near the electrical termination, a second fracture in the strap was found (Figure 6). In this case the fracture appeared to be ductile. It was apparent, however, that a large section of the strap was missing between the two fractures when compared to the strap on the de-icing boot of blade 2 (Figure 7).

Bonded De-icing boot from Blade 2

2.4 The de-icing boot from Blade 2 was removed for comparison with the failed boot. The boot strap was cut near the electrical termination and the tie wrap around the strap was removed, the de-icing boot was then peeled-off from the root end. The boot was removed from the blade relatively easily indicating that, even though this boot was well bonded, the peel strength of the adhesive used was low, however, this may have been affected by the thinness of the adhesive layer applied. Figures 8 and 9 show the surface of blade 2 after the removal of the boot and Figure 10 shows an image of the boot surface. Although, the adhesive appeared to have failed in a similar manner to the boot on Blade 1, i.e. mostly adhesive failure, in this case, the failure generally occurred at the adhesive-blade interface rather than the adhesive-rubber interface, as observed on Blade 1.

Adhesive

2.5 There was also a notable colour difference between the adhesive on the surfaces of the de-icing boots from Blade 1 and Blade 2. The adhesive on Blade 2 was a light yellow colour whereas the adhesive on Blade 1 was light brown, see Figure 11. Two weeks after the removal of the de-icing boot from Blade 2, the de-icing boot from Blade 3 was removed and it was observed that the adhesive from Blade 2 had significantly darkened during this period (Figure 12). This darkening has been noted by other users of the adhesive at

QinetiQ and appears to be a natural consequence of the exposure of this adhesive to environmental conditions.

Tie wraps

2.6 Figures 13 and 14 show the tie wraps from the failed and good de-icing boots. It was observed that the tie wraps from the undamaged boots showed no evidence of marking. On the tie wrap from the failed de-icing boot there was a build up of residue on the root edge (near electrical termination) suggesting that the boot strap had been pulled through.

2.7 The position of the tie wraps on Blades 2 and 3 was significantly further from the root end of the boot than shown in the manufacturer's example images (Figure 1). The tie wrap is applied over the bonded region in the manufacturer's example but on Blades 2 and 3 the tie wrap was applied over the strap beyond the bonded region. This resulted in a region of unbonded strap, approximately 5-8 mm long between the bonded root of the boot and the tie wrap, see Figure 15. The position of the tie wrap with respect to the bonded region on the failed de-icing boot is unknown as the piece of strap that would have been beneath the tie wrap is missing.

2.8 As a consequence of the positioning of the tie wrap with relation to the bonded region of the de-icing boots on the examined propeller it is suspected that peel stresses would have developed at the root of the de-icing boot during flight which would not have been seen in the example bond. This is shown schematically in Figure 16.

2.9 Figure 17 shows a summary of the bonded fracture surfaces from boots 1 and 2.

3 NDE

3.1 Before the de-icing boots were detached from Blades 2 and 3, they were examined using the ANDSCAN non-destructive evaluation (NDE) technique. This technique utilises high frequency ultrasonic scanning with water as the contact medium. Changes in material properties, such as the presence of voids in the adhesive bond, result in a change in the bulk attenuation from which a map of damaged areas can be obtained. A number of different ultrasonic probes were tried with the ANDSCAN. However, the material was found to be highly attenuative and a scan of the whole bonded area was not possible. A 5MHz single crystal probe worked relatively well on the thin section of the boot. In these areas of the de-icing boot the bond appeared to be good, however NDE was not able to detect changes in the adhesive where the rubber thickness increased near the root region or at the leading edge where a tight radius of curvature existed.

3.2 An alternative technique, which used a lower frequency probe, was also unable to clearly map the bonded region. In thin areas of the boot, the detectors were unable to establish a signal due to the thinness of the rubber. In the thicker regions, where it was expected that the technique might be more successful, the radius of curvature in that location prevented a good signal as the probe had a footprint larger than the bonded surface. Furthermore, to obtain a quantified map of the bonded region, the technique requires parameters to be set with both a good bonded region and an area with a known defect.

3.3 A technique suggested for further investigation is the use of a thermal camera to examine the de-icing boot once power has been supplied. The technique should identify hot-spots in poorly bonded regions.

4 Detailed Analysis

4.1 Detailed analysis of the failed de-icing boot from Blade 1 and the de-icing boot from Blade 2 was carried out using a range of techniques including Differential Scanning Calorimetry (DSC), Thermomechanical Analysis (TMA), Infra-Red spectroscopy (IR) and Scanning Electron Microscopy (SEM). Figures 18 and 19 identify the sample locations for analysis from each of the de-icing boots. Samples were taken from the root, middle and end of the boot and from the strap region.

Differential Scanning Calorimetry (DSC) of adhesive

4.2 Differential scanning calorimetry (DSC) was carried out on samples of the adhesive from blades 1 and 2. This was done to identify any possible differences in the physical properties of the adhesive used between blades1 and 2 and, also, to establish any differences in the physical properties of the adhesive across the surface of the de-icing boots. Seven samples of adhesive were analysed. They were designated as described in Table 1. Specimens 1-4 were from the failed boot on blade 1 and specimens 5-7 from the boot on blade 2. Specimens were encapsulated in aluminium pans and placed in the DSC cell, which was cooled to -100°C with liquid nitrogen, then heated under a nitrogen atmosphere to 100°C at 5°C min^{-1}.

