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# Report IN-003/2011

Incident involving an Airbus 330, registration EC-LKE, operated by Air Europa, at FL240 in the vicinity of the Toledo VOR/DME (Spain), on 13 February 2011

GOBIERNO DE ESPAÑA

MINISTERIO DE FOMENTO

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# Foreword

This report is a technical document that reflects the point of view of the Civil Aviation Accident and Incident Investigation Commission (CIAIAC) regarding the circumstances of the accident object of the investigation, and its probable causes and consequences.

In accordance with the provisions in Article 5.4.1 of Annex 13 of the International Civil Aviation Convention; and with articles 5.5 of Regulation (UE) n.° 996/2010, of the European Parliament and the Council, of 20 October 2010; Article 15 of Law 21/2003 on Air Safety and articles 1, 4 and 21.2 of Regulation 389/1998, this investigation is exclusively of a technical nature, and its objective is the prevention of future civil aviation accidents and incidents by issuing, if necessary, safety recommendations to prevent from their reoccurrence. The investigation is not pointed to establish blame or liability whatsoever, and it's not prejudging the possible decision taken by the judicial authorities. Therefore, and according to above norms and regulations, the investigation was carried out using procedures not necessarily subject to the guarantees and rights usually used for the evidences in a judicial process.

Consequently, any use of this report for purposes other than that of preventing future accidents may lead to erroneous conclusions or interpretations.

This report was originally issued in Spanish. This English translation is provided for information purposes only.

# Table of contents

## Abbreviations

| | |
|---|---|
| 00° | Degree(s) |
| ACC | Area control center |
| AD | Airworthiness directive |
| ATC | Air traffic control |
| ATPL(A) | Air transport pilot license (aircraft) |
| CAAM | Continous airworthiness assessment methodologies |
| CAS | Calibrated airspeed |
| cm | Centimeter(s) |
| CSN | Cycles since new |
| CVR | Cockpit voice recorder |
| EASA | European air safety agency |
| ECAM | Electronic centralyzed aircraft monitoring |
| EHM | Engine health monitoring |
| EPR | Engine Pressure Ratio |
| FBO | Fan blade off |
| FCTM | Flight crew training manual |
| FDM | Fight data monitoring |
| FDR | Flight data recorder |
| FL | Flight level |
| ft | Foot |
| GS | Ground speed |
| h | Hour(s) |
| HCF | High cycle fatigue |
| HP | High pressure |
| ILS | Instrument landing system |
| IR | Instrument rating |
| kg | Kilogram(s) |
| kt | Knot(s) |
| L | Left |
| LCF | Low cycle fatigue |
| LP | Low pressure |
| m | Meter(s) |
| MCT | Maximum continuous thrust |
| MHz | Megahertz |
| MLW | Maximum Landing Weight |
| mm | Milometer(s) |
| µm | Micra(s) |
| N1 | Low pressure spool speed |
| N3 | High pressure spool speed |
| NMSB | Non-modificable service bulletin |
| OM | Operations Manual |
| P/N | Part number |
| PF | Pilot flying |
| PFR | Post Flight Report |
| PNF | Pilot not flying |
| QAR | Quick access report |
| R | Right |
| RFFS | Rescue and Firefighting Service |
| S/N | Serial number |
| SEM | Scanning electron microscope |
| SID | Standard instrument departure |
| TSN | Total since new |
| TWR | Tower |

# Synopsis

| | |
|---|---|
| Owner and operator: | Air Europa |
| Aircraft: | Airbus 330-243, registration EC-LKE |
| Date and time of accident: | Sunday, 13 February 2011; 16:16:03 local time[1] |
| Site of accident: | FL220 in the vicinity of the Toledo VOR/DME (Spain) |
| Persons onboard: | 11 crew, uninjured; 333 passengers, uninjured |
| Type of flight: | Commercial air transport-Scheduled – International – Passenger |
| Phase of flight: | En route |
| **Date of approval:** | 24 June 2015 |

## Summary of accident

On Sunday, 13 February 2011, aircraft EC-LKE, an Airbus 330 operated by Air Europa, was on a flight from Madrid (Spain) to Cancun (Mexico) with 344 people on board. At 16:16:03, fourteen minutes after starting the takeoff run, a partial FBO (fan blade off) event occurred in the number 2 (right) engine. The crew declared an emergency (MAYDAY MAYDAY MAYDAY) and returned to Madrid, where the aircraft landed uneventfully.

