

**AIRCRAFT ACCIDENT REPORT 5/89**

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**Air Accidents Investigation Branch**

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**Department of Transport**

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**Report on the accident to Boeing 747-136  
G-AWNM on approach to runway 27L  
at London (Heathrow) Airport  
on 11 September 1988**

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*LONDON*

HER MAJESTY'S STATIONERY OFFICE

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## List of Aircraft Accidents Reports issued by AAIB in 1989

2/88	Boeing Vertol BV 234 LR G-BWFC 2.5 miles east of Sumburgh, Shetland Isles on 6 November 1986.	April 1989
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**Department of Transport  
Air Accidents Investigation Branch  
Royal Aerospace Establishment  
Farnborough  
Hants GU14 6TD**

16 November 1989

The Right Honourable Cecil Parkinson  
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr E J Trimble, an Inspector of Air Accidents, on the circumstances of the accident to Boeing 747-136, G-AWNM, on approach to runway 27L at London (Heathrow) Airport on 11 September 1988.

I have the honour to be  
Sir  
Your obedient servant

**D A COOPER**  
Chief Inspector of Air Accidents

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## GLOSSARY OF ABBREVIATIONS

AAIB	Air Accidents Investigation Branch
AC	Alternating Current
AD	Airworthiness Directive
agl	Above Ground Level
°C	Degrees Celsius
CAA	Civil Aviation Authority
CAS	Calibrated Airspeed
CPR	Control Position Roll
CVR	Cockpit Voice Recorder
ESM	Electron Scanning Microscope
FAA	Federal Aviation Administration
FAR	Federal Aviation Requirements
FDR	Flight Data Recorder
ILS	Instrument Landing System
kg	kilogram(s)
kt	knot(s)
NDT	Non Destructive Testing
NTSB	National Transportation Safety Board
PRR	Production Rework Requirement
SB	Service Bulletin
V <sub>ref</sub>	Target Threshold Speed



## **Air Accidents Investigation Branch**

### **Aircraft Accident Report No. 5/89 (EW/C1085)**

Owner and Operator:	British Airways PLC
Aircraft:     Type and Model:	Boeing 747-136
Nationality:	British
Registration:	G-AWNM
Place of Accident:	Approaching Runway 27L at London (Heathrow) Airport
	Latitude 5128N Longitude 000 27 W
Date and Time:	11 September 1988 at 0525 hrs
	All times in this report are UTC

## **SYNOPSIS**

The accident was notified to the Air Accidents Investigation Branch at 0730 hrs on 11 September 1988 and the investigation began that morning. The AAIB team comprised Mr E J Trimble (Investigator in Charge), Mr P R Coombs (Engineering), Mr A W Skinner (Operations) and Miss A Evans (Flight Data Recording).

The aircraft was engaged on a scheduled international passenger flight from Abu Dhabi to London (Heathrow) Airport with a total of 378 persons on board. The flight had proceeded normally until the final stages of an Instrument Landing System (ILS) approach to land on runway 27L at Heathrow. Shortly after 30° of flap had been extended, there was a noticeable "thump" and immediately the aircraft started to yaw and roll to the right. The commander, who was the handling pilot, maintained control by the use of considerable control wheel deflection and the aircraft was landed without further incident.

Examination of the aircraft after landing revealed that a failure of the number 6 flap track had occurred. The direct cause of the flap track failure was stress-corrosion cracking initiation from a corroded forward (No. 1) bolt hole which induced fast brittle fractures of the steel track at a point where the design was not fail-safe.

A contributory cause was the failure of a special inspection to detect such cracking before full fracture occurred despite many revisions of its requirements following other instances of flap track cracking and failure.

Six safety recommendations were made during the course of this investigation.

# **1 Factual Information**

## **1.1 History of the flight**

The aircraft was engaged on a scheduled international public transport passenger flight from Abu Dhabi to London (Heathrow) Airport with a crew of 18 and 360 passengers on board. The flight from Abu Dhabi was uneventful and a radar vectored approach was flown to intercept the ILS for runway 27L at London Heathrow. The aircraft commander was the handling pilot. ILS interception took place at 3000 feet above ground level (agl), with an aircraft configuration of flap 20 and landing gear up. The landing gear was selected down at 2400 feet agl and the aircraft was established in a stable approach with flap 30 by 800 feet agl. The Target Threshold Speed ( $V_{ref}$ ) for the aircraft weight and ambient conditions was 137 knots. However the commander elected to use a  $V_{ref}$  of 145 knots, due to the possibility of low level wind shear.

Shortly after flap 30 was achieved, and at a height of about 600 feet agl, a 'thump' was felt and the aircraft immediately started to yaw and roll to the right. Suspecting a bird strike and associated engine failure, the commander corrected the yaw, levelled the wings, and asked the flight engineer if they had lost an engine. His answer was negative. Thereafter the commander had to use considerable control wheel deflection to return the aircraft to the ILS centreline. The first officer subsequently confirmed that he considered that almost full deflection of the control-wheel was used. The aircraft was landed without further incident.

After landing the aircraft was stopped clear of the runway, and the commander requested a visual inspection of the aircraft. Considerable distortion of the right side inboard flap assembly was observed, but no other damage was apparent. The commander therefore left the flaps down and taxied the aircraft to its stand, where the passengers disembarked normally.

## **1.2 Injuries to persons**

None.

## **1.3 Damage to aircraft**

On close examination, the aircraft was found to have sustained considerable damage to the right side inboard flap system and adjacent wing structure. This is itemised in section 1.12.1.