4.3 Figure 20 shows typical DSC traces obtained; these being from samples 2 (root of boot, blade 1) and 4 (outboard end, blade 1). The main discernible features are an apparent step transition at ca. -40°C (which, though weak, was reproducible), and a weak endothermic peak at ca. +40°C (which disappears on rescanning the specimen). These correlate with literature values for poly(chloroprene) of -45°C and +43°C for T_g and T_m respectively, the main constituent of Bostik 2402. Table 1 tabulates these values for all adhesive samples. The traces do not show any significant difference between the samples (e.g. in T_g or degree of crystallinity), except that sample 7 (root end of boot from blade 2) appears to have a multiple T_m.

Thermo-Mechanical Analysis (TMA) of rubber

4.4 Thermo-mechanical analysis (TMA) was carried out on samples of the rubber from the de-icings boots from blades 1 and 2. The analysis was used to establish if any degradation had occurred to the de-icing boot on blade 1 which may have resulted in its premature debonding from the blade. Eight samples of rubber were examined; four were from the failed boot from blade 1 the other four from the boot on blade 2. They were designated as described in Table 2.

4.5 Specimens, ~4-5 mm square were cut and placed on the sample platform under a flow of helium. A flat-face expansion probe (diameter 3.66mm) rested on the specimen, with an applied force of 50mN (nominal stress 4.7kPa). The specimens were generally not perfectly flat, which meant that a higher actual pressure may have been experienced at points of contact. The sample chamber was cooled to -80°C in a liquid nitrogen jacket, and when the height reading had stabilised the specimen was heated at 3°C min^{-1} to 100°C. Typical curves are shown in Figure 21 (strap samples 11 and 15). The specimen height gradually increases until at ~-40°C, when there is a dramatic increase in the coefficient of thermal expansion (CTE). The glass transition temperature, T_g, is taken as the midpoint of the step increase in CTE. Sample T_g values are given in the Table 2.

4.6 A number of observations have been made with respect to TMA data:

- T_g variation across the sample range is small and not considered significant, however root samples from de-icer boots of blade 1 and blade 2 show a double transition.
- All CTE curves obtained were quite noisy, this being most pronounced for the root samples. CTEs were found to be typically 50 x 10^{-6} K^{-1} when below T_g, rising to ~300-400 x 10^{-6} K^{-1} above T_g. At higher temperatures (~40°C), CTE values fall in the region of 200-300 x 10^{-6} K^{-1}, though this is likely to be a softening of the rubber allowing the probe to compress the sample.
- There are no appreciable differences between CTE or T_g of the boots from blade 1 (failed) or blade 2 (good).

Infrared Spectroscopy (IR) of adhesive

4.7 Infrared spectroscopy was used to examine the chemistry of the adhesive and to establish if there were any differences between the adhesive on blade 1 and blade 2 and further to compare the adhesive from the blades with a sample freshly prepared at QinetiQ, using material supplied by Jade Air, through AAIB. Infrared spectra were recorded on adhesive samples taken from the outboard end of the boot from blade 1 (sample 4), and the freshly prepared sample of adhesive (Figures 22 and 23 respectively). The latter sample was cast as a thin film on a KBr plate; while the former consisted of fragments of thin film which were sandwiched between two KBr plates.

4.8 The IR spectrum of the freshly prepared sample (Figure 23) showed the peaks expected for poly(chloroprene) and additional peaks, particularly that at 2275 cm^{-1}, which corresponds to unreacted isocyanate from the Bostikure hardener. Peaks at 1715cm^{-1} and ~3400cm^{-1} are indicative of the hydrolysis of nitrile groups to generate acid and amino groups. The spectrum of the adhesive from blade 1 (Figure 22) is much weaker and noisier, due to the practical difficulties imposed by its physical form, but is clearly the same basic material. The only distinct differences noted are larger peaks at ~1715 cm^{-1} and 3400 cm^{-1}, suggestive that a greater degree of hydrolysis may have occurred.

4.9 Further analysis was carried out on the adhesive from blade 2. The IR traces obtained exhibited similar behaviour to that of the adhesive from blade 1. This suggests that there is no chemical difference between the adhesives from blades 1 and 2

4.10 To ensure that the colour difference of the adhesive from blade 1 was a result of exposure to the environment, an assessment of the effect of incorrect mixing of the adhesive was made by preparing further castings of Bostik 2402. One casting was prepared using the recommended ratio of 100 parts adhesive to 6 parts hardener, while a second was prepared using 12 parts of the hardener (this resulted in a much darker adhesive film). Comparison of these scans (Figure 24) shows that, despite the increased concentration of isocyanate in the starting mixture, there is no appreciable difference in the presence of nitrile groups suggesting that any excess is readily lost.

4.11 While this does not rule out the presence of excess isocyanate in the blade samples (it is possible that such material would have been lost after the removal of the boots), it does indicate that chemically the adhesive is unaffected. However, if free isocyanate was present, it may have acted as a plasticiser.

Mass Spectrometry (MS)

4.12 The infrared analysis found that the signal from the blade adhesive was weak and noisy, therefore an alternative technique for analysing the adhesive chemistry, mass spectrometry (MS), was used. Mass spectrometry is significantly slower to perform that infrared spectroscopy but typically offers a more quantitative analysis.

4.13 Adhesive samples from the root (location 1) and the middle (location 2) on Blade 1, inboard (location 5) on Blade 2 and a control casting prepared from adhesive supplied by AAIB were subjected to Temperature Programmable Pyrolysis Mass Spectroscopy (TPPMS) to assess variations in the structure of the cured adhesive. This technique subjects the sample to a temperature programme and constantly monitors the degradation products during the course of the programme. The programme used held the sample at 35°C for 2 minutes (to drive off residual moisture) followed by heating at 60°C min^{-1} to 750°C where it was held for a further 5 minutes. Rather than a single spectrum, TPPMS generates a series of time and temperature dependent spectra for each sample.

