AIRCRAFT ACCIDENT REPORT 5/93

Air Accidents Investigation Branch

Department of Transport

Report on the accident to British Aircraft Corporation/SNIAS Concorde 102, G-BOAB, over the North Atlantic, on 21 March 1992

This investigation was carried out in accordance with ***The Civil Aviation (Investigation of Air Accidents) Regulations 1989***

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Department of Transport
Air Accidents Investigation Branch
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Farnborough
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20 October 1993

The Right Honourable John MacGregor
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 associated with the accident to British Aircraft Corporation/SNIAS Concorde 102, G-BOAB, which occurred over the North Atlantic on 21 March 1992.

I have the honour to be
Sir
Your obedient servant

K P R Smart
Chief Inspector of Air Accidents

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GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	-	Air Accidents Investigation Branch
AAR	-	Aircraft Accident Report
AD	-	Airworthiness Directive
AFD	-	Acoustic Flaw Detection
ARTCC	-	Air Route Traffic Control Centre
°C	-	degree Centigrade
CAA	-	Civil Aviation Authority
FDR	-	Flight Data Recorder
FL	-	Flight level
hrs	-	hours
Mach	-	Ratio of true airspeed to speed of sound
MEK	-	Methyl Ethyl Ketone
N_1	-	Engine fan speed
N_2	-	Intermediate pressure compressor speed
NDT	-	Non-Destructive Test
PFCU	-	Powered Flying Control Unit
QAR	-	Quick Access Recorder
UTC	-	Coordinated Universal Time

Air Accidents Investigation Branch

Aircraft Accident Report No: 5/93 (EW/A92/3/2)

Registered owner and operator:	British Airways PLC
Aircraft Manufacturer:	British Aircraft Corporation/SNIAS
Aircraft Type and Model:	Concorde 102
Nationality:	British
Registration:	G-BOAB
Place of accident:	Over the North Atlantic, approximate position: Latitude: 48N Longitude 45W
Date and Time:	21 March 1992 at about 1300 hrs

All times in this report are UTC

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) by British Airways Safety Services at 1450 hrs on 21 March 1992. The French Bureau Enquetes-Accidents were invited to participate in the investigation, but elected instead to be kept fully informed. The National Transportation Safety Board (NTSB) of the USA assisted by obtaining operational evidence in New York. The AAIB team comprised:

Mr D F King, Principal Inspector (Engineering)	Investigator in Charge
Mr S W Moss, Senior Inspector (Engineering)	Engineering Matters
Mr A W Skinner, Senior Inspector (Operations)	Operational Matters
Mr P F Sheppard, Assistant Principal Inspector (Engineering)	Flight Data Recorders

The British Airways Concorde, G-BOAB was on a scheduled transatlantic passenger flight from London to New York. After the aircraft had been airborne for 1 hour and 57 minutes, when cruising at Flight Level (FL) 530 and Mach 2, the crew noticed a 'thump' which, in the absence of any unusual indications on the flight deck instruments, they assumed to be caused by a brief engine surge. However, approximately one hour later, as the aircraft was descending and decelerating below Mach 1.4, there was a sudden onset of severe vibration that was felt throughout the aircraft. Although the crew were unaware of the source of the vibration, portions of the upper rudder were probably separating from the aircraft at this time. In attempting to diagnose the problem it was found that increasing power on No 2 engine appeared to cause the vibration level to increase and accordingly, as a precaution, this engine was shut down. Aircraft handling was apparently unaffected until during the manual landing when more than normal right rudder was needed. However, an otherwise uneventful three-engine approach and landing was carried out at J F Kennedy International Airport, New York. Upon landing, the crew were informed that a large section of the upper rudder was missing.

The bonded honeycomb structure of the upper rudder, upper wedge had broken away as a result of delamination of the skin/honeycomb bond. The reason for the delamination could not be positively established because a major portion of the failed rudder was not recovered. However, the balance of evidence pointed to possible accidental ingress of preparation materials into the core during the course of a major repair performed 254 flying hours before the failure.

Three safety recommendations have been made.

1 Factual Information

1.1 History of the flight

The British Airways Concorde, G-BOAB with the callsign Speedbird Concorde 1 was operating a scheduled passenger flight from London Heathrow to New York J F Kennedy Airport. The crew comprised commander, co-pilot, flight engineer and six cabin crew; the co-pilot was handling the controls.

The aircraft departed Heathrow at 1047 hrs and the flight progressed uneventfully until 1244 hrs when, cruising at Mach 2 at FL 530, the crew noticed a 'thump' or momentary vibration, lasting between one and two seconds. Nothing abnormal was shown by the flight deck instruments, and at that time it was assumed that a brief engine surge may have occurred. The ocean crossing continued without further incident and at 1333 hrs Concorde 1 contacted the New York Air Route Traffic Control Centre (ARTCC), reporting level in the cruise at FL 550. At 1343 hrs New York ARTCC cleared Concorde 1 to descend to FL 290.