#### 1.4 Other damage

Nil.

#### 1.5 Personnel information

- 1.5.1 *Commander:* Male, aged 54 years
- Licence: Airline Transport Pilot's Licence valid until 20 April 1998
- Aircraft ratings: Auster variants, Comet 4, VC 10, Boeing 747
- Instrument rating: Valid until 13 October 1988
- Medical examination: Class I, valid until 31 December 1988
- Certificate of Test: Dated 28 August 1988
- Flying experience: Total flying hours: 12,327  
Total flying hours on type: 6,510  
Total flying hours in command on type: 6,403
- Total flying hours in last 30 days: 85
- 1.5.2 *Co-pilot* Male, aged 40 years
- Licence: Airline Transport Pilot's Licence valid until 30 July 1989
- Aircraft ratings: Beechcraft 95, VC10, Boeing 747
- Instrument rating: Valid until 18 September 1989
- Medical examination: Class I, valid until 30 November 1988
- Certificate of Test: Dated 1 January 1988
- Flying experience: Total flying hours: 10,132  
Total flying hours on type: 7,253  
Total flying hours in last 30 days: 80
- 1.5.3 *Flight Engineer:* Male, aged 50 years

Licence:	Flight Engineer's Licence valid until 25 April 1998
Aircraft ratings:	Comet 4B, Lockheed 1011, McDonnell Douglas DC10, Boeing 707/720 & 747 series 100 & 200
Medical examination:	Valid until 31 January 1989
Certificate of Test:	Dated 11 August 1988
Flying experience:	Total flying hours: 8,046 Total flying hours on type: 154 Total flying hours last 30 days: 74

#### 1.5.4 *Rest and duty periods*

Each flight crew member had been on duty for 8 hours and 10 minutes at the time of the accident. Before reporting for duty in Abu Dhabi, each flight crew member had a rest period in excess of 24 hours.

### 1.6 Aircraft information

1.6.1. <i>Type:</i>	Boeing 747 Series 136
Constructor's Serial No:	20708
Date of Construction:	May 1973
Certificate of Airworthiness:	Transport Category (Passenger) Issued 18 December 1986, valid until 26 October 1989
Certificate of Maintenance Review:	Completed 14 July 1988
Total Airframe Hours:	63,162
Total Airframe Cycles:	15,746
Cycles since last special check of flap track No. 6:	152
Cycles available before next special check of No. 6 track due:	148

(Special check was carried out in accordance with Boeing Commercial Airplane Company Alert Service Bulletin 747-57A-2229 Revision 5 which has since been incorporated into FAA Airworthiness Directive 88-16-03)

### 1.6.2 *Description of Flap System*

The Boeing 747 is equipped with a flap system comprising 2 inboard and 2 outboard flap units which are structurally independent. Each flap unit consists of a mid flap, a foreflap and an aft flap (see Appendix 1, Fig 1). Each foreflap and aft flap is mounted from its mid flap and is positioned relative to the mid flap by sequencing mechanisms, which operate as the mid flap is extended or retracted. Each mid flap is attached to the aircraft by means of two sequence carriages and two tracks. Each sequence carriage is driven backwards along its track as the flaps are extended, and vice-versa. Each sequence carriage of the inboard flap is driven by means of a ball screw which is in turn driven, via an angle gearbox, by a spanwise shaft driven from a point inboard of the flaps. Each outboard flap is driven via similar shafting which passes along the spoiler support beam, adjacent to the corresponding inboard flap.

The inboard and outboard flaps are safeguarded by asymmetry protection systems, *ie* any significant difference in position between one flap and the corresponding flap on the other side of the aircraft will cause the drive to that pair of flaps to stop.

The tracks are numbered 1 to 8, from left to right across the aircraft. Each track takes the form of a steel forging, of modified channel section, with an aluminium alloy rectangular section member bolted into the channel, thus forming a closed box. The aluminium alloy member is termed the Fail-Safe Bar (see Fig. 2).

The numbers 3 and 6 flap tracks are supported from the wing rear spar at a point approximately 1/3rd of their length back from their forward ends. The forward end of the beam is formed into a pair of lugs and is attached to the wing underside by means of a bolt (termed the fuse bolt) passing through the lug of a special fitting, which is in turn bolted to the underside of the wing at the mid spar position (see Fig 2). A further attachment takes the form of a strut running vertically upwards from a point approximately mid-way along the track to a fitting on the spoiler support beam.

Early production Boeing 747 aircraft were fitted with flap tracks which had a titanium alloy fail-safe bar. This was quickly superceded by an aluminium alloy fail-safe bar. Later production tracks were made stronger, with increased web thickness. G-AWNM had flap tracks which had the original web thickness.

#### 1.6.3 *History of No. 6 flap track*

No evidence has been found to indicate that the track at the No. 6 position was changed between manufacture of the aircraft and the time of this accident. The track, however, underwent modification in accordance with P.R.R. 73912-1 between the time of its manufacture and the time of its installation on the aircraft. This modification introduced the aluminium alloy fail-safe bar, in place of the titanium alloy channel.

#### 1.6.4 *Corrosion protection*

The steel material of the track was protected with cadmium-titanium alloy plating, followed by chromate post-plate treatment and primer. Wet sealant was also used on installation of fasteners.

Examination of uncorroded bolt holes has indicated that the holes were machined after plating and were then primed. Most of the primer appears to have been removed during the fitting of the bolts at assembly. Sealant at wet assembly appears to have been applied between the fail-safe bar and the steel of the track, as well as under the bolt heads. No sealant was evident between the bolt shanks and the bores of the bolt holes.