4.14 Adhesive samples from blade 1 and blade 2 were analysed in this manner and no appreciable difference in their spectra was found. However, differences were noted when these were compared to spectra recorded for samples of freshly prepared adhesive. Spectra from the aircraft samples show an increasing relative abundance of high mass fragments, such as m/z = 362, with time, up to a time of 7 minutes. The control samples do not exhibit the significant presence of any fragment above m/z ~ 300. This difference implies that a greater degree of cross-linking has occurred in the blade adhesive with time.

4.15 Analysis of adhesive prepared with the use of excess curing agent (twice the recommended amount) exhibited no differences compared to the control samples.

Scanning Electron Microscopy (SEM)

4.16 Scanning electron microscopy was used to examine the fracture surface on the three failures within the failed de-icing boot; the failure at the electrical connection; at the root of the boot; and in the middle of the boot. And a further fracture surface was generated in the undamaged boot through tensile loading for comparison. SEM analysis was also carried out on the bonded surface of the failed de-icing boot and the de-icing boot from Blade 2.

Failure near electrical termination

4.17 The failure surface near the electrical termination showed a typically ductile tensile failure in both the rubber (Figure 25) and the copper wires (Figures 26). To establish the rate of failure of this surface, a fracture was generated in the strap of the de-icing boot from Blade 2 using tensile loading at a rate of approximately 5m min^{-1}. These failures are shown in Figures 27 and 28. Comparison of the morphologies of in-service and simulated fracture surfaces revealed them to be very similar, suggesting that failure had occurred in a similar manner. One notable difference between the two surfaces was that on the in-service failure there was significant micro-cracking on the surface (Figure 29), which was not seen on the laboratory created fracture. This implied that the fracture on the failed de-icing boot may have been subject to environmental conditioning. A comparison with the external surface of the strap (Figure 30) showed similar cracking on the surface. The similar features on the fracture and external surface of the rubber would support the case for environmental ageing.

Failure of the main boot

4.18 The rubber surface of the root failure showed a typically brittle fracture surface (Figure 31). The evidence from the TMA showed that the region had not seen any specific heating or degradation that may lead to a brittle failure. The failure was therefore assumed to be the result of a high strain rate load. Failed wires within the fracture show significant deformation consistent with twisting and a high strain rate failure (Figure 32).

4.19 The fracture surface in the middle of the boot, shown in Figures 33 and 34, exhibited a similar fracture surface to that of the boot root. This again suggests that failure was a result of high strain rate loading.

4.20 Of note, was that neither of these failed surfaces showed the same environmental micro-cracking seen in the strap failure near the electrical termination. This would suggest that the high strain rate failures in the boot section occurred subsequently to the strap failure.

Adhesive surface

4.21 SEM analysis was carried out on the bonded surface of the failed and good de-icing boots. Both surfaces showed the same failure; adhesive failure at either the rubber or paint surface (Figures 35 and 36). In the central region of the leading edge, the failure in both blades appeared to be cohesive. Examination of this cohesive failure showed that the adhesive was very porous for both the failed and good de-icing boots (Figures 37 and 38 respectively). The varying morphology of the porous region prevented the failure mode and direction from being obtained. Furthermore the lack of surface features in the adhesive failed regions (riverlines, etc) typically used to map failure modes, made it impossible to establish the direction in which the de-icing boot from blade 1 failed.

5 Conclusions

5.1 A fractographic examination has been carried out to establish the cause of the in-service bond failure between the de-icing boot and blade 1 on Trislander G-BEVT. The two de-icing boots which remained bonded (blades 2 and 3) were also examined for comparison. Further comparisons were made with a freshly prepared sample of the adhesive prepared at QinetiQ, using material supplied by Jade Air, through AAIB and to photographs showing an example bonded de-icing boot recommended by the manufacturer.

5.2 A number of conclusions have been drawn from the inspection and analyses performed;

- Firstly, the addition of de-icer boots to the blades on the Trislander propeller unit examined did not include the sealant shown in the manufacturer's demonstration.
- The position of tie-straps on this unit was not consistent with the manufacturer's example. On the propeller examined there was a region of unbonded strap between the root of the de-icing boot and the tie wrap whereas there is no gap on the manufactures example. The unbonded region would be expected to allow moisture ingress into the joint and allow peel stresses to be generated at the root end of the boot during rotation of the propeller.
- Residue matter found on the tie wrap associated with the failed de-icer boot appears to have been deposited there due to the pull-through of the boot strap during failure.
- The discolouration of the adhesive, as observed for the adhesive near the root of the failed de-icer boot, appears to be the result of environmental exposure. Its presence may not therefore be directly indicative of the cause of failure, but rather the exposure of the adhesive to the environment after failure.
- Thermal analysis has indicated that there are no significant variations in the properties of the adhesives taken from various locations on the failed and remaining boots and control samples. IR has suggested some minor differences between aircraft and control adhesive samples, with the former appearing to show a higher degree of hydrolysis through the increased intensity of amino and hydroxyl absorptions. These may actually indicate an increase in cross-linking through the further reaction of isocyanate. This is supported by the presence of higher mass fragments in TPPMS analyses.
- Analysis of the rubber failed to identify variation between good and failed de-icer boots. The presence of a dual transition at the root of both of these may be an artefact of the presence of the wires.

5.3 Analysis of the remaining bonded boots has determined that ultrasonic-based NDE techniques are not suitable for the identification of debonded areas in de-icing boots.

