Concorde Type 1 Variant 102, G-BOAC, 25 May 1998 at 1850 hrs

AAIB Bulletin No: 12/2000 Ref: EW/C98/5/8 Category: 1.1

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):	25 May 1998 at 1850 hrs
Location:	60nm north of Isles of Scilly, 51° 08' N 006° 38' W
Type of Flight:	Public Transport
Persons on Board:	Crew - 11 - Passengers - 53
Injuries:	Crew - None - Passengers - None
Nature of Damage	No 3 Left elevon honeycomb wedge separated
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	49 years
Commander's Flying Experience:	14,926 hours (of which 952 were on type)
	Last 90 days - 106 hours
	Last 28 days - 44 hours
Information Source:	AAIB Field Investigation

History of the flight

There were four flight crew on the flight deck of the aircraft because the operating flight engineer was in the final stages of completing a conversion to type and was operating under supervision. He completed an external inspection of the aircraft, which included a visual inspection of the elevons which appeared normal and undamaged.

The aircraft departed from the stand at 1804 hrs and took off at 1823 hrs. Shortly after take off it was cleared to climb to FL 280 en-route to the acceleration point which was just to the North of Lundy Island in the Bristol Channel. The subsonic cruise to the acceleration point was flown at Mach 0.95 and FL 280 (approximately 385 KIAS). At the acceleration point full power was applied to accelerate the aircraft following the normal speed schedule with the commander handling and the No 1 autopilot engaged. At 1850 hrs as the aircraft climbed through FL 415 at about 500 KIAS the flight crew felt the aircraft shudder slightly for some two or three seconds as if it had passed through some depleted wake turbulence. Both before and after this brief period of shudder, the air was very smooth and so the crew considered the possibility that one of the engines had suffered a pop surge (a momentary disruption of the air flow through the engine which is self-clearing and which sometimes produces an audible 'pop' noise). Checks of the engine instruments revealed no abnormalities and so the crew continued with the climb. However, because the reason for the shudder was unexplained, the operating flight engineer pressed the Flight Data Recorders event button in order to annotate the appropriate section of the recordings for post-flight analysis.

After a short while the supervisory engineer remarked that the brief shudder reminded him of an earlier experience when, after landing, it was discovered that part of a rudder control surface had separated in flight. The crew appreciated that it was not possible to see the rudder from within the aircraft but the flight engineer also remarked that control surface failures were not confined solely to rudder failure. Air France had reported two cases of elevon failure. At the commander's suggestion, he left the flight deck and went aft to inspect the elevons through the cabin windows. At the rear of the aircraft he could see that part of one of the six elevons on the left wing trailing edge had separated and that the upper skin of the remaining portion was deflected upwards at its outboard trailing edge and oscillating rapidly. He returned to the flight deck and informed the commander. The crew checked the flight controls position indicator which showed a steady and logical position for the damaged elevon but its deflection appeared to have changed slightly. There were no other system abnormalities and there had been no perceptible trim changes.

At about 1917 hrs the commander decided to return to Heathrow and to reduce speed and altitude towards the subsonic domain. By this time the aircraft was approaching 20°W on Concorde track SM and climbing through FL 495. Air traffic control had been transferred to Shanwick Oceanic control on HF and the first officer sought clearance to turn about, decelerate and return to Heathrow.

The initial request message at 1917 hrs was not prefixed with an emergency code word (PAN or MAYDAY) and when asked if they were about to declare one the reply was "negative emergency at the moment". The crew were anxious to turn around and decelerate, and so repeated their request to turn back at 19:20:30 hrs and 1921 hrs. Each time they were instructed to standby. At 1921 hrs the commander decided that he had to turn about without further delay. The co-pilot then declared an emergency on the Shanwick Radio HF frequency using the PAN prefix but again they were instructed to standby. At that stage the commander decided to turn back without waiting for formal clearance. He declared his intentions on the VHF distress frequency of 121.5 MHz as he commenced a right turn at 1922 hrs. The aircraft's position was approximately 23°W on track SM as it began the turn at Mach 1.96 and FL 500. The commander limited the aircraft's bank angle to 20° and, about one minute after starting the turn, engine thrust was reduced to commence the deceleration and descent. At 1926 hrs a clearance to descend to FL 390 was granted but this was too high for subsonic flight and so clearance to a lower level was sought and given at 1930 hrs. During the turn the aircraft was decelerated without incident apart from a short period of unusual and marked airframe buffet passing through Mach 1.3. This buffet stopped once the aircraft was subsonic.