The investigation determined that incident on aircraft EC-LKE occurred due to the detachment of fan blade no. 4 (P/N FW23741 S/N RGF18472) on the right engine (Trent 772B-60 S/N 41222) after 4367 cycles due to a crack propagated by fatigue starting from a bonding defect measuring 600 × 70 μm and located 150 mm away from the root and 113 mm away from the leading edge, at the bond line between the suction panel and internal membrane.

This defect, caused by the presence of an organic contaminant during the manufacturing process, in addition to impeding the bonding of the material, modified the material's properties locally without causing any visible microstructural changes. Under normal operating conditions, this defect, in isolation, could not have grown and fractured the blade after 4,367 cycles. It is thus likely that the blade was subjected to higher than normal loads. The circumstances under which said loads could have been produced could not be determined.

The report contains one safety recommendation for the European Aviation Safety Agency (EASA)[2], as the certifying authority for the fan case of the engine.

[1] All times in this report are local, as taken from the flight data recorder.
[2] EASA: European Aviation Safety Agency.

# 1. FACTUAL INFORMATION

## 1.1. History of the flight

On Sunday, 13 February 2011, aircraft EC-LKE, an Airbus 330 operated by Air Europa, was on a flight from Madrid (Spain) to Cancun (Mexico). Onboard were 333 passengers, 8 cabin crew[3] and 3 flight crew[4] (one captain and two first officers).

The pilot flying was one of the first officers, who was seated in the RH seat. The captain was in the LH seat and was acting as the pilot not flying (pilot monitoring). The second first officer was in one of the vacant crew jump seats in the cockpit.

The initial contact with the Madrid control tower took place at 15:26, during which the crew requested start-up clearance. The wind was from 210º at 13 kt, gusting to 29 kt.

At 16:02 the aircraft was at the runway 15R threshold, ready for takeoff and then continue with the standard instrument departure (SID) CCS1AS, as cleared.

At 16:13 the aircraft was cleared to climb to FL240, and one minute later to FL270.

At 16:16:03, fourteen minutes after starting the takeoff run, a partial FBO (fan blade off) event occurred in the number 2 (right) engine. The noise was heard in the cockpit and the entire aircraft shook and continued to vibrate for the rest of the flight. The ECAM (Electronic Centralized Aircraft Monitoring) showed ENGINE STALL and ENGINE FAIL warnings. At the time the aircraft was climbing through 24,100 ft, with N1 on both engines at 86%. The ground speed (GS) was 378 kt and the calibrated airspeed (CAS) was 306 kt. The operating parameters on both engines had been normal prior to the event. The crew reacted immediately and within five seconds of the partial FBO the throttle lever on the number 2 engine was placed in IDLE. At 16:16:38, 35 seconds later, the engine was off (ENGINE MASTER OFF).

At 16:16:24 the crew declared an emergency (MAYDAY MAYDAY MAYDAY) and its intention to return to Madrid. ATC gave priority to the aircraft over all others to facilitate its return to Madrid. At 16:21 the local alarm was activated at the Madrid-Barajas Airport.

At 16:36, twenty minutes after the partial FBO event, the aircraft made an overweight landing (228,400 kg[5]) on runway 18R. The wind was from 240º at 16 kt and gusting to 24 kt. The landing was uneventful.

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[3] Operations Manual, Part A, Section 4.1.4.2. The minimum cabin crew for the Airbus A330-200 is eight.

[4] The cockpit crew was augmented by one relief pilot due to the scheduled flight time. The minimum flight crew for the Airbus A330-200 is two pilots (OM Part A, Section 4.1.3).

[5] The maximum landing weight (MLW) was 180,000 kg. It had taken off with 233,000 kg, its maximum takeoff weight.

The aircraft left the runway via exit taxiway Z10 and continued along taxiways W, MZ, M16 and M17, the intention being to go to parking stand 40, as assigned. While taxiing, however, the temperature of the tires started to increase and the crew decided to stop the airplane. After consulting with ATC, the aircraft stopped at 16:42 on R7. Minutes later, with the aircraft already stopped, there was a small fire in tire number 4 of the left main gear. The firefighters, who were alongside the aircraft, applied water and quickly brought the fire under control. As a preventive measure they cooled down the entire landing gear.

