AIRCRAFT ACCIDENT REPORT 6/89

Air Accidents Investigation Branch

Department of Transport

Report on the accident to Concorde 102 G-BOAF, over the Tasman Sea, about 140 nm east of Sydney, Australia on 12 April 1989

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List of Aircraft Accidents Reports issued by AAIB in 1989

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Department of Transport
Air Accidents Investigation Branch
Royal Aerospace Establishment
Farnborough
Hants GU14 6TD

16 November 1989

The Right Honourable Cecil Parkinson
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr D F King, an Inspector of Air Accidents, on the circumstances of the accident to Concorde 102, G-BOAF which occurred over the Tasman Sea, about 140 nm east of Sydney, Australia on 12 April 1989 at 0210 hrs.

I have the honour to be
Sir
Your obedient servant

D A COOPER
Chief Inspector of Air Accidents

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Air Accidents Investigation Branch

Aircraft Accident Report No: 6/89
(EW/A334)

Registered owner and operator:		British Airways PLC
Aircraft:	*Manufacturer:*	British Aerospace/Aerospatiale
	Type:	Concorde 102
	Nationality:	British
	Registration:	G-BOAF
Place of accident:		Over the Tasman Sea, about 140 nm east of Sydney, Australia Approximate position: Latitude: 35° 30' South Longitude: 153° 40' East
Date and time:		12 April 1989 at 0210 hrs All times in this report are UTC

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) on 12 April 1989 at 0800 hrs and a telex inviting the French Bureau Enquetes-Accidents to participate in the investigation was sent at 0930 hrs. The Bureau Enquetes-Accidents elected not to participate. The AAIB team comprised Mr D F King (Investigator in Charge), Mr A Simmons (Engineering), Mr R G Matthew (Operations) and Miss A Evans (Flight Data Recorder). The Australian Bureau of Air Safety Investigation (BASI) and the Australian Civil Aviation Authority (CAA) provided scientific and technical support throughout the initial investigation.

The Concorde had been chartered for a world tour with 100 passengers. En-route from Christchurch to Sydney, as the aircraft was accelerating through Mach 1.7 and climbing through Flight Level (FL) 440, a "thud" was heard by the crew and passengers. Subsequent analysis suggests that this was a mild engine surge not connected with the accident sequence. However, as the aircraft was descending through about FL 400 and decelerating through Mach 1.3, moderate vibration occurred, lasting two to three minutes. Although the crew were unaware of the source of the vibration, portions of the upper rudder were almost certainly separating from the aircraft at this time. Eventually almost all of the top wedge of the upper rudder aft of the main spar, and above the Power Flying Control Unit (PFCU) attachment structure, separated but the aircraft handling was unaffected and an uneventful approach and landing was carried out at Sydney Airport.

The following causal factors were identified:

i) The in-flight breakup of the bonded honeycomb structure of the upper wedge of the upper rudder occurred as a result of extensive prior delamination of the skin from the honeycomb core.

ii) Moisture ingress past the rivets in the trailing edge lead to corrosion between the honeycomb structure and the skin of the upper wedge, and to deterioration of the adhesive bond strength.

iii) There was incomplete compliance by production staff with the drawing requirements relating to the modification of the rudder trailing edge.

iv) The rudder trailing edge extension modification, as specified in the relevant drawings, placed requirements on production and inspection personnel which were difficult to attain.

1. Factual Information

1.1 History of the flight

The British Airways Concorde, G-BOAF, had been chartered to fly 100 passengers on a world tour which included day or multi-day stops during the journey. The flight began at London and was planned to progress to New York, Acapulco, Oakland, Honolulu, Tahiti, Christchurch, Sydney, Perth, Columbo, Mombasa, Capetown, Monrovia and London.

The crew comprised the normal complement of commander, co-pilot, flight engineer and six cabin staff; also carried on board were a public relations captain, a route planner and a ground engineer. The outbound crew were to be changed at Sydney.

The flight had progressed uneventfully, on schedule, arriving at Christchurch on Sunday 9 April, where a normal en-route inspection had been carried out on the aircraft. No significant fault was discovered either during this check or during the pre-departure external check carried out by the flight engineer. The aircraft took off on schedule, at 0100 hrs on Wednesday 12 April, for Sydney. The co-pilot was handling the controls.