6 Recommendations

6.1 The analyses undertaken have not revealed a definitive cause of the failure of the de-icing boot. However, it appears that it did not result from any defect in the adhesive used or from degradation of the boot itself. The cause of failure appears to be due to peel stresses developing at the root end of the boot during rotation of the propeller. Therefore, the criticality of the filler and sealant and the correct positioning of the tie wrap to the adhesion of the de-icing boot in service should be investigated. Furthermore, the suitability of the bonding process should be considered, a tougher adhesive or thicker adhesive layer could reduce the risk of sudden failure due to peel stresses developed from the rotation of the propeller in flight.

6.2 The use of thermal imaging to detect hot-spots and, hence, identify debonded areas in de-icing boots should be investigated.

7 Tables

Sample	Location, and boot	T_g (°C)	T_m (°C)
1	Root, failed boot	≈-40 (v wk)	42
2	Middle/root end of failed boot (adhesive failure between adhesive and blade)	-43	41
3	Cohesive resin failure, failed boot	-42	39
4	Outboard end of failed boot	-44	46
5	Inboard end of boot from blade 1	-44	41
6	Root from blade 1	-43	40
7	Middle from blade 1	-43	31, 39, 46

Table 1: T_g and T_m values of adhesive samples taken from aircraft

Sample	**Description**	**T_g (°C)**
8	Failed root	-41; -26
9	Failed middle	-36
10	Failed end	-35
11	Failed strap	-38
12	Good root	-42; -27
13	Good middle	-37
14	Good end	-37
15	Good strap	-37

Table 2: T_g determined by DMA for de-icing boot rubber samples

Figures

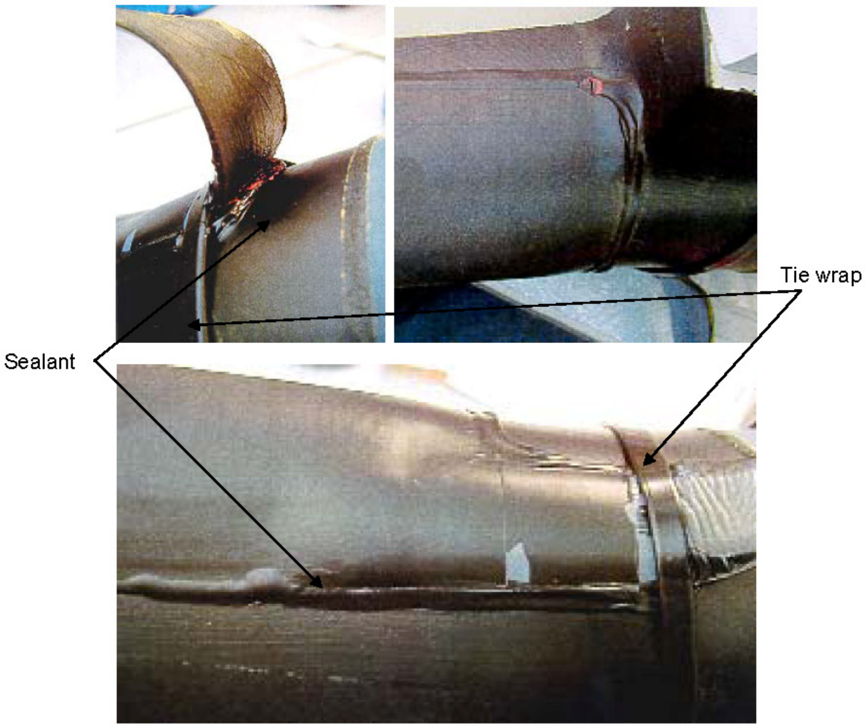

Figure 1: Photographs from the manufacturer showing recommended bonding of the de-icing boot.