The 770 nm return flight to Heathrow was flown at subsonic speeds at FL 330 during which 17 tonnes of fuel was jettisoned to reduce to maximum landing weight at Heathrow. The final approach was flown at normal speed although the commander decided to reduce speed to VREF at 1,000 feet instead of the more usual VREF+7 kt at 800 feet (used for noise abatement). On short finals and during the landing flare the commander perceived that he needed slightly more back pressure on the control column than normal; all the flight crew were aware of slightly more than normal airframe buffet during the approach. The landing was otherwise uneventful and the aircraft was met and followed by the emergency services who had been at an advanced state of readiness.

ATC delays

The delay between the crew first requesting a clearance to decelerate and return to London and the request being granted was 13 minutes. There were three reasons for this delay. Firstly, transatlantic procedures require HF radio operators in Ballygirreen to relay all messages to ATC controllers in Prestwick, either by telephone or by telex. This inevitably incurs a communication delay and denies the controller any intuitive grasp of the crew's predicament from the tone or style of their RTF message. Secondly the crew did not declare an emergency until the fourth request at 1921 hrs. Consequently, although the earlier requests to turn back were unusual, in the absence of a declared emergency the Prestwick controller was entitled to assume that the request was one which attracted no greater priority than any other request. When the emergency was declared, the controller then gave the request suitable priority. Thirdly, with no radar coverage, the controller needed to know the aircraft's position and intentions before co-ordinating a safe clearance. The information was relayed to Prestwick at 1928 hrs; clearance to descend and return was issued two minutes later. Given the built-in handicap of split responsibility for transatlantic air traffic, the ATC response was reasonable and consistent with standard operations.

Flight recorders

Recorded information was available from the Flight Data Recorder (FDR) and Quick Access Recorder (QAR) fitted to the aircraft. The Cockpit Voice Recorder retained the last 30 minutes of flight deck communications and so the recording of the period pertinent to the event and the subsequent landing had been erased and recorded over. An annotated ground track of the entire flight is shown at Appendix 1.

Following the take off at 1823 hrs, the auto-pilot was engaged and the aircraft climbed subsonic to FL 280. At 1841 hrs, on a heading of 270°M, it accelerated through Mach 1.0 and re-commenced the climb. At 1850 hrs, whilst climbing through FL 410 at M 1.6, recorded data showed that the control column moved forward slightly and the pitch-up of the aircraft reduced by half a degree to 3.1°. Within two seconds of this movement the pitch trim altered to give a small nose-up adjustment and the aircraft rolled 0.5° to the right. The crew depressed the event button within one minute of the occurrence to provide a marker on the FDR and QAR recordings. Engine reheat was deselected at M 1.7, two minutes after the event. No unusual indications were observed on the recordings of the three accelerometer parameters at the time of the event. A plot of selected parameter values recorded at the time of the event is shown at Appendix 2.

The aircraft accelerated to M 1.96 and climbed to a maximum altitude of FL 500 until, at 1922 hrs, a 180° right turn was commenced onto 095°M. During the turn the aircraft descended to FL 330, decelerated and flew the return leg at M 0.9. There was no evidence of any handling anomaly during the remainder of the flight although slightly larger peak-to-peak values of normal acceleration were recorded during the transonic deceleration phase (M 1.3 to M 0.9) and also during the final ILS approach, which was flown at an airspeed of 166 kt.

The aircraft landed at 2110 hrs, with thrust reverse being used to decelerate during the rollout.

Description of the elevon and 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 control surfaces are of metal honeycomb construction faced with aluminium alloy skins, chemically milled locally to achieve the optimum skin thickness. On the elevons, unlike the rudders, the skins are chemically milled on the outer surface leaving thickness changes visible on the outer surfaces of the control panels. The skins are bonded to the honeycomb core using an autoclave-cured film adhesive, this process being carried-out under pressure to ensure positive contact of the skin to the core.

Previous incidents of elevon failure

There have been two previous recorded occurrences of elevon failure, both occurring to a French Concorde in 1986 and 1992. Investigations were conducted by the manufacturer which were hampered by the same lack of hard evidence which afflicts this investigation, the failed parts not being recovered. Therefore, the reports do not have any firm conclusions as to the cause of the failures and neither do they make any form of safety recommendations. It is possible that some related action may have been taken by the manufacturer, however.

