Concorde Type 1 Variant 102, G-BOAC, 8 October 1998 at 1300 hrs

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Aircraft Type and Registration:	Concorde Type 1 Variant 102, G-BOAC
No & Type of Engines:	4 Rolls-Royce Olympus 593/610 turbojet engines
Year of Manufacture:	1975
Date & Time (UTC):	8 October 1998 at 1300 hrs
Location:	Over North Atlantic Ocean, approx. 47°N 50°W
Type of Flight:	Public Transport
Persons on Board:	Crew - 9 - Passengers - 62
Injuries:	Crew - None - Passengers - None
Nature of Damage:	Portion of lower rudder control surface separated
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	54 years
Commander's Flying Experience:	12,850 hours (of which 8,000 were on type)
	Last 90 days - 108 hours
	Last 28 days - 40 hours
Information Source:	AAIB Field Investigation

History of the flight

The aircraft was operating a scheduled passenger service between London Heathrow Airport and New York JFK Airport. While cruising at Mach 2.0, FL 547, close to 50°W off the coast of Newfoundland, the crew felt 'vibration plus a thump'. Scrutiny of the instruments and available indications revealed nothing untoward. The commander suspected that a section of flying control might have become detached and went aft to conduct a visual inspection. At that time, the aircraft had about 38 tonnes of fuel on board and some 1 hour 22 minutes to destination.

Only the outer and middle elevons are visible from the cabin and they were seen to be intact and reacting normally. There was a continuous slight vibration felt in the cabin, similar in feel to light turbulence.

As the aircraft was otherwise performing normally, the commander elected to continue supersonically to the planned destination. The normal flight profile was followed up to the Deceleration Point. In anticipation of increased vibration during transonic flight, the crew reduced thrust to idle power below Mach 1.8 to expedite passage through that regime. At around Mach 1.0, there was more noticeable vibration felt. This subsequently decreased as the aircraft reduced speed further.

The remainder of the flight and the landing were normal, the aircraft landing with about 15 tonnes of fuel remaining. During taxi-in, ATC reported that a piece of the aircraft's rudder appeared to be missing.

Flight recorders

The data from this flight was examined using the Operator's Quick Access Recorder; this records substantially the same parameters as the Flight Data Recorder (FDR). The FDR and Cockpit voice recorder were not replayed. There were no abnormal indications from the data to indicate when the rudder detachment took place. The vibration felt in the cabin was not detected by the three axis accelerometer.

Handling characteristics with partial detachment of a rudder control surface

Each rudder control surface is made up of two independently constructed 'wedges' which are physically linked, each linked pair being positioned by a single Powered Flying Control Unit (PFCU). Previous experience from incidents of partial loss of one rudder wedge has shown that the aircraft's handling characteristics are not significantly degraded after such an event. In order to keep all flight crew members fully appraised of the experience to date, the operator has issued a Flight Crew Notice, giving detailed guidance on the handling of such an event. The investigation team also received a presentation from the manufacturer in which aerodynamic test data and theory established that the 'fail-safe' design objective would be met in the case of failure of any single rudder wedge.

Description of the rudder structure

The Concorde aircraft rudders and elevons are similar in construction although the former were and remain the design responsibility of BAE Systems (was BAe) whilst the latter are the responsibility of EADS (was Aerospatiale), France. In order to maintain the stiffness required of a slender cross-section with the minimum weight, the surfaces are of metal honeycomb construction faced with aluminium alloy skins, chemically milled locally to achieve the optimum skin thickness. The skins are bonded to the honeycomb core using an autoclave-cured film adhesive, this process being carried-out under pressure conditions to ensure positive contact of the skin to the core.

Rudder arrangement

In order to cater for the loss of function of a single PFCU, the rudder is split into two totally separate upper and lower sections, each actuated by independent PFCU's. In addition, each upper and lower rudder section is constructed of upper and lower 'wedges', linked by a substantial structural member called the PFCU arm, which forms the attachment for the PFCU to move the surface in response to control inputs. The reason for this is to provide a degree of structural redundancy against failure of one wedge so that such a failure would only compromise roughly a quarter of the total rudder area.

Following the in-service failure of three original-build rudder wedges, the operator commissioned British Aerospace (BAe) to manufacture new upper and lower rudders to completely re-equip their fleet and prevent any further failures. The new rudders were based on the original design with the addition of minor changes from in-service experience and used alternative approved materials where the originals were no longer available.