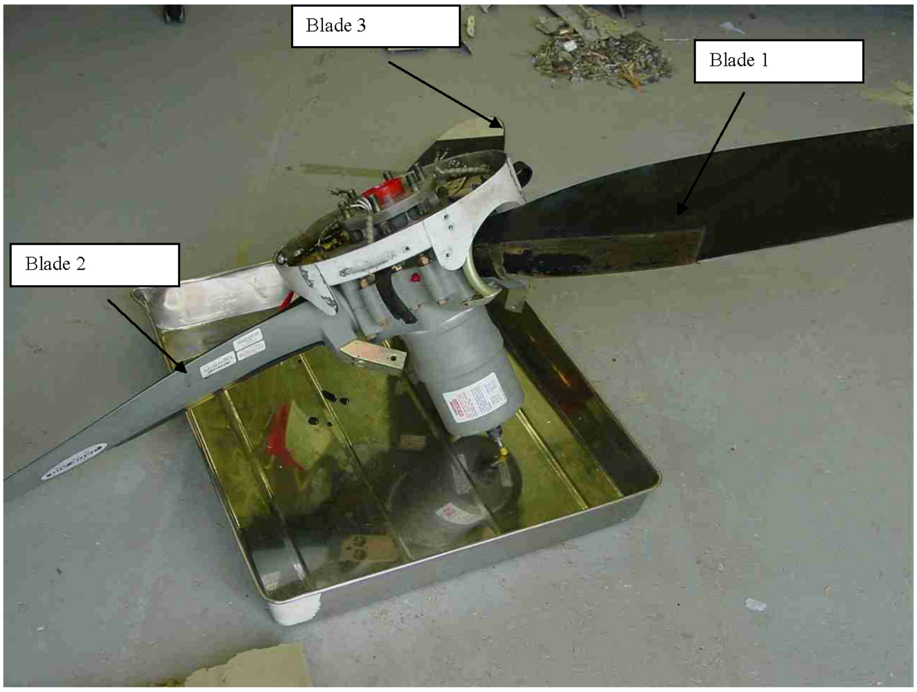

Figure 2: Photograph showing propeller from Trislander G-BEVT

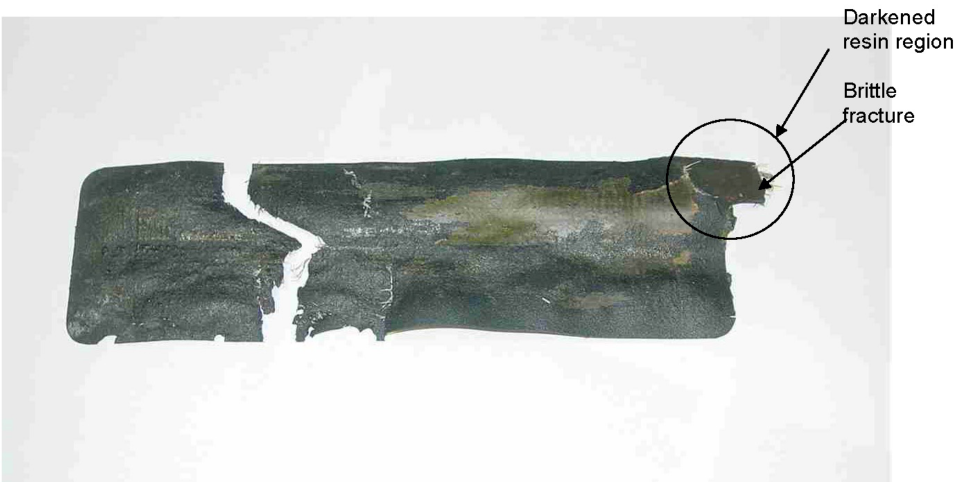

Figure 3: Photograph showing failed de-icing boot from Blade 1

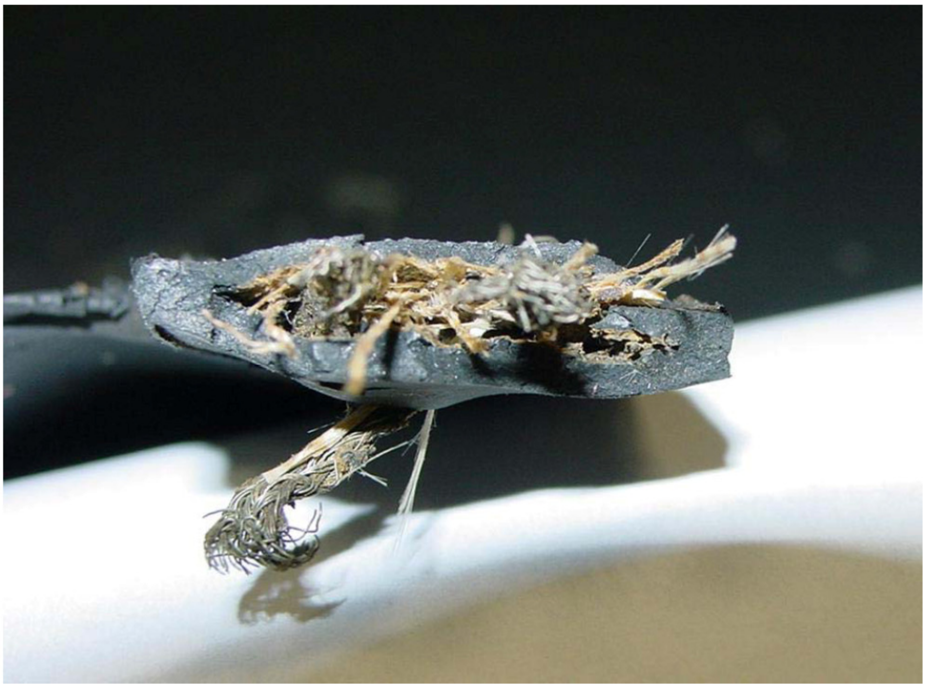

Figure 4: Rubber failure at the root end of boot from Blade 1

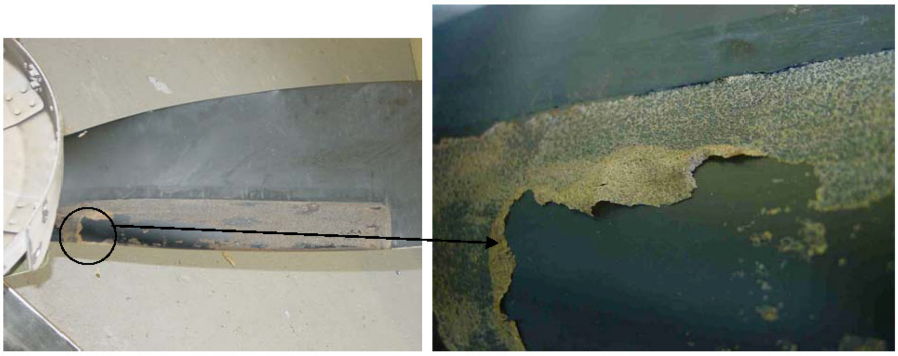

Figure 5: Bonding area of Blade 1, showing disbonded adhesive

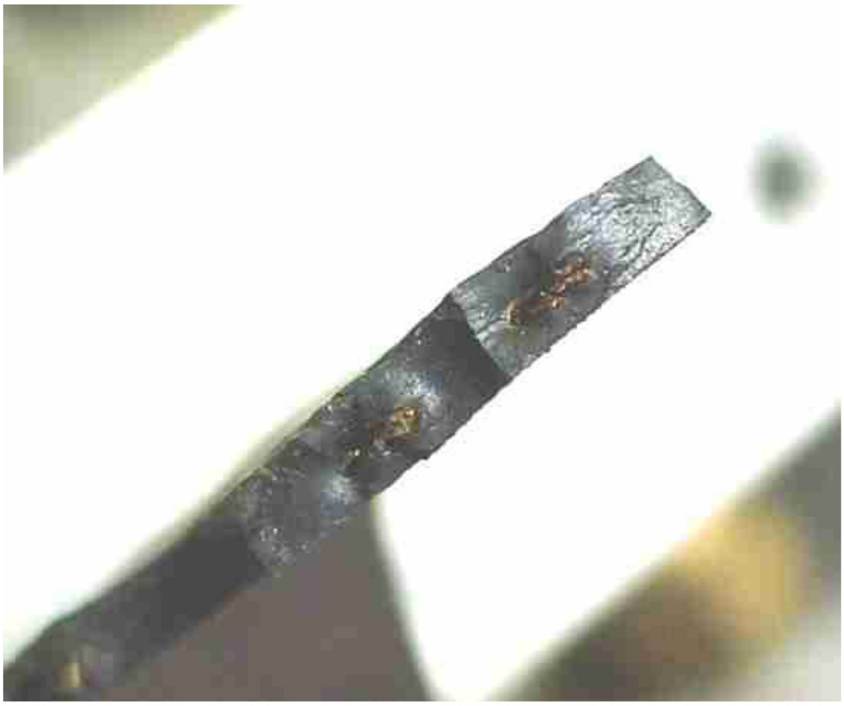

Figure 6: Second fracture in strap, near electrical termination

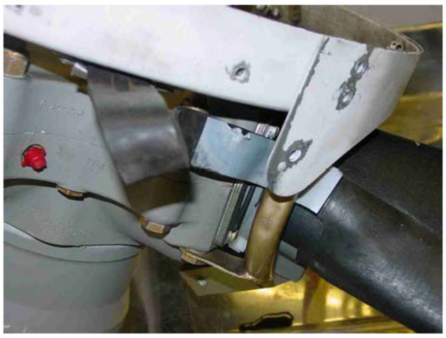

Figure 7: Remains of strap attached to hub from Blade 1 de-icer boot (left-hand image) and equivalent strap on Blade 2 (right hand image)