The departure was normal and the aircraft climbed subsonically to FL 280 where it remained until entering the supersonic corridor about 100 nm west of Christchurch. It arrived there at its subsonic cruising speed of Mach 0.95 and then began an accelerating climb to the optimum ceiling defined by the aircraft weight, which on this occasion was eventually FL 575, achieved in a cruise-climb at Mach 2.0.

During the supersonic climb, shortly after the engine reheats had been switched off, at Mach 1.7 and FL 440, a "thud" was heard by the crew. The sound was variously described as being similar to a "pop-surge" in an engine or a bird strike. Nothing abnormal was shown by the flight deck instrument readings and the flying controls felt normal. The commander has stated that the sound and lack of flightdeck indications suggested that there had been a pop-surge and so he elected to continue the flight to Sydney. He has also stated that a return to Christchurch, which would have necessitated deceleration to subsonic speed whilst remaining in the area cleared for supersonic flight, would have taken as long as the continued flight to Sydney. Furthermore, Sydney had more maintenance facilities.

The flight continued normally until, during the decelerating descent into Sydney, at around Mach 1.3 and FL 400, a moderate vibration of the whole aircraft began.

It was however more severe in the rear cabin than in the cockpit. Because the No 4 engine had displayed slightly different, though perfectly acceptable, parameters throughout the flight, the crew closed the No 4 throttle to see if that had any effect upon the vibration. As it did not, all four throttles were then closed in order to reduce speed but this, and the reduction through Mach 1, again made no difference. However, after about 2 minutes the vibration reduced for some 15 seconds but then returned and became intermittent before ceasing altogether as the aircraft passed through FL 200. The total duration was about 3 minutes. During this period of vibration there was no other flightdeck indication of a malfunction and, both during it and subsequently, the aircraft handled normally.

The descent was continued towards Sydney where the aircraft was guided by radar onto the Instrument Landing System for runway 34. A normal landing was carried out at 0243 hrs and there was again no difficulty or abnormality in control of the aircraft. It was not until the control tower informed them of the absence of their upper rudder that the crew were aware of the separation.

The Airport Fire Service, hearing the tower's transmission on their common frequency, immediately proceeded to the aircraft at the end of the runway. The five vehicles arrived less than 30 seconds after the aircraft had stopped. As there appeared to be no emergency, only two vehicles remained with the aircraft and, after a ten minute wait whilst a parking bay was vacated, followed it into the apron area. The passengers disembarked at the terminal.

1.2 Injuries to persons

There were no injuries.

1.3 Damage to aircraft

Damage to the aircraft was confined to the upper wedge of the upper rudder.

1.4. Other damage

There was no other damage.

1.5 Personnel information

1.5.1 Commander:

Male, aged 54 years

	Licence:	Airline Transport Pilot's Licence, re-issued 14 June 1979, valid for 10 years
	Ratings:	DHC 1, DH 104, Britannia, VC 10, Concorde
	Last Base Check:	20 January 1989
	Last Line Check:	7 August 1988
	Instrument Rating:	Valid until 2 September 1989
	Medical Certificate:	Class I, valid to 30 November 1989
	Total pilot hours:	15,600
	Total hours on type:	3,675
	Hours in last 90 days:	50
	Hours in last 28 days:	16
	Hours in last 24 hours:	1
	Previous rest period:	72 hours
1.5.2	*Co-pilot:*	Male, aged 39 years
	Licence:	Airline Transport Pilot's Licence, re-issued 6 September 1979, valid for 10 years
	Ratings:	Beechcraft 95, VC 10, Concorde
	Instrument Rating:	Valid until 9 December 1989
	Last Base Check:	16 March 1989
	Last Line Check:	3 April 1989
	Medical Certificate:	Class I, valid to 30 October 1989
	Total pilot hours:	7,460
	Total hours on type:	3,830
	Hours in last 90 days:	75
	Hours in last 28 days:	32
	Hours in last 24 hours:	1
	Previous rest period:	72 hours
1.5.3	*Flight Engineer:*	Male, aged 51 years
	Licence:	Flight Engineer's Licence, re-issued 1 October 1988, valid for 10 years
	Ratings:	Concorde
	Last Base Check:	16 March 1989
	Last Line Check:	21 April 1988
	Medical Certificate:	Class I, valid to 30 September 1989

Total hours:	9,800
Total hours on type:	4,150
Hours in last 90 days:	66
Hours in last 28 days:	8
Hours in last 24 hours:	1

Previous rest period: 72 hours

1.5.4 Cabin staff

The Safety and Line Checks of the Cabin Service Director and each of the pursers had been completed and were valid.