The flight crew reported that as the aircraft was descending and decelerating below Mach 1.4, there was a sudden onset of severe vibration that was felt throughout the aircraft. The vibration became more intense as height and therefore Mach number reduced. The autopilot was disconnected and the Flight Control electronic signalling lanes were changed from Blue to Green, in order to ensure that signalling was not the cause of the problem. When the engine intake ramps came to a scheduled stop at Mach 1.3, the No 2 engine intake control lane B indicated failure. The vibration persisted and the airspeed was further reduced below 350 knots, when the engines were throttled back to idle. When sub-sonic the power on each engine was increased in turn to attempt to diagnose the source of the vibration. Increasing power on No 2 engine caused the vibration to increase significantly, and this engine was shut down in accordance with the precautionary shut down checklist. At 1350.20 hrs Concorde 1 advised New York ARTCC that No 2 engine had been shut down. During this period of vibration there were no other flight deck indications of a malfunction and the aircraft handled normally.

The descent was continued and the aircraft was positioned for an automatic three-engine Instrument Landing System (ILS) approach to runway 04R at J F Kennedy Airport. When the autopilot was disengaged prior to a manual landing, the co-pilot reports that more right rudder force was required than he expected to keep the 'ball' towards the centre and remove the drift before touchdown. The surface wind was 350/10 to 15 knots. Reverse thrust was selected on Nos 1 and 4 engines only, and sufficient braking used to bring the aircraft to taxi speed well before the end of the runway. The aircraft landed at 1412 hrs.

Once clear of the runway and after the aircraft was stopped, emergency vehicles of the New York Port Authority, who had previously been called to stand-by as a precautionary measure, were strategically positioned around the aircraft. The aircraft was examined externally and the flight crew informed that a large portion of the rudder had been lost. The aircraft was then taxied, accompanied by the emergency vehicles, to the allocated parking pier where the passengers disembarked through the normal channels.

1.2 Injuries to persons

There were no injuries.

1.3 Damage to aircraft

Damage to the aircraft was confined to the upper rudder.

1.4 Other damage

There was no other damage.

1.5 Personnel information

1.5.1	Commander:	Male, aged 50 years	
	Licence:	Airline Transport Pilot's Licence, re-issued 3 December 1991, valid for 10 years	
	Aircraft ratings:	DHC 1, Boeing 707, Boeing 747-100/200, Concorde	
	Medical Certificate:	Class C valid until 30 June 1992	
	Instrument Rating:	Valid until 3 August 1992	
	Last Base Check:	13 December 1991	
	Last Line Check:	15 January 1992	
	Flying experience:	Total all types:	12,164 hours
		Total on accident type:	4,602 hours
		Preceding 90 days:	80 hours
		Preceding 24 hours:	Nil
	Previous rest period:	In excess of 72 hours	

1.5.2	Co-pilot:	Male, aged 43 years	
	Licence:	Airline Transport Pilot's Licence, re-issued 14 November 1991, valid for 10 years	
	Aircraft ratings:	Boeing 737-200/300, Concorde	
	Medical Certificate:	Class C valid until 31 July 1992	
	Instrument rating:	Valid until 30 April 1993	
	Last Base Check:	13 March 1992	
	Last Line Check:	30 May 1991	
	Flying experience:	Total all types:	7,516 hours
		Total on accident type:	1,167 hours
		Preceding 90 days:	92 hours
		Preceding 24 hours:	Nil
	Previous rest period:	14 hours	
1.5.3	Flight Engineer:	Male, aged 48 years	
	Licence:	Flight Engineer's Licence, re-issued 28 March 1988, valid for 10 years	
	Aircraft ratings:	VC10, Concorde	
	Medical Certificate:	Class C valid to 30 November 1992	
	Last Base Check:	11 October 1991	
	Last Line Check:	8 May 1991	
	Flying experience:	Total all types:	10,107 hours
		Total on accident type:	5,096 hours
		Preceding 90 days:	51 hours
		Preceding 24 hours:	Nil
	Previous rest period:	20 hours	

1.5.4 Cabin Crew

The Safety and Line Checks of all members of the cabin crew had been completed and were valid.

1.6 Aircraft information

1.6.1 General Information

G-BOAB was a British Aircraft Corporation/SNIAS Concorde manufactured on the British Concorde assembly line at Filton and carried the manufacturer's build serial number 100-008. It was completed as a Variant 102 aircraft and first flew on 18 May 1976, being delivered to British Airways on 30 September 1976. At the time of the accident it had completed 15,387 flying hours and 5,010 braked landings. The aircraft was powered by four Rolls Royce/Snecma Olympus 593 Mk 610 14 28 turbojet engines with reheat.