#### 1.6.5 *Track inspections*

The track had undergone a series of special in-service inspections, in accordance with Boeing Alert Service Bulletin 747-57A-2229, over the period since serious problems in this region of such tracks were first encountered on Boeing 747 aircraft. This track design has a history of cracking problems, dating back to 1972, and a number of Boeing Service Bulletins and FAA Airworthiness Directives have been issued over this period to combat such problems. This track is of a design which was superceded in production after the manufacture of approximately 250 aircraft of this type.

#### 1.6.6 *Aircraft weight and centre of gravity*

The maximum permitted take-off weight was 332,900 kg, and the maximum landing weight was 265,300 kg. The actual weights were 324,341 kg and 235,740 kg respectively. At the time of take-off from Abu Dhabi, the centre of

gravity of the aircraft was within the prescribed limits and remained so throughout the flight.

## **1.7 Meteorological information**

After the accident, the Meteorological Office at Bracknell provided an aftercast of the weather in the London (Heathrow) area for the relevant period. The general situation consisted of moist and stable westerly airflow, ahead of a cold front lying over Humber, Birmingham, Cardiff, and Cornwall. The gradient wind over Heathrow at 0530 hrs was 270°/22 knots. The actual weather recorded at Heathrow at 0520 hrs was a surface wind of 240°/08 knots, visibility 18 kilometres, nil weather, cloud 5 oktas strato-cumulus at 1500 feet and 4 oktas strato-cumulus at 3500 feet, air temperature + 13°C.

Meteorological conditions were not a factor in this accident, which occurred during the hours of daylight.

## **1.8 Aids to navigation**

Not relevant.

## **1.9 Communications**

Communications on all the Very High Frequency (VHF) channels used throughout the accident were satisfactory. Recordings and transcripts of all relevant radio-telephony messages were available.

## **1.10 Aerodrome information**

London(Heathrow) Airport has three runways available for normal operations: 27R/09L, 27L/09R, and 22/04. At the time of the accident runway 27L was allocated to the aircraft as the landing runway. All aids to landing on that runway were serviceable.

## **1.11 Flight recorders**

### **1.11.1 *Flight data recorder (FDR)***

The aircraft was fitted with a Penny and Giles Type 800/D6400 FDR with a recording duration of 25 hours and was part of a Plessey PV1580 recording system. A total of 32 analogue parameters and 73 discrete "events" were recorded.

There was a fault apparent on the FDR which resulted in the corruption of the stabiliser position, control column lateral input and pylon pressure signals. Apart from these parameters, a successful replay was obtained. The fault was due to the loss of the 28V A.C. synchro reference as a result of circuit breaker C1237 tripping just prior to the roll disturbance. The fault which caused the circuit breaker to trip intermittently was traced to a chafed wire on the No 4. engine pylon. Simulation of the loss of the 28V synchro reference, during testing by the operator, revealed that the signals for stabiliser position and control column lateral input became extremely unreliable, and so recovery of the corrupted parameters was not possible.

#### 1.11.2 *Cockpit voice recorder (CVR)*

A Fairchild A100 CVR, an endless loop four track recorder with a duration of 30 minutes, was installed in the aircraft. It is designed to run whenever power is on the aircraft and records new data over the previously recorded information. In the case of this accident, the aircraft was towed back to the maintenance facility from the terminal building, requiring power to be applied, and so all data relevant to the landing was erased.

#### 1.11.3 *Flight recorder analysis*

Appendix 2 shows a plot of the approach from the selection of landing flap (30 degrees) at 1300 ft and 160 kts CAS.

The accident occurred 51 seconds before touchdown at 600 ft and 153 kts CAS (landing reference speed  $V_{ref}$  was 137 kts CAS). The initial maximum roll was 9° right; maximum left rudder applied was 44%. From a steady heading of 274°, an initial yaw right of 4° occurred to a heading of 278°, and then a yaw left of 10° to a heading of 268°, before the aircraft regained the centre of the localiser beam.

The average rudder position on the final approach was 25% left, at an average airspeed of 153 kts ( $V_{ref} + 16$  kts). The aircraft touched down at an airspeed of 150 kts.

### 1.12 **Wreckage and Impact information**

#### 1.12.1 *Examination of the aircraft*

The aircraft had severe damage to the forward part of the No. 6 flap track fairing,

and it was immediately evident that the flap track had fractured approximately 6 inches aft of the fuse pin. The damaged flap track fairing and fractured flap track are shown in Figs 3, 4 and 5. Secondary damage had been sustained by the foreflap, the spoiler above the flap track, the spoiler support beam, the sequence carriage on the No. 6 flap track and numerous wing panels in the area of the track. In addition, one of the bearing supports for the shaft which operates the outboard flap was fractured, and numerous mechanical components in the area of the track were damaged. This secondary damage is shown in Figs. 6, 7, 8, 9 and 10.

Examination of the failed area of the track revealed that the fracture had occurred through the No. 1 bolt holes on each web of the track and had also extended longitudinally along the top web for approximately 17.3 inches, as illustrated in Figs. 11 and 12. The fracture surface on the outboard web showed marked indications of surface corrosion when first inspected a few hours after the occurrence. The corresponding fracture surface on the inboard web had a clean, uncorroded appearance.

The area adjacent the track failure was very wet from the effects of atmospheric condensation on the wing undersurface, resultant from in-flight cooling of the structure and the volume of fuel remaining in the integral tanks at the end of the flight.