There was no emergency evacuation and the passengers started deplaning at 17:10 normally via the LH doors 2 and 4. By 17:20 all the passengers were off and they were transported in buses to the T4 terminal. At 17:41 the local alarm was deactivated at the airport and the passengers were boarded on another flight that same evening. No one onboard the aircraft was injured.

## 1.2. Damage to aircraft

A visual inspection of the aircraft after the incident revealed the following damage to the right (no. 2) engine:

- In the fan blades:
  - About 75% of blade number 4[6] on the fan was missing. This had been the first blade to fail.
  - About 50% of the trailing blade[7], number 5, was missing.
  - The remaining blades showed rippling and tearing to varying degrees.
- In the fan case:
  - There was an impact mark at the 2 o'clock position[8], and a smaller mark at the 3 and 5 o'clock positions.
- In the nose cowl:
  - There was an impact mark with upraised material at the 5 o'clock position, which also affected the fan case.
  - The inner barrel was perforated between the 3 and 4 o'clock positions.

[6] Reference to the position in which the blade is installed in the fan.
[7] Trailing in the direction of motion.
[8] Positions as on a clock face, with the engine seen from the nose cowl (e.g., 4 o'clock position refers to the position of the needles on a clock at 04:00).

– There was material missing from the outer panel between the 4 and 9 o'clock positions (3.38 m long and a maximum width of 60 cm).

- There had been no loss of fluid or fires in the engine.

The right outboard flap had a 2.5 cm crack. The rest of the aircraft was undamaged. After the initial inspection in Madrid, the fragment of blade 4, which had remained attached to the fan, was removed and taken to the manufacturer's facilities in Derby (United Kingdom). The engine was removed from the aircraft and also shipped to Derby for inspection. Once there, all of the remaining blades were removed.


Figure 1. Aircraft after the incident (view from the side of engine n.° 2)

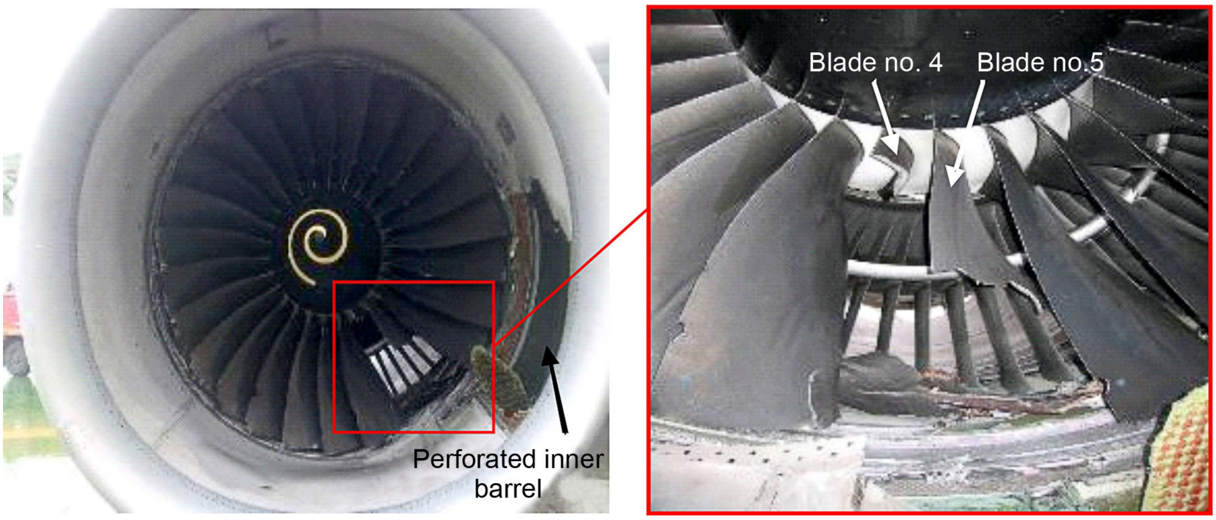


**Figure 2.** Aircraft after the incident (front view of engine n.º 2)

## 1.3. Personnel information

The crew consisted of one captain, two first officers and eight flight attendants, including the purser. The entire crew had reported for duty at 13:25 on the day of the incident.