1.6.2 Construction of the Upper and Lower Rudders

The basic design of the upper and lower rudders was similar (see Appendix A). Each featured two 'wedges' of metal honeycomb sandwich construction above and below the Powered Flying Control Unit (PFCU) beam which operated the surface. Each wedge was attached to the leading edge spar and the PFCU beam using adhesive bonding and mechanical fasteners.

The wedges used aluminium honeycomb which was bonded to the chemically etched left and right skins using an autoclave-curing adhesive. In the case of the accident rudder, this adhesive was Redux 322 manufactured by Ciba-Geigy, although some earlier rudders had used AF130 manufactured by the 3M company, an adhesive with similar properties.

As is normal in this type of structure, the number of rivets and fasteners penetrating through to the core was kept to the bare minimum in order to avoid leakage paths for moisture. However, as described in paragraph 1.6.3, a British Aircraft Corporation modification was introduced to the trailing edge of the subject rudder before delivery to British Airways which relied on a large number of rivet holes being drilled into the extreme trailing edge of the core.

The practice of using a solid wedge of metal honeycomb as the complete control surface was unusual in a civil aircraft primary flying control. Although other aircraft used metallic and non-metallic honeycomb in their construction, it has generally been the practice for it to be used to reinforce separate skins which would then be fastened together when building-up a surface as large as Concorde rudders. The technique was more widely employed on military aircraft where the surfaces were smaller. Clearly, use of this method on Concorde was dictated by the need to produce a slender, but very stiff, structure.

1.6.3 Component and Inspection History of the Upper Rudder

The upper rudder fitted to G-BOAB carried the manufacturer's serial number VW23. It was originally fitted to Concorde G-BOAG which was delivered in 1977 and the constructor's Modification No 1662, which introduced an extension to the trailing edges of both upper and lower rudders, had already been incorporated. The purpose of this extension was to provide a small but worthwhile performance improvement and a similar modification was applied to the elevons. Eventually, the majority of the British Airways Concorde fleet were modified to this standard.

The records show that G-BOAG flew a very small number of hours before VW23 was removed and fitted to G-BOAC in September 1978. It remained on G-BOAC until July 1989 when it was removed following a Non-Destructive Test (NDT) inspection which found evidence of disbond in the trailing edge area. This inspection had been instituted following the upper rudder failure on G-BOAF which had occurred in April of that year (see paragraph 1.17.2).

The rudder was sent to British Airways workshops for an extensive repair to the trailing edge (see paragraph 1.17.1), remaining there until November 1991 when it was fitted to G-BOAB. During the course of this repair it was decided not to refit a trailing edge extension which effectively reverted the rudder to the pre-modification configuration. VW23 flew 254 flying hours on G-BOAB before it failed having accrued a total of 10,861 hours and 3,724 landings since new. Since the rudder was well within the inspection intervals required by Airworthiness Directive (AD) No 022-04-89, it had received no further NDT or 'tap' tests since the repair.

1.7 Meteorological information

The en route and terminal weather had no significance in the circumstances of this accident. At J F Kennedy Airport the 1350 hrs weather observation as broadcast on the Aerodrome Terminal Information Service was: Sky clear, visibility 20 (statute miles), wind 350 at 10 (knots), temperature 35 (Fahrenheit).

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.

1.10 Aerodrome information

Not relevant.

1.11 Flight recorders

The aircraft was fitted with a Penny and Giles type D800 re-cycling Digital Flight Data Recorder, a Fairchild A100 Cockpit Voice Recorder, and a Penny and Giles Quick Access Recorder (QAR).

Only the QAR was removed and a successful replay was obtained using the British Airways facilities.

The data were examined and no visible indications of the vibrations mentioned by the crew were apparent from the accelerometer readings. As the only indication of rudder position was the measured pedal angle, this would show no signs of abnormality or oscillation. The sensed engine parameters, (N1, N2, exhaust gas temperature, jet pipe pressure and area, and fuel flow), showed no signs of unusual fluctuations that might have been associated with 'pop' surges.

1.12 Examination of the damage to the aircraft

The aircraft was examined at J F Kennedy International Airport, New York. It was obvious that almost all of the top wedge of the upper rudder was missing (see Appendix B). In fact, the fracture paths were virtually identical to those seen on the upper rudder failure suffered by G-BOAF in April 1989. Irregular-shaped flaps of the skin remained attached to the leading edge spar member and the PFCU attachment arm which connects the upper to the lower wedge. Some pieces of the honeycomb core remained attached to these skin fragments but had disbonded from one side or the other.

A small section at the bottom of the upper wedge trailing edge had remained and along with the apparently undamaged lower wedge clearly exhibited the presence of the repair carried out the previous year.