1.6 Aircraft information

1.6.1 General information

The aircraft was a British Aerospace/Aerospatiale Concorde manufactured on the British Concorde assembly line at Filton. It carried the manufacturers build serial number 100-016. It was completed as a series 191 aircraft and first flew on 20th April 1979. It remained unsold until it was re-assigned to British Airways and modified accordingly, when it became a series 102 aircraft. It first flew in this configuration on 30th April 1980. The aircraft was delivered to British Airways in June 1980 bearing the registration G-BOAF. At the time of the accident it had completed 8,333 flying hours total time and 2,786 landings.

The aircraft was fitted with four Rolls-Royce/Snecma Olympus 593 Mk 610-14-28 turbojet engines with reheat. The engines played no part in the accident sequence.

1.6.2 Component histories, upper and lower rudders

The upper and lower rudders were designed and built by British Aerospace and each carried the serial number VW 25. In May of 1980 the upper and lower rudder trailing edge extensions were added by British Aerospace as part of a performance improvement modification package. The aircraft records show that thereafter the rudders had not been removed between the date of delivery, with the modification embodied, and the date of the accident. The last recorded check on the upper rudder was an external inspection carried out on 25th April 1987, this was part of the Inter 4 check referred to in the next paragraph.

1.6.3 *Maintenance and certification*

The aircraft had a valid Certificate of Registration and Certificate of Airworthiness at the time of the accident. It had been maintained in accordance with the British Airways Concorde Approved Maintenance Schedule as amended by Approved Technical Publication number E7648. The Aircraft Technical Log did not contain any entries of relevance to the accident. The last check carried out on the aircraft was an Inter 4 completed on 26th April 1987. This check normally takes about 28 days.

1.6.4 *Aircraft weight and balance*

Maximum authorised take-off weight:	185,070 kg
Regulated (by landing) take-off weight:	142,630 kg
Actual take-off weight:	142,329 kg
Maximum authorised landing weight:	111,130 kg
Actual landing weight:	110,829 kg
Required take-off C of G:	53.5% Mean Aerodynamic Chord
Take-off C of G:	53.5% Mean Aerodynamic Chord
En-route and landing C of G;	Adjusted throughout the flight by fuel transfer as required.

1.7 Meteorological information

1.7.1 *Weather at Christchurch*

The only significant weather was that which occurred whilst the aircraft was parked on Tuesday 11 April, the day before the subject flight. There was a strong southerly wind of 210° with gusts of up to 43 kt and 20 mm of rain fell. The aircraft was parked on a heading of about 290°.

1.7.2 *En-route and landing*

The en-route weather had no significance in the build-up to the accident. The wind varied with height from westerly at 15 kt to westerly at 60 kt with no significant turbulence. At Sydney, the 0240 hrs weather was: Wind 010°/5-10 kt, CAVOK with a temperature of +25°C.

1.8 Aids to navigation

Not relevant.

1.9 Communications

Communications throughout the flight were normal and were recorded by the Air Traffic Control Centres. Transcripts are available. The Concorde crew, being unaware of any emergency situation, made no significant transmissions regarding either the "thud" or the vibration.

After the aircraft had landed at Sydney, the Aerodrome controller informed the Concorde that "..there appears to be a large section of the tailplane missing, about the top, the vertical fin, about the top ten feet of the trailing edge". This message was intercepted by the Airport Fire Service (AFS) who attended the aircraft. The aircraft commander was subsequently able to converse with the AFS on the ground movements control frequency, 121.7 MHz.

1.10 Aerodrome information

Not relevant.

1.11 Flight recorders

1.11.1 Flight Data Recorder (FDR)

The aircraft was fitted with a Penny and Giles Type 800/D6400 FDR with a recording duration of 24 hours and was part of a Plessey PV1580 recording system. A total of 40 analogue and 55 discrete parameters (events) were recorded.

The recorder was removed in Sydney and returned to AAIB where a successful replay was obtained. From the FDR, the descent and landing appeared normal, with no apparent control difficulties, and there were no indications on the FDR of where the rudder separated or of the vibrations reported by the crew.