The captain of the aircraft, who at the time of the incident was the pilot not flying, was a 47 year old Spanish national and had been working for Air Europa for 19 years. He had a valid medical certificate, an ATPL (airline transport pilot license), and A330 and instrument type ratings. He had a total of 14,757 flight hours, 1,880 on the type. The day before the incident he had rested. In the previous week he had flown 25 h, 85 h in the previous month, 197 in the previous three months and 783 in the previous year. The last training courses he took had been a simulator refresher (December 2010), the operator's proficiency check (September 2010), a refresher theory course (June 2010) and the JAR-FCL proficiency check (May 2010).

The aircraft's first officer, who at the time of the incident was the pilot flying, was a 38-year old Spanish national and had been working for Air Europa for six years. He had a valid medical certificate, an ATPL (airline transport pilot license), and A330 and instrument type ratings. He had a total of 5,386 flight hours, 2,084 on the type. In the previous week he had not flown, he had 76 hours in the previous month, 228 in the previous three months and 861 in the previous year. His most recent training had been the simulator refresher (November 2010), the operator's proficiency check (June 2010), a refresher theory course (May 2010) and the JAR-FCL proficiency check (May 2010).

The second first officer, who was flying as the relief pilot, was a 30 year old Spanish national and had been working at the company for six years. He had a total of 5,995 flight hours, 2,164 on the type. He had a valid medical certificate, an ATPL (airline transport pilot license), and A330 first officer and instrument type ratings. The day before the incident he had rested. In the previous week he had flown 18 h, 78 h in the previous month, 239 in the previous three months and 876 in the previous year. In October 2010 he had passed his last theory and simulator refresher courses, the operator's proficiency check in August 2010 and the JAR-FCL proficiency check in April 2010.

The purser was a 44 year old Spanish national and had been working for the company for 23 years. He had rested the week before and had flown 30 hours in the last month, 92 in the last three months and 460 in the last year. His last periodic training had been in June 2010.

The remaining cabin crew were between 30 and 35 years old, Spanish nationals and had rested the day before (except for two of them). They had been at the company between five and eleven years.

## 1.4. Aircraft information

### 1.4.1. *General information on aircraft EC-LKE*

The aircraft, an Airbus A330-243, S/N 461, was owned by the Orbest Airlines[9] group. Until 23 December 2010, it had been operated by Orbest Portugal, a subsidiary of the company, under registration CS-TRA. On 23 December 2010, it started operations for Air Europa with registration EC-LKE.

The aircraft had two Rolls-Royce Trent 772B-60 engines. The right one (number 2) had S/N 41222 and the left one (number one) had S/N 41223. At the time of the incident the aircraft had a total of 39,563:58 h. Its last flight had been Cancun-Madrid, arriving in Madrid at 12:02, that is, four hours before the incident.

Orbest Airlines, in addition to being the owner, was also responsible for managing the aircraft's airworthiness, both during its operations with Orbest Portugal and with Air Europa. The operators (Orbest Portugal and Air Europa) handled the flight data monitoring (FDM), the tracking of faults using the AIRMAN system and the statistical monitoring of engine performance, subcontracted to Rolls-Royce. As part of this monitoring, the engine operating reports were received by the operator and by Rolls-Royce, which informed the operator of any operating limit exceedances and of the recommended maintenance actions.

[9] Previously known as Iberworld.

### 1.4.2. *Information on the right engine (number 2)*

The right engine, a Rolls-Royce Trent 772B-60, S/N 41222, had been manufactured in 2001 and had always been installed on the incident aircraft. Its total time since new (TSN) was 34350 hours and its cycles since new (CSN) was 4,367.

Since its installation on the aircraft, the engine had been removed for maintenance three times, in July 2002, April 2007 and April 2010. On this last check, with a TSN of 33,409 h and a CSN of 4,258, six new fan blades were installed and the remaining blades (including the one that fractured) were repaired and reinstalled in the engine. A total of 940 h and 109 cycles had elapsed since then.