Again, as with the 'AF' accident, there was evidence of torsional distortion of the leading edge but not so severe as to cause tearing of the 'D' section as had occurred then. The lower remnants of skin had rubbed on the top of the PFCU arm fairing implying that, at some stage after the failure, the airflow had forced the fragments to bend downwards and outwards. The lower closing rib of the upper wedge had been distorted upwards and a substantial reinforcing doubler plate at the junction with the PFCU arm was bent outwards. It was later found that the forces which caused this had also cracked the PFCU arm machined forging.

Beyond the failures noted above, there was no additional damage to the aircraft. A detailed examination of the No 2 engine similarly revealed no abnormalities; in particular no indications to confirm that a surge had occurred nor any reason for abnormal vibration were found.

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 Laboratory Inspection of the Failed Rudder

In addition to the failure features noted in paragraph 1.12, the laboratory examination revealed four major observations which relate to a possible failure sequence.

The first was that the direction of tearing and rubbing damage visible on the fracture faces of portions of skin remaining indicated that the skins had most probably broken away in fragments (as opposed to stripping off in a single piece). The rubbing damage showed that cracks in the skin developed, presumably due to some form of aeroelastic oscillation, whilst fracture surfaces remained in contact. Where unrubbed surfaces were seen, the fracture mechanism was ductile tearing.

The second observation was that a bulge appeared to have developed in the left skin sufficient to leave a crease adjacent to the front spar and along what remained of the upper closing rib. It was reasoned that this most probably occurred when the left skin was substantially intact but disbonded from the core. Final failure had, however, been fragmentation of the skin as described above.

The third observation concerned the failure of the PFCU arm and the apparently associated upward bending of the lower closing rib. In order to generate sufficient forces to cause such distortion, it was argued that the trailing edge must have been intact. Additionally, indications were seen that the bulge noted above had extended almost back to the trailing edge and thus obviously the skin was present as far back as the trailing edge when the bulge occurred.

The fourth observation was the presence of a torsional buckle on the leading edge 'D' fairing. It was reasoned that to exert such torsional forces would imply the presence of a large, intact area at the top of the rudder combined with a relatively weak section below it.

1.16.2 Non-Destructive Testing

With the failure of upper rudder Serial No VW23, British Airways and British Aerospace re-examined the Acoustic Flaw Detection (AFD) technique used to inspect the rudders to check its effectiveness and improve as necessary. AFD essentially uses a similar concept to the ultrasonic crack detection commonly employed on solid metal components but operates at lower sonic frequencies. It also became necessary to lease a spare rudder, Serial No VW13, from Air France to maintain the British Airways fleet schedule. Before fitting to the aircraft, it was subjected to an improved AFD method which had been developed by British Aerospace to enhance the probability of disclosing hitherto undetected disbonds. This inspection revealed extensive disbond from the trailing edge and upper closing rib in several areas.

Clearly unsuitable for fitting to an aircraft, it was decided to subject the rudder to a technique known as 'Through-transmission C-scan'. Such a technique requires the rudder to be mounted in a rig with a pair of water jets spraying one on either side. Ultrasound signals are transmitted to the rudder using one jet, pass through the structure and are then received by a transducer via the other water jet. The water jet, transmitter and receptor assembly traverse the entire surface area of the rudder and any discontinuities, such as disbonds or cell collapse are displayed as 'blank' areas as the scan picture builds up. The method has extremely good resolution and is the only one currently known (other than X-ray) which is capable of detecting cell wall breakdown deeper into the core. It could not, of course, detect on which side of the rudder a disbond may be present but it was considered the least fallible and most authoritative NDT available. Such equipment is, however, large and costly and used primarily in production inspection. It was therefore necessary to transport the rudder to British Aerospace Salmesbury where a fixture had to be fabricated to accept it.

The main purpose of performing the through-transmission scan was to ratify the British Aerospace AFD technique used by British Airways. There was close similarity between the AFD and the C-scan results, in particular there were no significant areas of disbond which had not been noted by the AFD. This, together with physical inspection when VW13 was returned to France, gave confidence that the AFD was capable of detecting any significant disbonding between the core and the skins. Further refinements in the technique increased this confidence, but British Airways took the decision to subject their entire holding of rudders to the C-scan technique and to repair any defects found.

The results of this 100% inspection did not reveal any major defects but did reveal a certain amount of disbond and corrosion at the leading edge associated with moisture ingress through sealant at the hinge doubler plates. This had hitherto been unknown but was not considered to have been sufficiently advanced to have threatened the integrity of the structure. Re-inspection of the accident rudder, VW23, did show very slight indications of corrosion in these areas but again was not considered to have contributed to its failure. The C-scan results generally did not reveal any indication of significant disbonding occurring in the middle of the wedge; the majority was associated with corrosion from moisture ingress at edge members.