Elevon arrangement

The aircraft has twelve elevons which control the aircraft in pitch and roll. They are numbered from 1 (outboard) to 6 (inboard) left and right, and each is linked with an adjacent surface (1+2, 3+4, 5+6) as a pair with a common Powered Flying Control Unit (PFCU). Thus failure of a PFCU will result in the loss of function of two elevon surfaces. Extensive analysis and testing was done at the design stage to ensure that, in such a situation, the aircraft remained controllable throughout the flight envelope. Clearly, loss of a single surface due to structural failure should not be as onerous as the loss of function of two due to PFCU failure.

The elevon involved in the incident was S/No 1006R fitted in position 3L and it was one of the original-build components dating from the 1970's. Aerospatiale had retained the original tooling, thus new elevons were available and this operator had at least one complete ship-set of new elevons. As with several of the original-build items, 1006R had received a repair to the trailing edge during its service life; in fact the entire trailing edge had been replaced due to the discovery of disbonding and corrosion in 1993. In June 1995, the elevon was sent to BAe to re-work the previous trailing edge repair and two further repairs at the leading edge, which had been achieved using AF163 adhesive. Aerospatiale had advised that they would only approve the use of Redux 322 adhesive. As far as the trailing edge was concerned, this re-work involved removal of both top and bottom trailing edge skins and completely re-fabricating the section (normally attempts are made to retain one of the original skins to maintain the profile). In the course of the repair, a 'U'-section channel trailing edge member was incorporated to enable mechanical fastening of the trailing edge extension without penetrating the core. After repair, the entire elevon was inspected by the manufacturer using the through-transmission 'C' scan technique. This method uses ultrasound, transmitted to the structure by a water jet and similarly received at the other side. It is probably the most effective NDE available for detecting disbonds but requires placement of the component in a rig whilst the jets automatically traverse the surfaces. One additional advantage is that the results are electronically 'mapped' and stored as a colour-coded diagram.

History of non-destructive examination (NDE) of the elevon

The British and French airworthiness authorities required NDE of the elevons every 520 hours or 7 months. The technique employed was specified in manufacturer's Service Bulletin (SB) 55-009 but with some manufacturer-approved variations applied by the operator. In essence, the upper and lower surface of each elevon was inspected for skin/core disbonds using a Mechanical Impedance Analyser (MIA), an instrument which essentially looks for local changes in the stiffness of a structure due to voids. Because of the variation in skin thickness, different calibrations for the MIA have to be used across the surface and, in a region where the thickness exceeds 1.8 mm, an ultrasonic Ring-Pattern technique has to be used instead. This technique is so-called because it measures changes in the acoustic 'ringing' of a structure and a maximum paint thickness limitation of 0.2 mm is specified. This mandatory inspection had been accomplished 285 hours prior to the incident.

In addition to the mandatory NDE described above, the operator had also unilaterally instituted their own examination schedule every 16 flights. In using a similar approach to that employed on the rudders, the elevons were also visually inspected for the presence of repairs. Where these were found, the repair itself and the area of the skin on the opposite side were inspected using the MIA or ring-pattern technique as appropriate to the skin thickness. A specially-devised ultrasonic roller probe device was also used, to through-transmission inspect the trailing edges. However, the geometry of the probe meant that it could only be used on about the last 8 inches of the trailing edge and the operator's technique stated that this method was not appropriate to repaired areas. The last of these inspections had been carried-out on 23 May 1998.

Examination of the aircraft

The aircraft was examined at the operator's engineering base at Heathrow Airport. It was obvious that No 3 Left elevon was missing approximately the rearmost one third of its area (see photograph Appendix 3). As was the case with the rudder failure, the most material remained in the area supported by the PFCU arm and the least at the 'free' (outboard) end. A small piece of the repaired trailing edge remained at the PFCU end but 30% of the outboard closing rib was missing. In general, the remains of the core appeared to be still bonded to the upper skin but was disbonded completely from the lower skin. There were signs of violent post-failure fluttering as well as creasing of the lower skin and leading edge 'D' fairing due to gross torsional distortion. Apart from some very superficial chafing of No 4 Left elevon, there was no additional resultant damage to any other part of the aircraft.

Detailed examination of the failed elevon

As with the rudder, after removal from the aircraft the elevon was despatched to DERA Farmborough for detailed examination under AAIB supervision. Three distinct areas of expertise were deemed necessary for the investigation, material failure analysis, adhesive failure analysis and NDE technique evaluation.