Figure 8: Aft surface of Blade 2 after removal of de-icer boot

Figure 9: Forward surface of Blade 2 after removal of de-icer boot

Figure 10: De-icer boot removed from Blade 2

Figure 11: Comparison of adhesive colouration on de-icer boots from Blades 1 (bottom) and 2 (top)

Figure 12: Comparison of colouration of de-icer boots removed from Blades 3 (top) and 2 (bottom), showing discolouration of the former with time

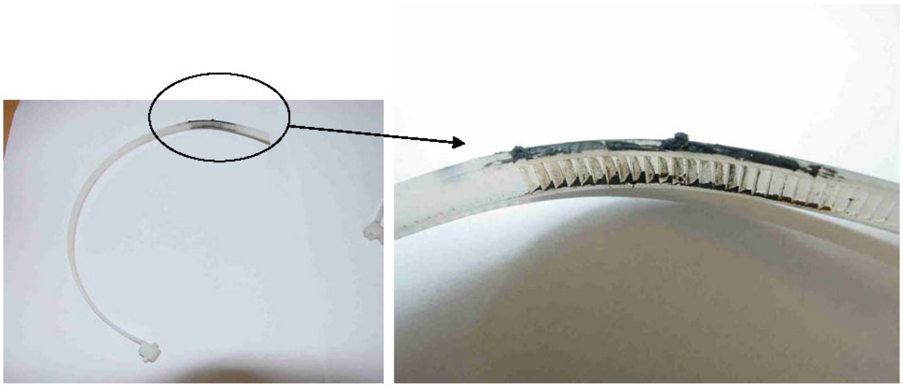

Figure 13: Tie wrap from failed de-icer strap showing residue on root edge.

Figure 14: Tie wrap from good de-icer boot (Blade 2)