Probably the most important change introduced by the new rudders was to the construction of the trailing edge. In the original design the honeycomb core extended completely back to the trailing edge with a thin closing member simply to seal the core from the atmosphere. This resulted in a somewhat 'blunt' trailing edge but did not use any mechanical fasteners. A modification was developed shortly after the aircraft entered service to fit a sheet-metal wedge extension to the trailing edges of the rudders and elevons to decrease aerodynamic drag. This required drilling holes through the skin and into the core cavity before fitment of blind fasteners. Previous incident investigations concluded that the loss of sealing at these fasteners is generally believed to have led to moisture ingress and consequent corrosion and disbonding of the trailing edge with the passage of time.

On the new-build items, the manufacturer took the opportunity to re-design the trailing edge by extending the skins aft and incorporating a solid aluminium full-length trailing edge member (see Appendix 1). This was bonded to the skins and the core and, after curing of the wedge, holes were drilled and rivets squeeze-formed to reinforce the assembly. It should be noted that the holes and rivets do not penetrate the core cavity and that information from the manufacturer advised that the rivets are capable of taking the loads even if the trailing edge member suffers complete disbond along its length.

The lower rudder involved in this incident, Serial No.BDH0909B, was one of the new-build components. During manufacture of the lower wedge, post-cure Non Destructive Examination (NDE) revealed a disbond of the trailing edge member to the left side skin over a length of 310 mm. The disbonded section of the member was cut out and a replacement section bonded-in before the right skin was added.

History of NDE of the rudder

The failed rudder was manufactured in June 1994. In addition to the trailing edge repair described above, two further small areas of skin/core disbond were found and repaired by the manufacturer before the final skin bond. Several NDE processes were performed during the manufacturing process, including an ultrasonic through-transmission 'C' scan (see later) of the entire wedge after the final cure, prior to drilling and forming of the rivets in the edge members and the trailing edge. A new in-service NDE inspection cycle was devised for the new rudders by BAe, promulgated in Service Bulletin (SB) 55-010, which called-for an initial frequency of every 16 flights up to 160 flights total, thereafter every 65 flights until 420 flights achieved, whence the frequency dropped to every 160 flights. The technique called-for a Mechanical Impedance Analyser (MIA - see later) check of the entire surface, together with additional techniques to confirm any MIA indications. The rudder was fitted to G-BOAC on 23 July 1995 and had accumulated 798 Landings and 2,499 hours in-service and would therefore have had at least 16 complete MIA scans up to the time of the failure, although the majority of these would have occurred early in its life. The last of these checks was completed on 9 May 1998 and included a detailed visual inspection.

In addition to the above checks, the operator had introduced a visual check every 16 flights to identify defects and repairs on the rudders and elevons. Where repairs were found, the MIA technique was called-up to inspect the repaired areas and the equivalent area on the opposite skin for disbond. It was considered preferable to require an examination each time and thus ensure good visual coverage of the entire surface, rather than provide NDE staff with a 'register' of repairs to be inspected. The last of these inspections was carried-out on 25 September 1998, 5 flights before the failure. None of the above inspections had revealed any defects and hence the rudder had not been subject to any in-service repairs, nor was it carrying any acceptable defects, such as detected disbonds within the limits of the structural repair manual.

Examination of the aircraft

Examination of the aircraft was carried out in New York by the operator's engineering personnel, prior to fitment of a replacement lower rudder. It was apparent that about 60 to 70% of the lower wedge was missing and that the remainder of the core had disbonded completely from the left skin (see Appendix 2) Surface damage was present on the upper face of the tailcone (as had been noted before with previous rudder failures) but there was some additional and, in places, heavier damage to the upper face of the stub fairing which sits directly below the lower rudder and is attached to the tailcone. It was also noted that this fairing had lifted away from the tailcone at its rearmost locating bolts such that the fairing/rudder gap had been decreased.

Subsequent examination of the rudder

After shipment back to the UK, the failed rudder was sent to DERA Farnborough for detailed examination under the supervision of the AAIB. Three distinct areas of investigation were identified requiring particular specialist attention:- metallurgical examination of metal fractures, adhesion failures and an appraisal of the methods used by the operator to inspect the structure.