Analysis of the engine data during the climb out revealed two instances of Exhaust Gas Temperature (EGT) fluctuations symptomatic of mild surges. The first occurred as the aircraft climbed through 41,810 feet at Mach 1.6 (500 kt Calibrated Air Speed (CAS)) and showed the EGT on No 2 engine rise and then fall again, over a period of 4 seconds, from around 717°C to 725°C and back to 716°C. This event was not commented on by the crew. The second occurred on engine No 3 as the climb passed 44,038 feet at Mach 1.7 (524 kt CAS), when the EGT rose from 695°C to 703°C and then fell to 691°C, again over a period of 4 seconds. This was the event noted by the crew.

The FDR data was also reviewed by Rolls-Royce plc at Bristol, and compared with data obtained from previous flights. Their report states - " The powerplant incident on engine 3 during the Christchurch to Sydney flight of G-BOAF on 12/4/89 was entirely attributable to reduced stability of the N1 control loop - it was not related to any airframe incident reported to have occurred at about this time." Advice received from British Aerospace indicates that this type of event is not a "pop-surge" and although the symptoms may be similar it is better described as a mild single pulse surge.

1.11.2 Cockpit Voice Recorder (CVR)

A Fairchild A100 CVR, an endless loop four track recorder with a duration of 40 minutes, was installed in the aircraft. The recorder continues to run whilst power is on the aircraft and records new information over data which has previously been recorded.

Replay of the recorder was carried out by the BASI. Their report stated that no conversation or signals relevant to the accident were present due to over-recording of the critical period.

Examination of the tape transport revealed damage to the head assembly due to moisture ingress, which had caused significant wear to the recording tape. A strong interference signal was present on one of the tracks of the CVR.

1.12 Examination of the damage to the aircraft

After landing at Sydney the aircraft was removed to a hangar for investigation. The initial inspection showed that the top wedge of the upper rudder (ref Appendices 1, 2 and 3) was, for the most part, missing with only the most forward portion behind the rudder front spar and the lowest portion above the PFCU remaining. There was also some torsional damage between the two topmost hinge stations. There appeared to be no damage to the rest of the upper rudder or to any other part of the aircraft. At the lowest and most aft portion of the damage (see Appendix 4) there was outward bending damage on both skins. Within these skins, over a small area, was seen evidence of adhesive bond overstress, delamination of the adhesive bond and surface corrosion inside the skins. It was also noted that the nature of the skin tears indicated a progressive breakup.

1.13 Medical and pathological information

The crew were medically fit to carry out their duties and there were no injuries caused by the accident.

1.14 Fire

There was no fire.

1.15 Survival aspects

Not relevant.

1.16 Tests and research

1.16.1 Initial inspections

A number of inspection requirements were imposed to further the investigation. Where possible these were arranged to expedite the release to service of the aircraft. The purpose of these inspections was to determine the full extent of the damage and simultaneously to identify all the aircraft components which contributed to the occurrence, ensuring that the aircraft, when repaired, was fit to return to service. The work carried out was as follows:

The PFCU fairing was removed to permit examination of the PFCU. No defect was apparent apart from some minor chafing of a spiroflex protective sleeve on a glass fibre bracket, which did not affect the operation of the PFCU. The rudder throws were checked with and without the PFCU connected and these were all satisfactory. The upper rudder was then removed from the aircraft and despatched under the direction of BASI to Canberra for further investigation.

Checks on the aircraft continued with visual and/or Non-Destructive Test (NDT) inspections of the following items:

The fin rear spar;
The PFCU cradle and installation;
The rudder hinge assemblies;
The tailcone internally;
The fin root attachments to the fuselage.

Also, the following work was carried out:

A visual check aft of frame 66;
A Maintenance Manual check for alignment and backlash;
The part of the turbulent air check applicable aft of frame 60;
Visual and "tap" checks on the elevons and rudders;
Neutral rigging checks and function checks on the rudders.

A replacement upper rudder was fitted prior to the last of these checks. The function checks showed that the operation of the upper rudder PFCU was satisfactory with hysteresis, backlash, and neutral changes with signal lane changes well within normal limits. Following satisfactory completion of all the tests required by the AAIB the aircraft, less the damaged rudder, was released to British Airways who subsequently returned it to service.

1.16.2 *Laboratory examination*

The damaged upper rudder was shipped by BASI to the Australian CAA laboratories at Canberra. BASI make extensive use of CAA facilities when these are required.