In order to contain the problem of Concorde rudder failure pending delivery of newly manufactured items from British Aerospace, British Airways have instituted an inspection cycle which calls (at the time of preparation of this report), for NDT checks of the trailing edge area and areas associated with repairs every four flights. After every eight flights, the entire surface of both rudders was to be subjected to AFD with no amount of disbond allowed without repairs. This was in addition to the requirements of AD 022-04-89 described earlier.

1.16.3 Hot Flatwise Tensile Testing of Coupons

The lower wedge of VW23, being intact and free of significant disbonds according to NDT, was sectioned to provide coupons for testing of the adhesive strength, both of the original manufacturing adhesive and the repair adhesive which was believed to have been applied at the same time as that used in the upper wedge. It was decided to perform these tests both at room temperature and at 90°C (a typical supersonic cruise temperature of the rudder).

The method of flatwise tensile testing required that the coupons be prepared in two ways:

1 by sectioning and removing the skin on one side, machining the core and re-bonding a new 'skin' to enable a parallel-sided specimen to be obtained and;

2 leaving both skins intact and bonding purpose-made tapered blocks to them to produce a true flatwise tensile loading. The latter method was employed for the repair patch area where the section was slender and it was necessary to test both skin bonds. It did, however, cause problems inasmuch as the blocks had to be bonded to the skin with a cold-cure adhesive which tended to fail before the specimen itself.

The results of tests on coupons at room temperature indicated that both the repair and original adhesives were at least up to specified strength although it was noted that there was a consistent difference between the strengths of the left and right original skin bonds; essentially the results were higher for the right skin. It was postulated that the reason for this lay in the fact that the right skin was the first to be bonded to the core during manufacture and that the greater control during lay up and subsequent double cure resulted in a superior bond.

Results from the specimens tested at 90°C suffered due to test block adhesive failure described above. However, although the coupons displayed a mean significant reduction in strength at this temperature to a level which would be considered below specification, some individual examples exhibited strength well above specification.

The conclusion of these tests was that there was no evidence of a drastic reduction in flatwise tensile strength of either the original or repair adhesives, hot or cold, which could account for the in-flight failure of VW23. It should be noted that the manufacturing and repair adhesives themselves or the lay up and curing processes were not necessarily identical to the upper wedge but, in the absence of any suitable material from this source, were the closest that could be tested and had undergone the same duty cycles.

1.16.4 Instrumented Flight Trials

It was considered prudent to verify the manufacturer's original test data concerning fatigue stresses on the rudders, of which the most potentially damaging were calculated to be the sonic effects from the engine nozzles, particularly at take-off power.

To this end the rudders of G-BOAG were fitted with a series of strain gauges and accelerometers coupled to a suitable recording device. The figures obtained from the recording were subjected to analysis over a number of routine flights by this aircraft. Temperature sensitive tapes were also applied to record the maximum skin temperatures experienced by the rudders.

The conclusion of this analysis was that the strain and acceleration levels were similar to those measured during ground testing in 1974 which suggested that the rudders would be free from sonic fatigue damage for the aircraft design life. Problems were encountered with adhesion of the temperature tapes and their programme was curtailed after only one flight. However, the limited results obtained showed that the temperatures were within the expected range.

1.16.5 Effects of Repair Materials on Bonding

In September 1992, as part of the ongoing British Airways programme of inspection and repair of Concorde rudders, upper rudder VW20 was inspected by through transmission C-scan. This inspection found only one area requiring attention, a small disbond on the left side apparently associated with mechanical damage. This was addressed by cutting out a disc of skin around the area, applying filler and re-bonding a repair patch. The rudder was returned to service after having extensive post-repair AFD tests which showed no indications of additional disbond having been introduced. The same negative results were recorded when the rudder was re-checked after eight flights according to British Airways' own schedule for NDT examination (see paragraph 1.16.2).

However, after a further eight flights the same AFD inspection found a large disbonded area on the right side skin directly opposite the repair. Removal of this area confirmed the disbond between the skin and the adhesive film but also showed varied discolouration of the adhesive film. This discolouration could be seen as a darkening of the film over the disbonded area with the original repair patch disc 'mirrored' as a ring of lighter grey. Furthermore, the adhesive film appeared 'quilted' between the cells as though the adhesive had been plastic at the time of the disbond. The overall impression was that the repair to the left skin had in some way affected the adhesive on the right skin over an equivalent area and that this had grown to a larger diameter over the 16 flights since repair.

Laboratory examination of minute quantities of powdery deposit found in the honeycomb cells showed the presence of chromium and sulphur which strongly suggested the presence of the chromic/sulphuric acid anodising solution used as part of the repair preparation procedure. Such chemicals should not have entered the core, and any that had done so should have been washed out.