Further examination of the track also revealed a crack which originated at the No. 4 bolt hole and extended upwards for approximately 1 inch. During the sectioning of the beam to enable electron scanning microscope (ESM) examination of the rear faces of the fracture, it was found that a small crack was also present at the No. 2 bolt hole position.

The track failure was the subject of metallurgical examination by the Materials and Structures Department of the Royal Aerospace Establishment, Farnborough.

## 1.12.2 *Laboratory examination of fractured flap track*

### 1.12.2.1 *Fracture through the outboard flange*

This fracture, shown in Figs. 11 and 12, was heavily corroded. "Chevron" markings on the fracture indicated that the cracking had emanated from this bolt-bore. After removal of the corrosion products, it was evident that the crack below this bore had originated from a semi-elliptical area of intergranular cracking (approximately .3 inch x .175 inch), with a corrosion pit of .0016 inch depth within the mid-region of the bore, as shown in Fig. 14. The intergranular area was consistent with stress-corrosion cracking.

The fractured surface above this bolt-bore indicated that this crack had emanated from the inboard corner of the bore, where a small area (approximately .04 inch in radius) of fatigue appeared to have originated at the bore surface. This fracture is shown in Fig. 13. The bore surface was generally corrosion-pitted, as was the adjacent inboard surface of the flange.

After initiation, both of these cracks had extended in a fast brittle manner, the upper crack having run up the outboard flange into the upper web, before extending aft for some 17.3 inches (Fig. 12). This area of the fracture was also generally corroded, and there was evidence of a number of "arrests" in the propagation of this crack, over the final (approximately 4 inches) extension.

#### 1.12.2.2 *Fracture through the inboard flange*

This fracture, also shown in Figs. 11 and 12, was uncorroded. The crack below the bolt bore had originated from an area of intergranular cracking, which had extended from the outboard side of the flange (*ie* adjacent to the aluminium alloy fail-safe bar), just below the bore surface. This area of the flange surface, at the alloy bar interface, was corrosion-pitted. The area of intergranular cracking was approximately .07 inch x .05 inch. The remainder of this lower fracture was consistent with the fast brittle extension. Figs. 15 and 17 show this lower fracture, and the position of the intergranular origin.

The fractured surface above the bolt-bore indicated that this crack had originated from a very small area of corrosion penetration, of approximately .005 inch depth, located at the inner corner of the bore, *ie* adjacent the flange/alloy bar interface. The adjacent flange surface was relatively uncorroded. The remainder of this fracture was consistent with fast brittle extension upwards through the flange section and into the web, where it had linked with the corroded crack emanating from the outboard flange. Figs. 15 and 16 show this upper fracture and the position of the origin.

#### 1.12.2.3 *Crack at No. 4 bolt hole*

This crack is shown in Fig. 12, extending vertically upwards from the top of the No. 4 bolt-hole. When opened-up, the associated fractured surfaces of this crack were generally heavily corroded. This crack had originated from the inner corner of this bore, where an initial intergranular crack of some .18 inch x .04 inch was present, with corrosion also present on this area of the flange, at the interface with the alloy fail-safe bar. No evidence of fatigue growth, or arrests, were found associated with this crack at the No. 4 bolt-hole, which was approximately 1 inch

in total length.

#### 1.12.2.4 *Crack at No. 2 bolt hole*

This crack was discovered during cutting of the forward end of the flap track. The associated fracture-path is shown in Fig. 18. The crack had propagated forward on the inboard flange from the No. 2 bolt-hole, before turning downwards to the bottom edge of the flange. The origin of this crack was a semicircular area of intergranular cracking which had extended from the inner surface of the flange, which was again corroded. This region was approximately .1 inch horizontally and .04 inch wide. Other indications on the fracture surfaces indicated that, after a burst of fast rupture, further growth of a relatively slow nature had occurred to a total length of approximately .64 inch, before the final onset of fast fracture extended the crack to the bottom edge of the flange.

A diagram of the flap track section, with the No. 1 bolt hole crack origins, is at Fig. 19.

#### 1.12.2.5 *Condition of bolt-bores*

In general, the inboard bores were more corroded than those in the outboard flange. It was apparent that corrosion was also a problem on the sides of both flanges, adjacent the bolt bores *ie* on the inner surfaces at the alloy fail-safe bar interfaces and on the outer surfaces, under the washers.

The bores of the holes showed no evidence of any protective treatment, but the inner surface of the flap track and the surfaces of the alloy fail-safe bar were coated with a yellow/green primer paint and a grey mastic material was present on the contact area. This protection was noticeably thinner around the bolt holes. It was observed that where the worst corrosion had occurred around the holes in the flanges, the protection had been worn away due to fretting. There was some exfoliation around the rim of one of the holes in the alloy fail-safe bar, the surface of which had been peened.

#### 1.12.2.6 *Flap track material*

The microstructure and hardness of the steel from this flap track were satisfactory and consistent with the specified ultra high tensile strength steel.

The composition of the steel was checked by electron probe analysis, and was found to be consistent with AISI 4340M.

### **1.13 Medical and pathological information**

Not relevant.

### **1.14 Fire**

Not relevant.

### **1.15 Survival aspects**

Not relevant.

### **1.16 Tests and research**

None.