1 Metallurgical examination

Although this was the first case of a failure of a lower rudder, lower wedge, the pattern of failure was broadly similar to the previous incidents (all occurring on original-build rudders) inasmuch as the greatest loss of material occurred away from the edge supported by the PFCU arm. Approximately 40% of the lower closing rib remained. The left skin had completely disbonded from the core and the lower closing rib, but the right skin, away from the fracture line, appeared to be still well adhered. As with the previous cases, there was the same characteristic evidence of violent 'flapping' of the remaining wedge material after the initial break-up. This had left signs of fatigue around fasteners and on some of the skin fracture faces. There were no signs of internal corrosion of the skins or honeycomb core.

At the same time, the stub fairing from below the lower rudder was received for examination. This bore evidence of both light and heavy contact with the rudder lower closing rib. However, these marks were contained within the forward 60% of the length from the front of the fairing, with a very distinct edge where the paint had been worn away and the metal marked with a series of many 'striations'. This was probably due to contact with the edges of the rudder skins and/or the closing rib during left-and-right movement of the rudder. It should be noted that the area of most severe marking did not coincide with the fracture edge of the remaining closing rib. ie The heavy rubbing of the fairing had been caused by structure which had subsequently detached in-flight, indicating that there had been a further fracture of the closing rib after the marks had been caused. Whilst this implies that the closing rib and skins must already have been broken to have allowed the heaviest marks to have been made in the first place, it could not be established whether these overlaid damage caused before break-up.

The reason why the fairing had become partially detached at its aft attachment was that the bolt between it and the tailcone was missing. The attachment fitting further forward, whilst still retaining its bolts, was loose, indicating a long-term vibratory environment. A similar problem to this had been encountered before on another aircraft and was the subject of Concorde Service Newsletter No 0234-53 dated 7 November 1997, advocating a special inspection for this attachment. The operator responded to this by amending the Aircraft Maintenance Schedule to include a note to pay special attention to the area with reference to the SNL.

2 Adhesive observations

It is necessary to briefly define the terms 'adhesive failure' and 'cohesive failure'. In the case of adhesive failures, the bond between the adhesive and the metal components is the mechanism by which parts separate and which could, but does not necessarily, indicate a poorly prepared or contaminated metal surface. Cohesive failures occur when parts separate due to failure within the adhesive layer itself, with adhesive residue remaining on both metal parts. This would normally indicate a satisfactory bond, assuming that the adhesive was sufficiently strong. Test specimens are invariably made at the same time as manufacture of bonded components, using the same materials and undergoing the same cure cycles. Because the rudder wedges are exposed to at least three cure cycles, sufficient specimens are made to ensure that testing of an individual specimen can be undertaken at each stage, after each cure, to prove that the mechanical properties of the adhesive meets and maintains the required specification. In the case of the subject wedge, two extra cures were required because of repair concessions.

The destructively-tested specimens had been retained by the manufacturer and were examined by DERA, together with the data obtained. With one or two anomalies which could not be explained, the condition of the specimens appeared satisfactory and the bond strength figures within specification. The remains of the rudder generally showed cohesive failures between the skin and core with a few small areas of adhesive failure evident near the leading and trailing edges and lower closing rib, some associated with rivet holes in metal/metal joints. There were no signs of corrosion.

3 NDE observations

As mentioned previously, the primary routine NDE instrument employed to inspect the rudders (and elevons) is a Mechanical Impedance Analyser (MIA) which detects changes in local stiffness of the component caused by disbonded areas. This is a relatively laborious task involving several different machine set-ups depending on the area inspected, due to the different skin thicknesses. If the MIA records a defect, then the area is required to be re-examined using a 'woodpecker' tap-test device and/or an ultrasonic scan. All three of these techniques are capable of detecting disbonds of the skin/core bond but none are capable of locating defects in areas which feature a metal/metal bond, such as the skin to trailing edge member joint or the repaired areas where a repair patch overlaps the original skin. Since the incident rudder had no in-service repairs and only small production repairs not requiring external plates, the latter was probably not relevant but the inability to detect disbonds at the trailing edge and upper-and-lower closing ribs is a cause for concern. Because of the lack of any suitable technique, no requirement existed for detection of metal/metal disbonds and none had been found.

It was also noted that the surface had several layers of paint which resulted in areas where the paint thickness exceeded 0.5 mm and it was felt that this could compromise the sensitivity of the MIA and ultrasonic techniques employed by the operator. However, tests conducted by them indicated that there was little or no reduction in sensitivity for paint thickness up to approximately 0.4 mm. No upper limit of allowable paint thickness has so far been established, either for the NDE sensitivity or for the amount that can be applied. Because of concern regarding the use of chemical paint-strippers on bonded components, application of paint on the rudders and elevons has tended to become cumulative, with only a manual 'flatting' of the previous coat being carried-out. It is understood that the operator is investigating the use of mechanical abrasive techniques to remove unwanted layers of paint.