The CAA, under AAIB supervision, examined the rudder and cut out for analysis the portion of the damaged area which showed the corrosion and delamination. The surfaces were examined using an electron microscope. NDT techniques were used to establish the extent of the delamination on the remaining portions of the upper wedge and on the lower wedge. One of the rivets securing the trailing edge extension was sectioned and examined. A portion of the delaminated adhesive was removed and sent to the CAA's Chemical Laboratory at Melbourne for analysis.

The Australian CAA prepared a report on their investigation which, in brief, states that the damage prior to the accident was probably extensive, that moisture had penetrated the bonded structure through the break mandrel rivets used to attach the trailing edge extension, and that the bonding adhesive had been properly cured and the bonded surfaces were free of contamination. The report notes that the rivet sectioned and examined was not wet assembled with any sealing compound, however a residual trace of compound within the head of the rivet was visible. A photograph of the rivet cross section from the CAA report is reproduced in this report as Appendix 5. Later examination of the modification drawings showed that the rivet and the extension trailing edge member should have been wet assembled and sealed externally with epoxy compounds.

1.16.3 *Other tests and research*

At the request of the AAIB, British Aerospace carried out additional tests on the corroded areas of skin and the few remaining rivets, in their laboratories at Filton. Their report states:

i) that the rivets attaching the rudder extension probably provided the leak path which allowed moisture into the structure. The report speculates that the missing portion of rudder was probably more severely affected than the portion examined.

ii) that traces of filler or sealant material were found within the rivets but these did not correspond to either the Ciba AV138 or 3M EC3524 materials specified in the modification drawings. Also that there was no evidence of the specified primer between the skin and the adhesive film although it is not clear if this would have had a detrimental effect.

iii) that there was evidence of local high pressure between the skin and the adhesive film, most probably due to ice formation.

Consideration was given to the possible effect of repeated application of the paint stripper used by the operator, Turco 5351, on the epoxy materials specified to seal the rivets, Ciba AV138 and 3M EC3524. The material and paint stripper specifications were supplied to the Royal Aerospace Establishment Materials and Structures Department Adhesives and Sealants Group, who report that the paint stripper has relatively little effect on the Ciba AV138 material but could have caused significant deterioration of the 3M EC3524 material specified to seal the heads of the rivets.

The aircraft had been repainted twice during its life, as follows:

Stripped and re-painted	September 1981
Stripped and re-painted in new British Airways livery	January 1985

The repainting procedure used by British Airways included the identification and protection of areas susceptible to damage by paint stripper. The sealant at the leading edges of the trailing edge extension was identified as a susceptible area. The attachment rivets were not so identified.

1.17 Additional information

1.17.1 Photographs taken prior to the flight

The Concorde is not a frequent sight in New Zealand, consequently a number of photographs were taken by members of the public. In particular, some photographs were taken of the rudders because, being hydraulically damped and having no gust locks as such, it is possible for a rudder "split" to occur when hydraulic power is removed. This did happen at Christchurch and at least one person thought it sufficiently odd to be worth photographing. After the accident, the photographs were offered to BASI.

The photographs show that there was no marked or obvious damage which should have been seen during the pre-departure inspection. However, several of the photographs do show a very faint change in the colouration of the upper wedge of the upper rudder. Accordingly some computer image enhancement of the photographs was attempted. The results are reproduced as Appendices 6, 7 and 8, and show a distinct curved feature which was visible on two photographic negatives exposed at different times and from different angles.

1.17.2 *Effect of high winds at Christchurch, NZ*

A number of comments were received by BASI concerning the "high winds" to which the aircraft was subjected, especially as the rudders were seen to move during this period. Discussions with British Aerospace confirm that this is normal and that the Concorde rudders are cleared to withstand gusts of up to 100 knots from any direction.

1.17.3 *Design requirements*

The original design standard of the production Concorde rudders did not include the trailing edge extension. The number of rivets in the design had been kept to a minimum and none were employed in the basic construction of the aluminium honeycomb wedge, chemi-etched skins and trailing edge closing member, all of which were bonded together in an autoclave at an elevated temperature.

With the introduction of the trailing edge extension modification, it became necessary to introduce rivets to attach the new structure. The design required "blind" rivets to be used, which could be set without gaining access to the inside of the rudder skin. Monel hollow rivets to BAS 7035 were specified, these have a break head steel mandrel which is retained when set and plugs the body of the rivet. To prevent moisture from entering the structure the drawings called for the rivet holes and associated cavities in the honeycomb core to be completely filled with an epoxy filler, for the rivets to be degreased and coated in the same filler before installation, and for the rivet heads to be coated with a different epoxy base filler. The construction of the trailing edge is illustrated in Appendix 9.