The metallurgical examination essentially confirmed the on-aircraft observations. Although the fractures in the skin were (as expected) basically shear-type overload failures, it was not possible to determine any sort of directionality in the fractures which might have pointed-back to their origins.

Particular attention was paid to the small area of trailing edge repair remaining and comparison of it with the repair drawing. As previously mentioned, the repair had necessitated complete removal of about 9 cm of the chord at the trailing edge (but retaining the inboard closing rib and PFCU arm). A new skin section had been bonded to the original skin, overlapping by 40 mm (see Appendix 4). The edge of the overlapping repair, thus coincided with a chemically milled chord wise step to a thicker skin and, because the skin thickness also increased span wise towards the PFCU arm, a trapezoidal-shaped doubler was added over the top in this corner to maintain the overall skin thickness. Thus the majority of the trailing edge span had a single repair skin overlap of 40 mm but the inboard corner had an additional doubler over the top of the of the repair skin and the original skin, extending some 168mm forward of the trailing edge. The amount of overlap somewhat exceeded the repair drawing dimensions, which called-for 33 mm overlap for the repair skin and 70 mm for the additional doubler. This was probably done because, by slightly increasing the width of the repair skin by 7mm, the front edge would coincide with the original step-up in thickness of the skin and hence produce a smoother appearance to the repair.

After bonding the first repair skin, a shaped honeycomb repair wedge was bonded-in and the opposite skin, built up in a similar way to the first, was bonded to finally seal the assembly. The original line of bolts fastening the skins to the PCU arm was re-made and, in a manner which differed from schemes devised by BAe for rudder repairs, Aerospatiale had specified a line of anti-peel blind rivets to be inserted along the metal-metal overlap join.

As previously noted, the area of honeycomb replaced was almost equalled by the area of overlapped repair skin. Where the repair skin overlapped the original skin, in areas away from the PFCU arm, the adhesive appeared to disbonded from the original skin whereas towards the PFCU arm it was generally disbonded from the repair skin (adhesive failure). As far as the honeycomb/repair skin failure was concerned the appearance was one of largely cohesive failure as expected. This manifested itself as adhesive remaining around the honeycomb cells and also on the remaining original skin. There was one exception, however, in a small area adjacent to the cut-line of the original skin where there appeared to have been an adhesive failure of the adhesive/skin bond, adjacent to which three hexagonal patches could be lifted easily from the skin with a blade (also possibly indicating a weak bond). A band 15-20 mm wide immediately forward of this area contained cell patterns which differed in appearance slightly from the remainder, inasmuch as there was less adhesive fillet remaining on the skin than was generally the case. The significance of this observation is that it is similar to the type seen in the previous rudder repairs which were attributed to water ingress, but DERA specialists are of the opinion that the area remaining was too small to confirm this as the failure mechanism.

Discussion

As is perhaps inevitable, establishing the reason for the failure of this elevon was severely hampered by the inaccessibility of the vital pieces which departed from the aircraft over the ocean, ie those containing the origin of the disbond. Suspicion tends to fall on the nature or quality of the repair to the trailing edge, which was one of the most extensive carried-out on this operator's elevons to-date. The three previous cases of original-build rudder failures were attributed to either moisture ingress through rivets associated with the revised trailing-edge modification (also applied to the elevons) or to subsequent problems with inspection or repair as a result. In each case the lessons learnt from these investigations were applied, in particular more extensive NDE, to not only rudders but also the elevons. Thus, in theory, it is necessary to find a different explanation for the failure of this component.

The fact which has not changed is that repairs to these components remain very labour-intensive and require the highest standards of craftsmanship and quality control. There is no evidence that these were not applied, but with any such process, there is scope for errors to occur. Such errors might be quite small immediately after repair, but by their nature, there is potential for them to grow to sudden failure of the component. The major tool in preventing this is NDE, which should detect such defects before they reach critical size and there is no doubt that the operator had invested a lot of resources in this area, well beyond the statutory requirements. No other failure mechanism has been conceived other than that involving a progressive disbond of the structure apart from mechanical damage caused by, for example, ground equipment. A growing disbond should be detected by NDE before it reaches a critical size at which complete failure of the elevon may occur. However this 'critical size' and a propagation rate have not been determined.