### **1.17 Additional Information**

#### **1.17.1 *Previous failures***

On 15 December 1985 Boeing 747 G-AWNE suffered a failure of the attachment bolts, which connect the forward support fitting of flap track No. 3 to the wing structure, during an approach to Boston (Logan) airport. This failure was investigated by the National Transportation Safety Board (NTSB), with AAIB participation. The failure permitted displacement of track No. 3 to occur in a generally similar way to the movement of the No. 6 track after the failure on G-AWNM.

The flight recorder data from G-AWNE showed that land flap (30°) was selected at 1700 ft and 156 kts CAS as the aircraft turned left to intercept the localiser. The failure occurred as the aircraft returned to a "wings-level" attitude, about 50% of control position roll (CPR) was required initially, with a maximum roll of 8°. Maximum CPR was 70%, with the average CPR held on the approach being 50%. Speed on the final approach was around 153 kts ( $V_{ref} + 22$  kts), rising to 159 kts just before touchdown. The pilot reported that he had used an average of 70% CPR on the approach and up to 90% at touchdown. He also encountered more difficulty in roll control at lower speeds, and reported that he maintained the speed to  $V_{ref} + 10$  to 15 kts.

On May 9th 1988 a failure of the forward end of the No. 3 flap track occurred on Boeing 747 G-AWND during an approach to Chicago (O'Hare) airport. The position of this failure was almost identical to that which occurred in the No. 6

track of G-AWNM. That accident was also the subject of investigation by the NTSB.

The flight recorder data from G-AWND showed that the failure occurred at 1252 ft, 146 kts CAS, when the flaps had just reached 30° (Land Flap). The aircraft yawed left 7°, with an initial maximum roll left of 7.6°. Maximum control position roll (CPR) was 64%, and maximum rudder 39%. The average CPR used during the approach was 30%, the final approach speed was 150 kts ( $V_{ref} + 19$  kts).

Two further in-flight flap track failures are known to have occurred on Boeing 747 aircraft. These were associated with numbers 3 and 1 flap tracks, and occurred in 1984 and 1986 respectively.

The flap tracks of this earlier design, with the original web thickness, have a history of cracking in service. Approximately 80 instances are understood to have occurred worldwide between 1972 and 1988 where cracks have been detected in various parts of Boeing 747 flap tracks during inspection.

#### 1.17.2 *Action resulting from previous failures*

In 1984 the Federal Aviation Administration issued Airworthiness Directive 84.19.02, requiring special inspections at 1000 flight intervals in accordance with the Boeing Service Bulletin 747-57A2229, which was also issued in 1984. Issue of these documents followed the No. 3 flap track failure which occurred in 1984 and is referred to in para 1.17.1. The Boeing Service Bulletin underwent a series of revisions thereafter, reaching revision 6 by August 25th 1988. At that time its requirements included an ultrasonic inspection of parts of tracks Nos. 3 and 6 within 100 flight cycles of receipt of Revision 5 of the Bulletin, and thereafter ultrasonic and visual inspections of these tracks at 300 flight-cycle intervals. The details of the method of inspection and the requirements for other tracks on the aircraft are shown in Appendix 3 which is a reprint of Service Bulletin 747-57A2229. G-AWNM had already undergone the initial 100 cycle inspection of track 6 at the time of this accident in anticipation of the publication of Revision 5. This revision was published after the accident to G-AWND at Chicago (failure of No. 3 track) on 9 May 1988.

#### 1.17.3 *Action following this failure*

Later in the day of the failure on G-AWNM, following discussions between the operator, AAIB Inspector (Engineering) and CAA representatives, the operator issued a special check applicable to all Boeing 747 aircraft with the early standard of flap track (Note: at that date there were no Boeing 747 aircraft on the United

Kingdom register whose maintenance was not the responsibility of this operator). This special check required ultrasonic inspection of the forward area of all 8 flap tracks, to be completed within 15 landings of 2400 hrs on 11 September 1988.

It is understood that all affected aircraft were inspected within this period.

During the initial stages of implementation of this Special Check, a number of aircraft were found to have evidence of sufficient "distress" around the bolt heads to prompt bolt removal in accordance with item 3 of the Check. Once removed, substantial corrosion was evident within the bores of the steel tracks.

On the 14 September, AAIB wrote to the CAA and expressed concern that the revised track inspection, implemented after the No. 3 flap track failure on G-AWND at Chicago Airport on 9 May 1988, had not been successful in preventing a further similar track failure on G-AWNM.

On the 16 September, the operator issued a second Special Check which required track bolt removal and inspection of the bores. All tracks suffering from corrosion and/or cracking were to be removed from the affected aircraft and rectified by machining the bolt-holes oversize. Some tracks were replaced with newly manufactured tracks.

Also on the 16 September 1988, the CAA issued Emergency Airworthiness Directive (AD) No. 011-09-88. This included the requirements of the first Special Check, but additionally called for repeat inspections at 35 landings and an inspection for bolt hole corrosion by 31 October 1988. It is understood that a special extension of 6 days was subsequently granted in the case of 3 aircraft. On the 19 September, operational restrictions on the use of flap 30 were added to emergency AD 011-09-88 at Revision 1.

Revision 2 of Emergency AD 011-09-88 was issued on 19 December 1988 and required re-inspection with bolts/sleeves removed (in accordance with Boeing SB 747-57-A2229, Revision 7) at 30 month intervals; replacement of tracks by 30 April 1992 and a visual inspection in accordance with Boeing SB 747-57-2146 at intervals not exceeding 1000 landings.

Both Special Checks and Emergency AD 011-09-88, Revisions 1 and 2, are included at Appendix 3.