1.17.4 *Inspections for delamination*

At an early stage in the development of the Concorde, the lower rudder was identified as an area susceptible to acoustic damage. Checks, including delamination checks, were called up in this area, but did not include the upper rudder. Service experience has shown that the lower rudder is not as susceptible to damage as anticipated and, at the time of the accident, no checks specifically for delamination on the upper rudder were required before 12,000 flying hours were achieved. Accordingly, it is possible that no checks for delamination of the upper rudder fitted to G-BOAF had ever been carried out.

Following the accident an immediate "Special Check" was imposed across the Concorde fleet. This called for inspections for delamination of the rudders and elevons. The British and French airworthiness authorities, manufacturers and operators have recently established the details of new inspection requirements calling for regular inspections for delamination of the rudders and elevons, and these are predicated on the assumption that other rudders or elevons are susceptible to moisture damage.

1.17.5 *Similar damage to G-BOAB*

As a result of the "Special Check" carried out following the accident, a delaminated upper rudder was found on British Airways Concorde G-BOAB, which was undergoing a major inspection at the time. The rudder was removed for inspection and repair. It was found to have a similar pattern of corrosion damage to that seen on G-BOAF, except that it was limited to less than three inches chordwise and there was no delamination in areas where corrosion was not visible. The corrosion extended over most of the length of the trailing edge and included most of the rivets securing the trailing edge extension. Less than two years previously, in 1987, a small repair had been made to the rudder tip at the trailing edge but no other repair for delamination was made at that time. The damage to the rudder fitted to G-BOAB is illustrated in Appendices 10, 11 and 12.

2 Analysis

2.1 Conduct of the flight

The commander's stated reasons for not returning to Christchurch, following the "thud", appear to have been fully justified. Although the source of the "thud" was not at the time identifiable, the best evidence available now suggests, as had been reasoned by the crew, that it was caused by a mild surge.

2.2 Engineering analysis

2.2.1 Mode of break-up

The reported vibration during deceleration fits well with the condition of the rudder after the accident. The skin tears are typical of a fragmented and progressive breakup with the skins breaking away from the honeycomb core during the sequence. The torsional damage found between the top two hinge fittings also supports this view, since it is necessary for a substantial piece of the rudder to be attached at the top and also for most of the box strength below to be destroyed before such damage could occur. This firm evidence from the damaged rudder is supported by the less positive, but probably sound, evidence obtained from the computer enhanced photographs of the rudder taken when the aircraft was parked at Christchurch. These appear to show delamination following the line of the breakup but leaving a large sound area at the top of the rudder. If credence is given to the computer enhanced photography, it follows that the extent of the delamination was considerable, although it was unlikely to have been sufficiently visible to be seen during the pre-flight external check. Furthermore, progressive breakup of the upper wedge could explain the intermittent nature of the perceived vibration as well as its overall timescale of two to three minutes.

The fact that the damage ceased to progress significantly beyond the upper wedge may be due in part to the deceleration, but also supports the design philosophy which required the two independent rudders, each with two honeycomb wedges, to contain a single wedge failure without compromising control of the aircraft in normal flight. The tests carried out in the hangar at Sydney showed that the breakup sequence did not cause damage to any part of the aircraft other than the upper rudder, and that no other component, such as the PFCU, played any part in initiating the vibration.

2.2.2 *Failure mechanism*

The laboratory work carried out indicated that the breakup was initiated by internal corrosion at the trailing edge causing separation of the bonding adhesive from the aluminium alloy skins. This corrosion was a result of moisture ingress through the rivets in the trailing edge extension. The presence of moisture within the structure may well have led to a high moisture content within the adhesive itself. Such a condition seriously reduces its mechanical strength and would account for the areas where delamination had occurred without visible corrosion. It is also possible that repeated freezing and the effect of corrosion creeping between the skin and the adhesive played some part. The evidence is that the total amount of delamination from all causes was extensive.