During the course of investigation, it became apparent that the largest number of mid-panel repairs was occurring on elevons 5 and 6, due to mechanical damage during galley loading and unloading operations. Although elevons in the No 3 position are not affected this damage would appear to be quite avoidable and thus obviating the highly undesirable task of introducing intrusive repairs into the core.

There was some debate concerning the effects of paint thickness on the ultrasonic ring-pattern technique used to inspect the areas where the skin thickness exceeded 1.8 mm. This area represented largely the forwardmost section of the elevon and it was generally found that the thickness was less than the maximum 0.2 mm specified in the SB, although this was not necessarily the case in other areas.

Arguably the most significant NDE anomaly arises in the inspection of repairs. As stated previously, inspectors were not supplied with details of the location of repairs on elevons or rudders. The reasoning behind this was that it should make the visual inspection of the surfaces more thorough if the individual was actually looking *for* something rather than merely *at* the surface - a valid human factor with such a repetitive inspection. Unfortunately, the subsequent NDE inspection is inhibited by three factors:-

- The exact nature of the repair is unknown (patch thickness, extent of adhesively potted crushed core and foaming adhesive etc.) which affects the calibration of the technique or even the type of technique to be used.

- No procedure was required or specified which could detect the integrity of overlapped skin bonds or the skin/core bond underneath such overlapped areas.

- Repairs (concessions) occurring during manufacture may be undetectable visually and therefore overlooked.

The second factor becomes particularly significant when it is recalled that the degree of overlap applied to the subject repair was oversized compared with the drawing. It is estimated that nearly 50% of the repaired area was not adequately inspectable using existing techniques. A different technique, using a device known as a Fokker Bond Tester is currently being developed by BAE Systems and the operator to overcome most of the problems in this area. Such an instrument, which monitors one of the natural frequencies of the component under test, may also be able to detect disbonds at trailing-edge and edge members - something not possible using existing in-service techniques.

This investigation also highlighted the desirabilty of being able to re-visit the results of previous NDE inspections. When it is almost inevitable that the physical evidence of failure origin will be lost, at present there is usually only the Inspector's signature confirming that no defects were present. In general, the minimum defect size detectable is quoted as 0.8 sq.ins and the techniques call for a scan pitch of 0.5 ins. Thus the probe will theoretically only pass over such a defect once in any given inspection.

Computer-based 'mapping' techniques now exist which can provide a permanent record of the inspection and which also assist the Inspector in ensuring 100% coverage of the area. At the time of writing, it is known that the operator is developing and evaluating such a system and methodology for its use. It is also known that they intend to purchase more new-build elevons. As part of the latter intention, they have drawn-up a list to identify the most vulnerable units. All of their elevons are now classified according to number, size and location of repairs. Those with the most disadvantageous 'scores' will be singled-out for priority replacement.

Conclusions

1. The reason for failure of elevon 3L S/No 1006R could not be established, but circumstantially it may have originated in the repaired trailing edge area.
2. The most likely failure scenario probably involved the growth of a relatively small disbonded area to a critical size and subsequent instantaneous failure.
3. The growth of the suspected disbond was not detected by NDE, despite an inspection programme well in excess of mandatory requirements.
4. The NDE techniques applicable at the time neither required nor were capable of examining metal-metal bond lines for flaws. As such approximately 50% of the repair accomplished at the trailing edge was not inspectable.
5. Despite the almost complete loss of integrity of the surface, the effects on controllability of the aircraft were negligible. This corroborates the results of a theoretical and experimental study conducted by the manufacturers which was presented to the investigation team and also came to this conclusion.

Safety recommendations

Recommendation 2000-15

EADS/BAE Systems should revise the mandatory Service Bulletins relating to NDE of Concorde elevons and rudders to include an NDE technique capable of detecting metal-metal dis-bonds and skin-core dis-bonds beneath overlapped repair areas. Maximum allowable paint thickness values should also be specified.

Recommendation 2000-16

British Airways and Air France should investigate the feasibility of electronically 'mapping' the results of their NDE examinations of both Concorde elevon and rudder assemblies. Such results should be retained for any future investigation. NDE personnel should be provided with details of individual repairs so that an appropriate inspection technique can be used.

Recommendation 2000-17

British Airways and Air France should provide upper-surface protection for elevons 5 and 6 during ground replenishment operations.

Recommendation 2000-18

British Airways and Air France should examine the viability of replacing, at least those elevons most at risk of failure due to accumulated repairs, with newly manufactured items.