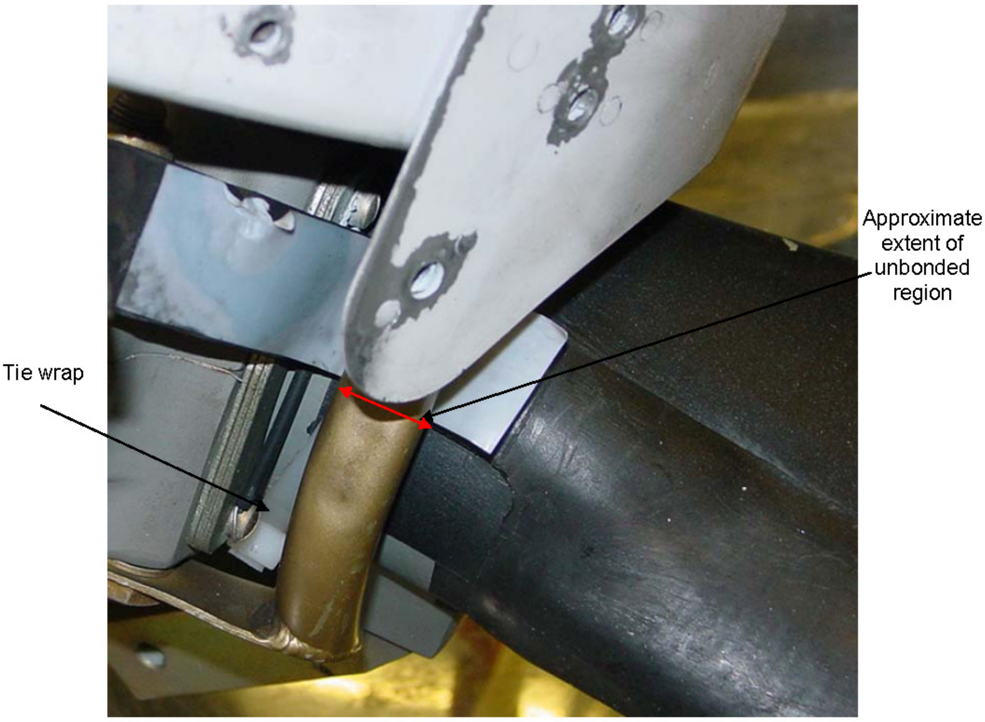

Figure 15: Photograph showing the location of the tie wrap with respect to end of bonded region on blade 3

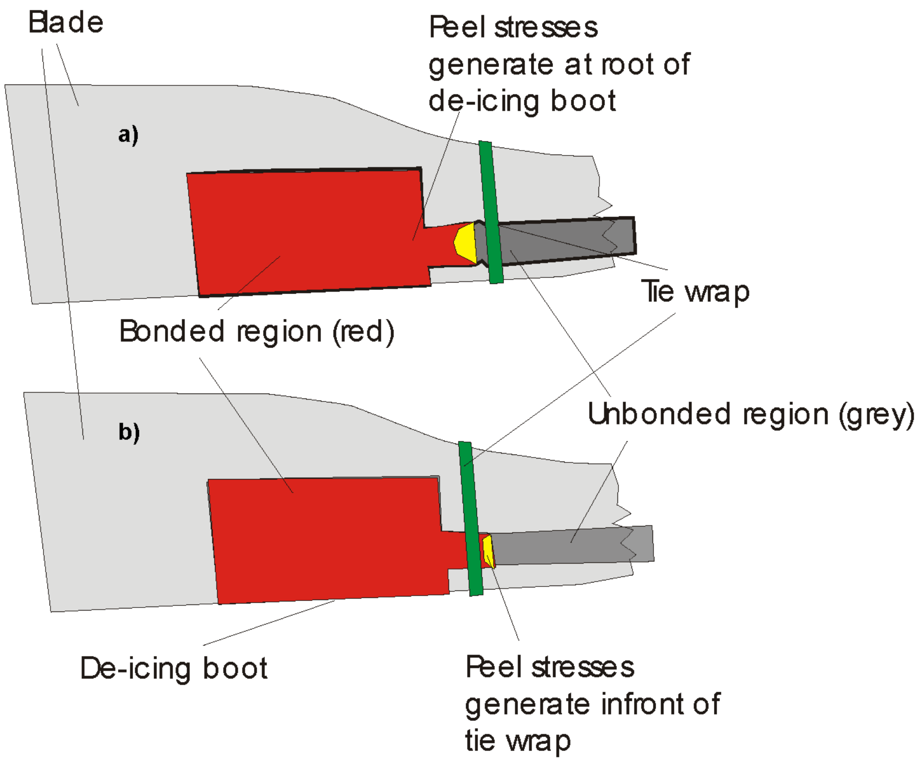

Figure 16: Schematic showing location of tie wraps and bonding on a) blade 2 and 3 from Trislander propeller examined and b) manufacturer's example

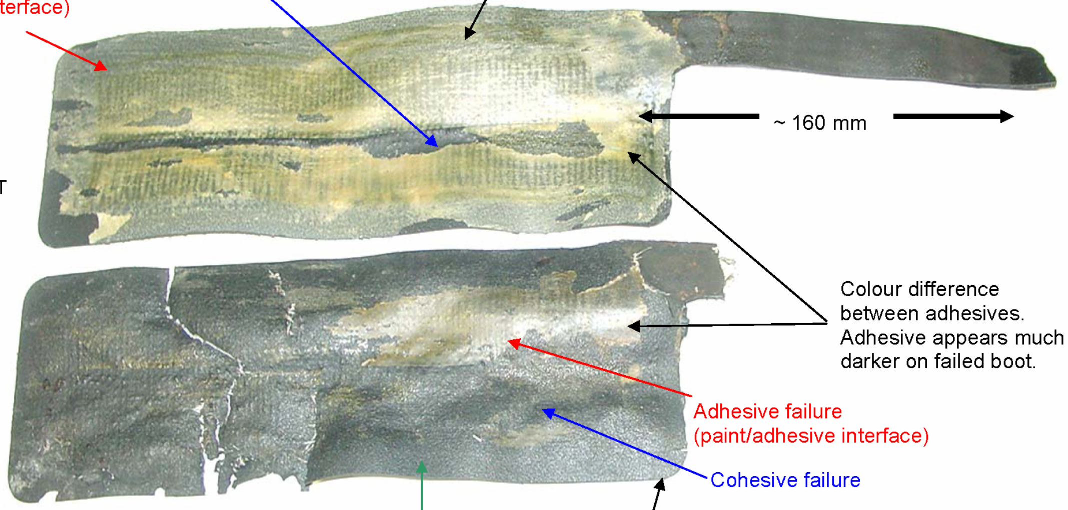

Figure 17: Failure across bonded surfaces of good (top) and failed (bottom) de-icer boots