Examination of the upper wedge

The upper wedge of the failed rudder was intact and undamaged and this was subjected to a full through-transmission 'C' scan (an ultrasonic technique which uses water jets to transmit and receive the signal) at BAe Filton. This indicated the presence of a significant area of disbond in the lower aft corner, roughly where the lower closing rib met the trailing edge member. Other NDE techniques confirmed the presence of a disbond, adjacent to rivets in the closing rib, but with some migration into the core and trailing edge member. Before cutting-out the defect for examination, helium gas was introduced into the disbonded area and a leak detector sensitive to helium was used to search around the panel edges to see whether there was any leak path from the outside into the disbonded area; none was found.

After cutting open, it could be seen that the disbond had occurred between the skin and a sacrificial strip forming part of the lower closing rib (see Appendix 2). Although roughly oblong in general shape, a likely point of origin for the disbond was an adjacent rivet through the skin, sacrificial strip and closing rib, thereafter progression occurring diagonally aft and upwards towards the core and trailing edge member. Close examination of the rivet hole showed that the metal immediately around the hole was slightly 'dished', due to deformation of the metal consistent with excessive pressure being applied during installation of the rivet. There was no sign of corrosion.

Although the upper wedge had not been manufactured co-incidentally with the lower wedge it had obviously been subjected to the same duty cycles and environmental effects, so the decision was taken to extract a representative sample from a sound section of the upper wedge for destructive testing to establish the bond strength. The result of this test indicated that the bond strength exceeded the minimum specification and was considered satisfactory.

Resonance testing of rudders

Although resonance testing of the new-build rudders had taken place during design and production, this had taken place with the component freely suspended. It was suggested that the resonant characteristics of both new and original build standard lower rudders should be undertaken with the units mounted on the aircraft and with hydraulic power applied to compare their characteristics. This was done and no significant differences were found. Additionally, BAe took the opportunity to examine the interaction of the tailcone with the lower rudder in terms of the possible transfer of excitation frequencies (the tailcone experiences a fairly harsh acoustic environment) into the rudder. The results of this testing identified a frequency at which vertical motion of the tailcone excited an out-of-phase response in the lower rudder, ie when the tailcone moved up the rudder moved down. The testing could not establish what the amplitude of any such motion might be and hence the degree to which the rudder/stub fairing gap might be reduced.

Technical and operational history of G-BOAC

G-BOAC was involved in the failure of a No 3 left elevon on 25 May 1998 (see report in this bulletin issue). The operator was asked whether 'AC had been undertaking flights atypical of the rest of the fleet, which could indicate that the two events might be related. The answer to this question was negative. However, two events from its recent history were singled-out for further study:- two cases of uncommanded in-flight thrust reverser partial deployment and a series of 50 flights with the tail-wheel doors removed due to damage. The two reverser partial deployments, occurring in November 1997 and July 1998 took place during supersonic and subsonic flight respectively. Both from crew reports and DFDR data, the events appeared to have had minimal effect on the aircraft's flightpath and hence on loads in the fin/rudder structure.

The flights without the tail-wheel doors fitted had taken place about 18 months before the rudder failure. Five flights without the doors were notified as permissible in the Minimum Equipment List but delays in repairing the damaged doors meant that the operator had sought, and obtained, clearance from BAe to operate for this much longer period. The theoretical study of tailcone/fin resonance described above had also identified the possibility of generation of a standing wave in the tailcone due to the effect of airflow across an aperture into a closed space (Helmholtz resonator), caused by flight without the doors. It was felt significant because the calculated frequency of the wave was close to the frequency which could excite the tailcone with a vertical motion out-of-phase with the rudder. However, after some deliberation, it was generally agreed that the flights had occurred too long before the rudder failure for such a scenario to be valid. It was difficult to believe that damage sufficient to compromise the structure had been missed by the numerous visual and NDE inspections which had taken place in the intervening period.

Discussion

As with the three previous rudder failures and the elevon failure mentioned, this investigation was severely hampered by the irretrievable loss of the structure containing the origin of the failure. The first rudder failure was ultimately thought to have had its origin in the trailing edge modification which, over a period of years, allowed moisture ingress into the bonded core. Problems with inspection and repair were thought to have been responsible for the other two.