## **1.18 New investigation techniques**

None.

## **2 Analysis**

### **2.1 Comparison with previous flap track failures**

This No. 6 flap track failure was very similar to the stress-corrosion initiated failure which occurred to the No. 3 flap track of Boeing 747 G-AWND at Chicago in May 1988. Its direct consequences were also very similar to those resulting from the fatigue failure of attachment bolts of the No. 3 track forward fitting on G-AWNE at Boston in December 1985.

In these 3 instances the aircraft landed safely, although considerable control-wheel deflection was required to regain the centreline, and in order to maintain a wings-level attitude throughout the latter part of the approach.

In all three cases, the outboard flap track (*ie* either No. 3, or the corresponding track No. 6 on the other side of the aircraft) remained attached.

Notwithstanding this, the spoiler support beam was disrupted in all three instances, and various amounts of structural and mechanical damage occurred in the flap area.

### **2.2 Possible effects of a go-around manoeuvre**

A common factor in this accident and the accident to G-AWNE in 1985, is that in both events the flight crews were completely unaware of what had happened and the exact nature of the failures. In both events the failures occurred on the final approach, after 30 degrees of flap had been selected and achieved, and with the aircraft in sight of the runway. At this stage it is reasonable to presume that all crew members were monitoring the final stages of the approach, the centre line was quickly regained, and an immediate landing was the sensible and correct command decision.

However had the failures occurred in IMC an equally sensible and correct command decision could well have been to carry out a go-around. Examination of the damage on this aircraft, and on G-AWNE in 1985, showed that disruption may occur to either inboard or outboard flap drives during failures at the forward end of the No. 3 or No. 6 flap track. The normal procedure for a go-around manoeuvre requires progressive flap retraction. Such damage could well have significant effects during this procedure.

The flap which is mounted on the damaged track, even if its drive is initially intact, is unlikely to retract a significant distance during flight before the geometric

displacement of the track causes the sequence carriage to jam, and the drive to fail. The flap asymmetry protection system should then prevent further movement of the drive to this flap, and to the corresponding flap on the other side of the aircraft.

Although the majority of the aerodynamic surfaces of the affected inboard flap systems remained attached to the aircraft in the accidents to both G-AWNE and G-AWNM, it should be borne in mind that each aircraft remained in flight (at approach power) for only a short period after the relevant failure. During a go-around at increased power and airspeed, it is possible that the affected track could detach from the aircraft. Complete separation of track Nos. 3 or 6 would almost certainly cause loss of the flap together with disruption of the spoiler support beam, which is connected to the flap track by a vertical link. This would produce a situation in which continued flight would have to be undertaken with the affected flap missing, the spoiler support beam damaged and the corresponding flap on the other side of the aircraft still at, or near, its original position. The position of the outboard flap pair not affected by the track failure would depend upon the extent of the damage which had occurred to the corresponding flap drive.

Disruption of a spoiler support beam may also affect the associated hydraulic systems. In the case of the left wing, all 4 hydraulic systems are routed through the bay between the spoiler support beam and the wing rear spar, and are thus vulnerable.

Failure of a flap drive shaft, during attempted flap retraction, could induce flailing damage to the hydraulic lines in this bay. Although damage to all four systems would appear unlikely, the loss due to leakage of systems 1, 2 and 4 for example, will in isolation produce an approximately 50% reduction in roll and yaw control power, coupled with a 75% reduction in elevator effectiveness. In view of the amount of control wheel deflection which was required to complete the approaches after the flap track failures to G-AWNE and G-AWND, it appears unlikely that sufficient roll authority would be available, after loss of these systems, to make a successful landing following a go-around.

Even with the loss of Nos. 1 and 2 hydraulic systems only, somewhat less than 50% roll control is lost, combined with 50% elevator control.

A further risk exists associated with the loss of a flap unit. This is the possibility of the flap striking and damaging the horizontal stabilizer, or striking and remaining impaled upon its leading edge. Clearly, the additional control problems arising from such secondary impact damage could present a critical control

situation, even in the absence of secondary hydraulic system damage from a failed rotating flap drive shaft.

Although a "worst case" situation where insufficient control power remains to maintain the flight-path of the damaged aircraft is demonstrably not inevitable, a combination of asymmetric structural damage and control system failure could create a level of cockpit workload that would jeopardise a further approach.

### **2.3 Damage tolerance**

Over many years a number of philosophies have been devised by various certification authorities in attempts to ensure the continued integrity of critical structural parts *ie* those parts the failure of which could cause significant hazard to the aircraft. These philosophies have involved such concepts as "safe-life", "fail-safe" and "damage-tolerant" structures. Those components where a safe-life approach is used are normally required to have undergone an evaluation to establish a retirement life, in terms of operating hours or flight cycles, beyond which continued safe operation cannot be guaranteed. The fail-safe and damage-tolerant philosophies rely upon the timely detection of structural damage, before the reduction in strength becomes critical. Complete fracture or cracking of structural elements may occur leading to re-distribution of loading, but continued safe operation is expected until the fracture or crack is detected at a subsequent inspection.

The Boeing 747 flap tracks are manufactured from ultra high tensile steel forgings and each incorporates an aluminium alloy fail-safe bar, which permits re-distribution of loading to this alternative path should cracking or fracture of the steel forging occur. After such a fracture, the track may continue to carry the normal flight loads by way of the fail-safe bar, until the fracture is detected by inspection. The track is not "lived".