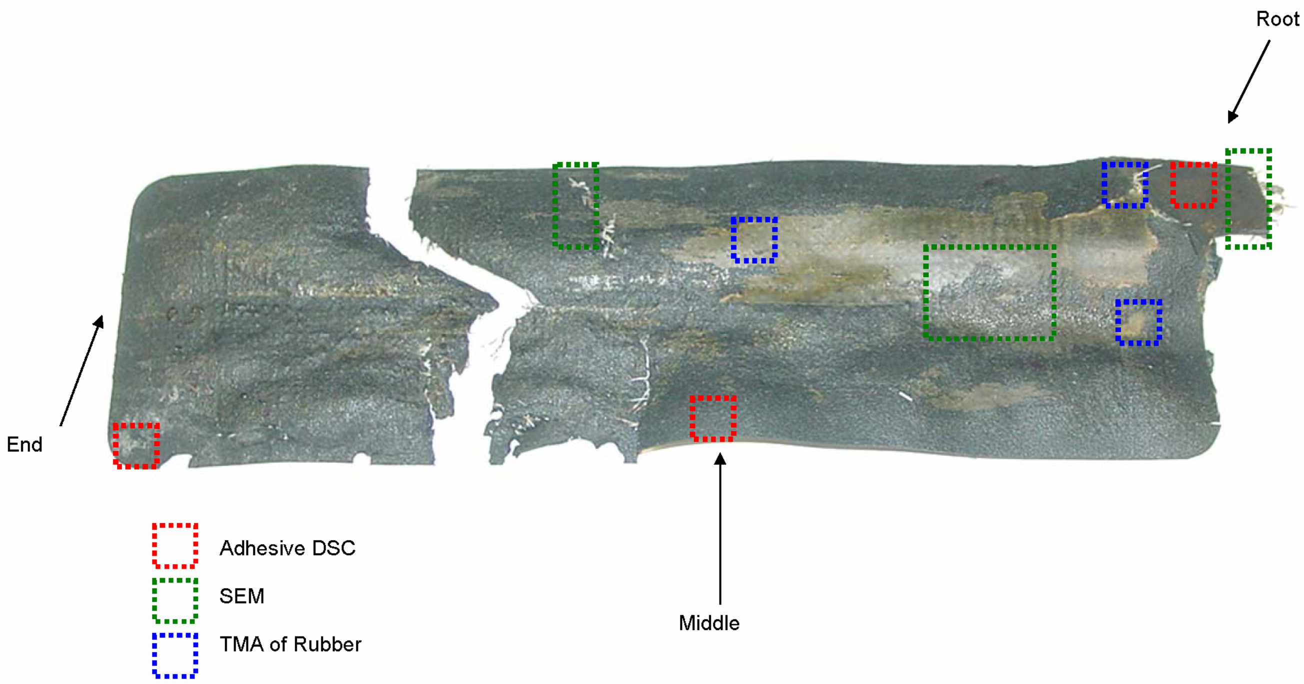

Figure 18: Sampling locations from failed de-icer boot

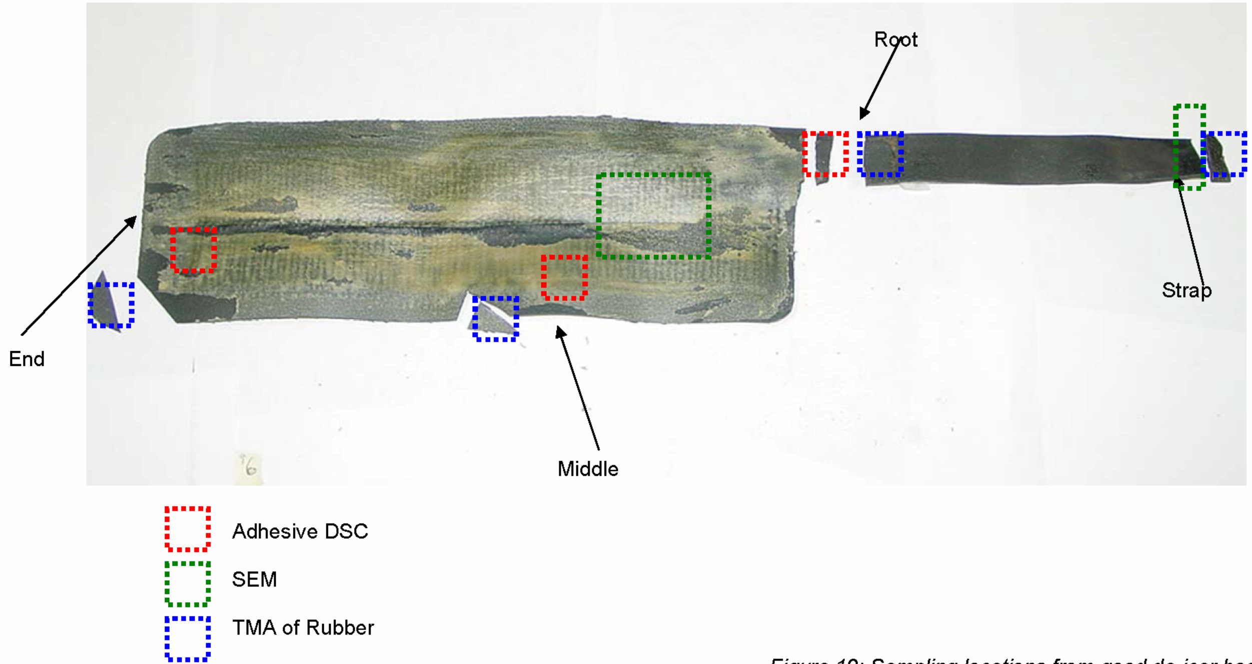

Figure 19: Sampling locations from good de-icer boot (Blade 2)