British Airways commissioned a metallurgical investigation of the possible effects of materials used during repairs. The conclusion of their investigation was that this was probably not an isolated occurrence or, indeed, limited to British Airways and that there were several chemicals used to prepare the metal for bonding which could lead to serious problems if inadvertently allowed to remain trapped in the structure. The most aggressive agent used which might affect the adhesive film itself was thought to be Methyl Ethyl Ketone (MEK). This was used to degrease and clean components at various stages of the repair. When samples of bonded structure were placed in boiling MEK and subjected to a heating/cooling cycle, leaching of colour and softening of the adhesive was observed. Such heating would occur at the supersonic cruise temperature of approximately 90°C but the adhesive appeared to re-harden when returned to normal temperature.

Consideration was also given to the possible effects of residual chromic/sulphuric acid, from the anodising process, in the structure. Although not directly attacking the adhesive, its aqueous and corrosive nature could lead to disbonding of the skin or core. Further analysis also noted that any residual liquid which might boil at the temperatures and pressures reached during the curing process or in-service within the core would exert considerable vapour pressure inside the structure and thus a mechanical as well as chemical disbond effect could occur.

1.17 Additional information

1.17.1 British Airways Repair Procedures

The repair to VW23 upper rudder went considerably further than the guidance contained in the constructor's Structural Repair Manual for repairs to honeycomb bonded structures. In such cases an airline with the resources of British Airways would task their own structural engineers to design a suitable repair scheme. Although not always strictly necessary under the terms of the approvals granted to them by the Civil Aviation Authority (CAA) it was common practice to submit the drawing to the manufacturer who would advise whether they had any technical objection to the scheme.

The repair carried out on VW23 therefore followed the above procedure and an appropriate letter was obtained from British Aerospace agreeing to the principle of the repair but recommending a different method of re-attaching the trailing edge extension. In fact, British Airways eventually elected not to refit the extension at all. The subject repair was the most extensive carried out on a Concorde flying control surface to that date and involved replacement of the honeycomb core along the entire length of the upper wedge trailing edge (see Appendix C).

Essentially the repair was accomplished by cutting back and removing the right side skin over a width of approximately 25 cm. The exposed honeycomb was then mechanically removed and the remains of the adhesive on the left skin abraded away. The edges of the remaining core were solid potted and sealed in an attempt to prevent ingress of the surface preparation materials used in the next stage of the process.

The surface was then degreased and cleaned using MEK before application of a chromic acid anodising process known as 'Selectron'. British Airways stated that they have now rewritten the procedures to clarify and expand on the actions necessary to prevent the ingress of 'repair preparation materials' into the honeycomb core. However, they have also stated that, to the best of their knowledge and belief, the practices as now laid down were those followed by the tradesman involved with the repair to VW23.

Following the metal preparation processes, a block of honeycomb was bonded to the left skin using AF163, a 120°C-cure adhesive and to the old core using a foaming adhesive. When fully cured, the new core was sanded to the correct, tapered trailing edge profile. Further cleaning and anodising was carried out in preparation for the final fitting of the closing plate (new right-hand skin) which was hot-bonded to the new core and overlapped onto the original right skin. Anti-peel rivets were used at the latter interface. Various detail processes were then specified to completely seal and finish the repair.

The foregoing is necessarily an abbreviated summary of what is a lengthy and involved process.

1.17.2 Previous Cases of Rudder Failure

On 12 April 1989, Concorde G-BOAF suffered an almost identical upper rudder failure to the one described in this report and following which the aircraft also landed without further incident. A formal AAIB report on the accident (AAR 6/89) concluded that the failure had occurred due to corrosion and disbond of the skin/core bond at the trailing edge which had slowly grown to a critical size before rapid propagation to failure. The corrosion was thought to be associated with moisture ingress into the core through rivets attaching the modified trailing edge. As with the accident to G-BOAB, most of the rudder surface was not recovered but the above conclusions were based on evidence of corrosion on the small fragment remaining of the trailing edge of the upper wedge and the complete lower wedge.

As a consequence of this failure, the CAA and French Direcion Generale de l'Aviation Civile issued AD 022-04-89, which mandated British Aerospace Alert

Service Bulletin SST 55-A-007. In essence, this called for a repeat NDT check of the rudder surfaces every 1,210 flying hours or 15 months coupled with a 'tap' test of the trailing edges every 520 hours or 7 months. The 'tap' test was a long established method of checking a bonded structure by tapping with a suitable coin and listening for the duller sound of a delaminated area.

On 4 January 1991, G-BOAE experienced a lower rudder failure in which the starboard skin of the upper wedge stripped away together with a triangular-shaped piece of the trailing edge (see AAIB Bulletin 9/91). Yet again, the physical evidence was largely lost but circumstantially it appeared that latent corrosion and disbond originating at the trailing edge was probably responsible. It was necessary to examine why such defects had not been detected since by now British Airways were well established on the programme of regular 'tap' and NDT checks required by the AD. It was found that this particular lower rudder had missed its required checks due to an administrative oversight.