Unfortunately, the fail-safe bar does not extend to the forward attachment of the Nos. 3 and 6 tracks. Consequently, a fracture of the steel forging close to the forward attachment results in complete failure of the track, with loss of geometric location of the flap and considerable secondary damage, as well as a risk of total flap separation. The tracks cannot therefore be regarded as "fail-safe" at this location.

The continued integrity of these tracks therefore relies on:-

- (1) Detection of fracture within the steel forging before significant fatigue damage occurs to the alloy fail-safe bar at the site of that fracture.

and

(2) Detection of cracking, specifically in the forward end of the steel forging, before such a crack reaches critical length.

This important difference in the significance of in-service defects in the two parts of the track only became evident to operators after the tracks had suffered the failures which preceded the publication of an Alert Service Bulletin by the Manufacturer.

The Bulletin introduced special inspections of the forward part of the tracks to ensure that no cracking was present (see Appendix 3). It is evident, however, from examination of the fractured tracks from G-AWND and G-AWNM that the critical crack length is exceedingly small, *ie* approximately .17 inches. Since the crack growth mechanism is initially that of stress corrosion, the rate of growth cannot be predicted with any accuracy. This raises questions concerning the frequency of such inspections and the sensitivity of the techniques required, (*ie* what size of crack such techniques must be capable of detecting - reliably).

During the investigation of the somewhat similar accident to G-AWNE at Boston in 1985, (see NTSB report No. AAR 87-02), it was noted that the bolts securing the flap track forward attachment fitting to the wing suffered failure as a result of the presence of very small fatigue origins in the bolt shanks. Once again, these bolts were not "lified" and no realistic inspection procedure was specified to ensure their continuing integrity.

#### **2.4 Certification considerations**

The Boeing 747 aircraft was originally certificated by the Federal Aviation Administration (FAA). The certification in the United Kingdom was carried out by the Air Registration Board (now the CAA) and took the form of a validation of the FAA certification, combined with an appraisal of those areas in which the then current British Civil Airworthiness Requirements (BCARs) differed from the corresponding US Federal Aviation Regulations (FARs).

The differences between requirements resulted in some changes to the aircraft, but the flap tracks were not affected and remained identical on British registered Boeing 747 aircraft to those registered elsewhere.

As part of the certification process, the Manufacturer produced a document summarising the fail-safe strength of important components whose failure could adversely affect the flight characteristics of the aircraft. This document stated that the flap tracks were fail-safe and implied that the inboard tracks, of the inboard

flaps, were the most critical from the fail-safe standpoint. It did not appear to identify the fact that no alternative load path existed should failure occur close to the forward ends of those tracks further outboard on the aircraft, *ie* the fact that no load can be carried by these tracks after failure of the steel forgings at the forward ends.

Although in practice the failures in question resulted from stress-corrosion and could therefore be considered as not falling under the "Fatigue Evaluation of flight structure" heading of FAR 25, (current at the time the Boeing 747 was certificated) the absence of fail-safe capability at this location has enabled this crack mechanism to exploit a structural weakness.

## **2.5 Materials considerations**

Although stress-corrosion cracks occur periodically in most aerospace structural materials, such cracks in light alloy components seldom cause catastrophic failure. This is largely the result of the lower working stress levels and relative ductility of such materials, which result in critical crack lengths which are sufficiently large to enable such cracks to be detected well before they cause a major reduction in strength. Ultra-high tensile strength/low ductility steels are generally used in highly loaded forgings where a small cross-section is required and are hence subject to high design stress levels. These result in a low critical crack length for the materials in question and can allow stress corrosion failure to occur unexpectedly, where the corrosion protection has become degraded. This problem can only be overcome if a demanding and effective inspection programme is implemented on aircraft in service. To put this in perspective, the detection of cracks of as little as .17 inches in length, in an inaccessible part of an aircraft of approximately 200 ft wing-span, is involved in this type of failure.

Although such cracks are detectable, there is the formidable problem on a large structure of knowing where to inspect, and at what frequency. Although this may be analysed mathematically for cracks originating by a fatigue mechanism, the stress-corrosion mechanism is not amenable to any current analytical treatment and must be regarded in practical terms as an almost random process.

Defence against stress corrosion failure in such ultra high tensile strength steel structures depends upon effective corrosion protection. This cannot be guaranteed in many areas without unrealistic amounts of dismantling at unreasonably frequent intervals. Major components manufactured from these high-strength steels can thus only achieve acceptable structural integrity if they are designed with effective fail-safe characteristics and are operated with corresponding inspection programmes.

## 2.6 Inspection techniques

Metallurgical examination found stress-corrosion cracking in the outboard flange of the track below the No. 1 bolt hole. It did not, however, prove possible to establish the crack growth rate or the time during which a crack was present at this point. It was not therefore possible to establish whether the ultrasonic inspection, carried out 152 cycles before the failure, was unsuccessful in detecting an existing crack, or whether crack growth had occurred in less than 152 cycles.

The ultrasonic technique introduced to inspect the areas in question can be a very effective means of crack detection. It is, however, subject to reduced sensitivity when moisture is present in the crack. The environment at the forward end of the flap-track is frequently very wet for some time after landing, where the wing box and residual fuel have been subject to a "cold-soak" at altitude and then produce considerable condensation under temperate lower-level conditions. During the latter part of a flight with flap deployed, the loads in such a crack in the bolt hole area are tensile, whereas under static conditions they are compressive. Such conditions can allow moisture to gain ingress into a crack during descent, when ambient pressure is increasing, and to remain there although the track appears to be perfectly dry during subsequent inspection.