However, in this case none of the above factors would appear to be relevant. The rudder had had no in-service repairs, the trailing edge was to a new design and the assembly was only some four years old. The improved, and more frequent, NDE and visual inspections should have been able to detect a growing disbond before it reached the critical size at which sudden, complete failure is predicted. As with the elevon, though, this still appears to be the most likely mechanism, despite the fact that no explanation was forthcoming as to the nature of the original defect or why it was not detected by NDE. Anomalies were found with such items as the stub fairing and the aircraft's recent operational history, but it was not possible to prove any realistic scenario connecting these to the rudder failure. Equally so, the possibility of mechanical damage having occurred due to collisions with ground equipment would appear to be remote.

At the manufacturing stage, great care is taken to prevent defects which could propagate in-service, however the fact that such a defect was found in the upper wedge is witness to the fact that it can and does happen. Neither the inspections during manufacture, nor subsequent in-service NDE detected any presence of the defect, probably because it may have originated largely in a metal-metal bond which was not inspected using the in-service MIA. There was no requirement at the time for an inspection to cover this aspect - the defect became apparent after close inspection of the 'C' scan conducted as part of this investigation.

The defect in the upper wedge appeared to be associated with a rivet which was formed after bond curing. Because it was known that, if a rivet were to be formed by the traditional process using a hammer and dolly, the relatively uncontrolled impacts could shatter the surrounding adhesive bond, BAe had specified a method of 'squeezing' the rivet hydraulically using a defined pressure. There were some indications that the pressure used may have been excessive. As stated previously, BAe advised that the rivets alone can withstand the flight stresses even if the metal-metal bond failed completely. However, adhesive experts are aware that a cracked bond can become an area of weakness in the adhesive film and lead to propagation under normal loading in a manner analogous to the stress-raising properties of a crack in notch-sensitive metals. This could explain why the disbond appeared to be propagating into the core to skin bond. A further problem is that the presence of the rivet can hold even disbonded surfaces together so tightly that NDE has difficulty in determining that a disbond is present. The number of rivets in the structure was significantly increased by the revised trailing edge design.

Conclusion

There is nothing other than purely circumstantial evidence to suggest that the process of forming rivets in the bonded structure led to a local disbond, which spread into the core and ultimately led to failure. However, as with the elevon failure, it is felt that the failure mechanism most probably involved some form of small disbond starting to grow after manufacture. The object of the stringent NDE regime was precisely meant to detect such defects in good time before they reached a critical dimension and it is in this field that the most significant steps can be taken to prevent further failures. The revised trailing edge design introduced a significant area of metal-metal bonding which could not be inspected in-service by the current techniques and it could have been there that a defect originated, growing in size and spreading into the core cavity. With hindsight, it is perhaps unfortunate that the final 'C' scan of the wedge took place before the rivets in the trailing edge members were formed, as it appears that this was the best, if not the only, way of detecting a localised disbond in the trailing edge member caused by the riveting process. Even this method would, however, be incapable of detecting disbonds in the upper and lower closing member/skin joints or the closing member/core bonds.

As with the elevon failures, the aircraft has demonstrated the effectiveness of its design philosophy, inasmuch as the failure of a rudder wedge remained limited to that wedge and the effects on controllability were minimal, apart from varying levels of vibration felt by the crew. However, this rudder failure is perhaps of even more concern than previous failures of either control surface, because it was a relatively low-time component which had not been subjected to in-service modifications or repairs, either or both of which appeared to have contributed to previous failures. The AAIB intend to remain in contact with the manufacturer and the operator to monitor whether the new NDE techniques under development reveal a pattern of hitherto undetected defects.

Any recommendations regarding improved NDE methods have been covered in the AAIB Bulletin report EW/C98/5/8 which dealt with the earlier failure of No 3L elevon, since reliable NDE seems to be the major tool in preventing failures of either component. An additional Safety Recommendation is, however, considered appropriate in view of the particular problems with location of the rudder stub fairing. Although it could not be proved to be a factor leading to the rudder failure, it is recommended that:

Safety recommendation 2000-19

The Civil Aviation Authority should require periodic inspection of the Concorde rudder stub fairing attachmnents.

Additional information

At the time of preparation of this Bulletin, the AAIB have been advised that, during investigation of a suspected skin/core disbond on a new-design lower rudder lower wedge, the manufacturer has discovered that the lower closing member had disbonded from both the core and the skins. The rib remained attached by the mechanical fasteners.

All remaining new-design rudders are currently being inspected by the airline with assistance from the manufacturer. AAIB are continuing to monitor the investigation.