1.18 New investigation techniques

None.

2 Analysis

2.1 Conduct of the flight

The reason for the momentary vibration felt at FL 530 and Mach 2 remains uncertain. In the absence of any cockpit indications or the ability to view the external surfaces of the aircraft, the crew followed a logical diagnostic procedure and it cannot be determined with absolute certainty whether this vibration was associated with the rudder breakup or, indeed, a co-incidental engine surge. No explanation can be offered as to why the vibration appeared to increase as the No 2 engine throttle was advanced but in the circumstances it is felt that the crew's actions in subsequently shutting down this engine were reasonable.

2.2 Engineering analysis

The two previous cases of Concorde rudder failures described in paragraph 1.17.2 were essentially ascribed to moisture ingress at the trailing edge causing corrosion and disbond which reached a critical size beyond which catastrophic failure would occur. Reasons for the ingress were thought to have been established and the second failure was ascribed to accidental omission of the NDT procedures.

The failure on G-BOAB was more difficult to understand, for it had received its prescribed checks revealing corrosion and disbonds which had been addressed by a repair scheme implicitly approved by the manufacturer. Yet only some 254 flying hours later it failed in a manner strikingly similar to the first upper rudder failure on G-BOAF in 1989.

It was unfortunate, if inevitable, that the vital physical evidence which may have revealed the cause was never recovered. The pieces of rudder which remained on the aircraft were insufficient to give any hard information on the nature of the failure but it appears almost certain that some form of loss of skin to core bond, growing to reach a critical size, was the basic failure mechanism as opposed to some other external influence. The following analysis postulates possible reasons for the presence of such a defect and discusses measures which can, or are, being taken to eliminate them.

2.2.1 Defects were not discovered and therefore not repaired at last workshop visit

There is no doubt that significant efforts were made by British Airways following this accident to improve both their knowledge of NDT and their equipment. They are now confident that they are using equipment capable of detecting any significant areas of disbond. They also unilaterally drastically reduced their repeat inspection times for both the rudders and elevons to a point well below that required by the CAA or British Aerospace.

It is possible that the relatively inferior technique used to inspect the VW23 upper rudder may have missed a defect deeper into the structure. However, the fleetwide through-transmission C-scan inspections did not reveal any significant problems away from the panel edges and so it was unlikely that there was an undiscovered defect located more towards the centre of the control surface.

2.2.2 The repair was inadequate either in design or implementation

As stated in part 1 of this report, the repair scheme was devised by British Airways and had been referred to British Aerospace who found no technical objection to it. Even with hindsight it is difficult to fault the theory of the repair but translating its requirements into workshop practice would involve high quality skilled labour and great care due to the size and nature of the renewed structure.

Testing of coupons cut from the repair on the lower wedge did not reveal any fundamental flaw with the adhesion and it is assumed that this applied to the upper wedge as well. A small area (about 15 mm diameter) indicating lack of core/skin contact was found in the small piece remaining of the upper wedge repair adhesive but it was impossible to say whether that was an isolated feature or indicative of more general lack of skin/core contact.

It can be seen from paragraph 1.16.1 that detailed analysis of the failure indicated that the trailing edge was an intact structural member at the time when a bulge developed in the right skin and would thus lend support to the theory that the repair itself was not the location of the initial critical defect.

2.2.3 The repair preparation materials degraded the original structure

The research carried out as described in paragraph 1.16.5 emphasised the need to ensure that all of the liquids used in preparation for the repair be kept from ingress into the original structure or from remaining in the repair itself. The potentially damaging effects of MEK and chromic/sulphuric acid mixture were noted as was the purely mechanical pressures exerted by a boiling liquid.

The potential for allowing ingress into the good structure certainly existed if the masking and sealing of the core was anything less than 100% effective and, over the length of the repair on VW23, this would have been difficult to achieve. The current procedures drawn up by British Airways would seem to represent the most stringent precautions which can reasonably be taken but the repair to VW23 was performed without the benefit of these rewritten procedures. Over-liberal application of fluids coupled with imperfect sealing could result in liquid remaining trapped in one or more honeycomb cells in sufficient quantities such that some still remained after the visible surfaces appeared dry.

What is clear is that some fluids were leaching into the structure despite the endeavours to exclude them. The repair to VW20 (see paragraph 1.16.5) had apparently allowed chromic/sulphuric acid into the core when the procedures should theoretically have prevented it. Had such evidence been found in the structure of VW23, it would have been a strong indicator that accidental ingress of repair materials was the most likely cause of the failure.