Also important, however, are the practical human-factor problems of carrying out such *in-situ* inspections. It has becoming increasingly recognised that a relatively straightforward non-destructive testing (NDT) process may be shown to be very effective under test and demonstration conditions, and yet have a high incidence of failure to detect existing cracks when carried out repetitively during line maintenance. In the case of this inspection on the Boeing 747, to examine all 8 flap tracks calls for ultrasonic inspections of 64 bolt holes. Yet failure to detect just one crack, of a depth substantially less than .17 inches, will permit this type of track failure to occur.

## 2.7 Corrosion

This failure clearly originated from a corrosion pit in the bore of the No. 1 bolt hole, in the outboard web. In order for this corrosion to have occurred, ingress of moisture must have taken place. In view of the apparent lack of protection within the bore of the bolt hole, the exclusion of moisture was primarily dependent upon the sealant under the bolt head and that between the fail-safe bar and the steel material of the track.

Although the extent of the deterioration of these areas of sealant before the failure initiated is not known, it is clear from the corroded state of the original fracture

surfaces of the track that this material corrodes rapidly when unprotected surfaces are exposed to the wet environment under the wing.

Due to the susceptibility of this material to stress corrosion cracking, that phenomenon could be expected to occur fairly rapidly after the first ingress of water.

It therefore seems likely that the presence of the sealant had successfully protected the bolt holes from corrosion throughout most of the life of the aircraft, but that fairly recent deterioration of the sealant had allowed the events leading to this failure to occur. The reason for the loss of effectiveness of the sealant must remain a matter of speculation, but does raise questions concerning the durability of such sealants.

## **2.8 Airworthiness assurance**

In view of the difficulty of introducing inspections which can be guaranteed to detect cracks in the forward ends of such flap tracks and the lack of a full fail-safe design in this structural location, the airworthiness management of this area cannot be said to have complied with any acceptable reliability philosophy.

### 3 Conclusions

#### (a) Findings

- (i) The flight crew were properly licensed to carry out their duties.
- (ii) During an ILS approach to runway 27L, and shortly after flap 30 extension, the crew experienced a "thump" at about 600 feet agl and the aircraft immediately started to yaw and roll to the right.
- (iii) The crew experienced control problems, but were able to continue the approach to a safe landing.
- (iv) The crew were not aware of the cause of their control problems until after landing.
- (v) The aircraft suffered a failure of the forward end of the No. 6 flap track shortly after the extension of 30 flap during final approach.
- (vi) The failure caused displacement of the right inboard flap unit, inducing considerable local secondary damage.
- (vii) The flap track failure occurred at a point where the structure was not fail-safe.
- (viii) Complete fracture of the flap track occurred due to cracking which originated at the No. 1 (forward) bolt holes, primarily the outboard hole where it had initiated from stress-corrosion, associated with a corrosion pit located in the lower bore.
- (ix) The flap track failure occurred at a time mid-way through a special inspection interval, whose methodology and frequency had been revised after an almost identical type of failure on another Boeing 747 aircraft, some 4 months earlier.
- (x) Corrosion pitting was found in other bolt holes in the forward section of this track, and has since been found in numerous bolt holes on other aircraft in the fleet.
- (xi) Corrosion protection of the bolt holes, and adjacent areas of the track flange, had deteriorated.

- (xii) The reliability of the special ultrasonic technique currently used to detect very small cracks in flap tracks is open to question, particularly where moisture may be present within such cracks.
- (xiii) A decision by this crew, on operational grounds, to perform a go-around manoeuvre after the flap track failure would almost certainly have resulted in more secondary damage, with the possibility of serious control problems.

(b) Causes

The direct cause of the flap track failure was stress-corrosion cracking initiation from a corroded forward (No. 1) bolt hole which induced fast brittle fractures of the steel track, at a point where the design was not fail-safe.

A contributory cause was the failure of a special inspection to detect such cracking, before full fracture occurred, despite many revisions of its requirements following other instances of flap track cracking and failure.

## 4 Safety Recommendations

The following Safety Recommendations were made during the course of the investigation:

- 4.1 The CAA should continue to liaise with the Boeing Airplane Company with the aim of bringing forward the 30 April 1992 deadline for replacement of flap tracks on those Boeing 747 aircraft which are currently fitted with the early standard of tracks.
- 4.2 The CAA should review the current inspection requirements applicable to Boeing 747 aircraft fitted with the latest production standard of flap tracks, with a view towards ensuring that such inspection techniques and frequencies can be relied upon to prevent future failure of such tracks.
- 4.3 The CAA should initiate action with the FAA with the aim of placing a requirement upon the Boeing Airplane Company that it undertakes modification of Boeing 747 aircraft to achieve a full fail-safe design of flap track assemblies.
- 4.4 The CAA, in conjunction with the FAA, should carry out a detailed audit of significant structure in Boeing 747 aircraft, and other large transport aircraft, where ultra high tensile strength steels are used in order to establish those points where the structure does not fully comply with fail-safe philosophy.
- 4.5 The CAA should formulate a requirement for special corrosion inspections, including corrosion protection condition, within those areas of transport aircraft structures where ultra high tensile strength steel components are used.
- 4.6 The CAA should re-assess the capability of existing inspection procedures to successfully detect, under realistic inspection conditions, potentially critical defects and cracks in ultra high tensile strength steel structure.

E J TRIMBLE  
Inspector of Air Accidents  
Air Accidents Investigation Branch  
Department of Transport

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