The susceptibility of bonded structures to moisture ingress is well known. Considerable experience of such structures had been amassed prior to the design of the Concorde rudders, and is reflected in the design standard and in the long calendar life which these components have now achieved. This awareness is also reflected in the drawing requirements for the trailing edge extension modification. However, the two rudders examined in detail, serial VW 25 removed from G-BOAF and serial VW 22 removed from G-BOAB, did not conform to the drawing requirements in several respects. The photograph at Appendix 5 shows a section through a typical rivet, and there is no evidence of wet assembly using an epoxy compound as specified. There are small traces of what may be filler material between the rivet and its mandrel but these would not prevent moisture ingress. While it is possible that stripping for re-painting may have caused deterioration of the external material, it is also clear that the rivet was not assembled in accordance with the drawing requirements.

2.2.3 *Design, manufacture and inspection considerations*

The drawing requirements for the trailing edge modification, if followed completely, would have made moisture ingress most unlikely, however they placed requirements on production and inspection personnel which were difficult to attain.

There were several difficulties facing the production staff assembling the rivets. The rivets were 3.2mm diameter. When drilling the holes for the rivets it was possible to break in to either a single cell of the honeycomb core, or the corner of several cells. To fill the cavity with epoxy compound would require different amounts of compound depending on how many cells were penetrated. Attempting to fill the cavity until the epoxy overflowed could lead to air pockets being left within the cavity. It was necessary to perform the operation through the rivet hole. Once done and the rivet set, the drawing called for the head of the rivet to be sealed with another epoxy compound. Once this was done, it was not possible for an inspector to determine whether the filling of the cavity or coating of the rivet before assembly was satisfactory, only the external surfaces could be examined. With a properly assembled rivet, for moisture to get within the structure it would have to penetrate the outer seal of epoxy, then break down the epoxy between the rivet and the structure, (or alternatively the mandrel) and then penetrate the filled cavity or break down the bond of the original structure. On the rivets examined, moisture had only to penetrate the outer seal, and this was susceptible to damage during repainting.

The manner in which the ingress of moisture leads progressively to increasing delamination damage, and the evidence that moderate degrees of delamination can be tolerated, indicate that appropriate inspections should detect any damage before it reaches serious proportions. In cases where moisture has penetrated the structure, as in the rudder fitted to G-BOAF, damage can be detected before flight safety is affected and while it is still economical to repair the component.

2.2.4 *Safety actions*

Shortly after the accident a requirement for a "Special Check" was issued. The check contained inspections for delamination of the rudders and elevons. The British and French airworthiness authorities, manufacturers and operators have recently established the details of new inspection requirements calling for regular inspections for delamination of the rudders and elevons.

3 CONCLUSIONS

(a) Findings

(i) The flight deck crew were medically fit and properly licensed to undertake the flight.

(ii) The aircraft had a valid Certificate of Airworthiness in the Transport Category and had been maintained in accordance with an approved maintenance schedule.

(iii) The event noted by the crew during supersonic acceleration was a mild surge in the No 3 engine and was not related to the rudder breakup.

(iv) The upper wedge of the upper rudder suffered progressive breakup during supersonic deceleration.

(v) The rudder trailing edge modification in the case of two known rudders, VW 25 fitted to G-BOAF and VW 22 fitted to G-BOAB, was not carried out entirely in accordance with the modification drawings. In particular, the rivets were not wet assembled and sealed as intended in the design.

(vi) Inadequate sealing led to moisture ingress and internal corrosion leading to delamination and subsequent in-flight breakup of the upper wedge of the upper rudder.

(vii) The aircraft had been repainted twice during its service life. The application of paint stripper can cause deterioration of the epoxy compound used to seal the rivet heads.

(viii) The upper wedge of the upper rudder was probably extensively delaminated before tha aircraft departed Christchurch.

(ix) The aircraft was subjected to significant rain and wind on the ground at Christchurch, however this alone would not have caused damage to the rudder.

(b) Causes

The following causal factors were identified:

i) The in-flight breakup of the bonded honeycomb structure of the upper wedge of the upper rudder occurred as a result of extensive prior delamination of the skin from the honeycomb core.

ii) Moisture ingress past the rivets in the trailing edge led to corrosion between the honeycomb structure and the skin of the upper wedge, and to deterioration of the adhesive bond strength.

iii) There was incomplete compliance by production staff with the drawing requirements relating to the modification of the rudder trailing edge.

iv) The rudder trailing edge extension modification, as specified in the relevant drawings, placed requirements on production and inspection personnel which were difficult to attain.

4 Safety Recommendations

None.

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