2.3 Summary

Since much of the above analysis is dependent on circumstantial or negative evidence, it is difficult to pronounce categorically on the cause of the failure of the subject rudder. British Airways improved their inspection procedures and reduced the periods between inspections in response to the first two rudder failures to identify and contain the disbonds associated with the life of the original structure. There had been no reason to examine the airline's repair procedures until the investigation of the VW23 failure, which occurred just 254 flying hours after a major repair. Subsequently the investigation of disbond opposite a recent repair on rudder VW20 highlighted the potentially damaging effects of the repair preparation fluids. It is considered that a lack of appreciation of these effects, possibly at repair workshop level, may have led to trapped materials being responsible for the initial disbond and its rapid growth to critical size.

Clearly, the British Airways programme of replacement with newly manufactured rudders should obviate a recurrence of this problem on the British Airways Concorde fleet but there are other components on the aircraft which are of similar structure, for example the elevons. Indeed there is evidence that the elevons are equally vulnerable to the same failure mechanism as the rudders and require similar care with inspection and repair.

3 CONCLUSIONS

(a) Findings

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

(ii) In the absence of any clear indications of the true nature of the problem, the vibration was diagnosed by the crew as a No 2 engine surge and under the circumstances the decision to shut down this engine as a precaution was reasonable.

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

(iv) The upper rudder, upper honeycomb wedge broke up whilst in supersonic flight. The severe vibration felt throughout the airframe as it decelerated through Mach 1.4 was almost certainly caused by final separation of most of the wedge.

(v) The crew had no indication of the rudder failure until it was reported to them by ground staff after landing.

(vi) The failed rudder had been subjected to extensive repair to its trailing edge some 254 flying hours previously. The repair was devised by British Airways who had also submitted the scheme to British Aerospace for comment. British Aerospace had found no technical objection to the repair scheme and so had implicitly deemed it an appropriate repair.

(vii) There was insufficient material recovered from the subject rudder to draw a firm conclusion as to the reason for its failure. It was concluded, however, that the failure sequence probably commenced with an internal bonding defect developing to a critical size, following which complete separation rapidly followed.

(viii) Insufficient evidence was recovered to meaningfully judge the quality of the workmanship employed throughout the repair. However, the bond strength achieved in the elements remaining for examination was adequate and only one small area of lack of adhesion was detected.

(ix) Samples of structure taken from the lower wedge did not suggest significant impairment of the adhesive properties of either the repaired or original bond.

(x) Since post-accident 100% inspection of British Airways Concorde rudders found no evidence of significant defects away from the edges of the panel, it is considered that the repair had addressed all such damage to the accident rudder and that failure was unlikely to have been caused by an undetected disbond at that time.

(xi) Post-accident studies have highlighted the possible damaging effects of residual fluids used during the repair process if accidentally allowed to remain within the structure after 'closing-up'.

(xii) The large size of the repair to the accident rudder created a commensurately high risk of ingress of repair fluids into unrepaired structure.

(xiii) Evidence was found on a smaller repair on another rudder which indicated that contamination by repair materials had taken place.

(xiv) British Airways' policy of fitting newly manufactured rudders should preclude further rudder failures of this type on their Concorde fleet. However, other items of structure, particularly the elevons, are of similar construction, and so are prone to similar problems and warrant some consideration if there are no plans to replace them.

(b) Causal factors

(i) The bonded honeycomb structure of the upper rudder, upper wedge broke-up as a result of delamination of the skin/honeycomb bond.

(ii) The reason for the presence of the delamination could not be established with certainty but the balance of evidence pointed to weakening of the skin/honeycomb bond, brought about by the accidental ingress of preparation materials into the core during the course of a major repair performed some 254 flying hours before the event.

(iii) The large size of the repair to VW23 would have made successful application of the repair procedures all the more challenging and sealing of the original structure to prevent the ingress of preparation fluids more difficult.

(iv) The potential for repair preparation materials to adversely affect the skin/honeycomb bond strength was not generally appreciated before this accident.

4 Safety Recommendations

The following safety recommendations were made to the United Kingdom Civil Aviation Authority and the French Direcion General de l'Aviation Civile on 13 April 1992:

4.1 They revise the content of Airworthiness Directive 022-04-89 and associated British Aerospace Alert Service Bulletin 55-A-007 to decrease the inspection intervals to prevent the possibility of further failures of Concorde rudder bonded structures. Particular attention should be drawn to rudders with existing repairs which should be re-inspected within a very short time. [Recommendation 92-23]

4.2 They investigate, in conjunction with the operators and manufacturers, improved NDT inspection methods for Concorde honeycomb bonded structures. In particular, devices which seek to replace the manual 'tapping' method by electronic instruments appear promising and should be given serious consideration. [Recommendation 92-24]

4.3 They re-examine with the manufacturers and the operators the approval and quality control procedures for large repairs and with the manufacturer the relevant chapters of the Structural Repair Manual. [Recommendation 92-25]

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