### 1.4.3. *Information on blade number 4*

Blade number 4, where the fault started (P/N FW23741, S/N RGF18472), exhibited the highest percentage of detached material (see figure 2). Its TSN was 34,350 h and its CSN was 4,367.

It had been manufactured in 2001 and then installed on engine number 2. The last maintenance action involving the blade had been in April 2010, and consisted of performing routine maintenance tasks on the blade, including reapplication of the root coatings, restoring the profile on the leading edge and the surface finish on the blade, and changing the shear keys. After a satisfactory blade inspection it was reinstalled in the engine. A total of 109 cycles and 940 h elapsed from that day until the incident.

### 1.4.4. *The Trent 700 engine*

The Rolls-Royce Trent 700 is a wing-mounted three-shaft engine. It has three compressors (low, intermediate and high pressure), each driven by its associated turbine. It is 7.3 m long and its nose cowl has a diameter of 3.2 m, with the fan diameter being 2.4 m.

The main components of the propulsion system are the nose cowl, the right and left fan cowl doors, the engine and its mounts, the exhaust nozzle and the thrust reverser.

The engine consists of eight modules. Of interest to this incident are the number 1 (low-pressure compressor) and the number 7 (LP compressor case or fan case):

- Module 1 (LP Compressor): consists of a simple rotor[10] with 26 blades attached to a disc. It is one of these blades that fractured during the incident. The fan disc is

[10] Normally called a fan.

attached to the LP compressor shaft, which provides the N1 reading shown in the cockpit. The fan blades have a typical hollow design to reduce weight. The manufacturing process of a blade involves three panels, two thicker ones that comprise the blade's outer surfaces, and a third panel between the first two, called the membrane, that is thinner and smaller. At specific points on the outer sheets a stop-off material is applied in a specific pattern using a screen that is only used 30 times. This stop-off material keeps the panels and membrane from sticking together, allowing the blade's hollow internal structure to form. After this stop-off material is applied, the panel undergo a diffusion bonding[11] process, a shaping process and a super plastic[12] forming process to generate the blade's structure (see figure 3). The panels bond at those points where the stop-off material has not been applied.

- Module 7 (LP compressor or fan case): houses module 1 (the fan) and is wrapped with Kevlar, a very strong material whose purpose is to contain any blade fragment that detaches during engine operation. In other words, the fan case is the containment system that keeps the damage from an FBO event from spreading to the engine or aircraft. This system is designed for the worst-case scenario possible, which is the detachment of an entire blade at takeoff power[13].

In addition to this system, the engine is designed with two fusses in the Module 2 (located behind the fan). The fusses area design to function during a FBO event allowing the fan rotor assembly to rotate around the new center of mass that results from the released blade material. This reduces the unbalance of the fan rotor and therefore limits the level of vibration transmitted to the engine and aircraft.

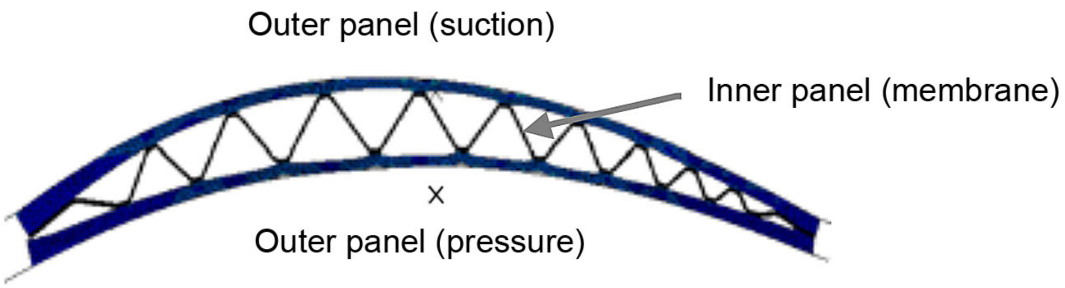


**Figura 3.** Cross-section of a blade with the outer panels and the inner membrane

[11] Diffusion bonding is a technique for joining materials in which the atoms on two solid metal surfaces mix under certain conditions, typically high temperature and/or high pressure.

[12] Super plasticity forming is a process in which a material is made super plastic, a state in which it is possible to deform it past its breaking point. This state is usually achieved under high-temperature conditions.

[13] This system is subject to testing during the engine certification process.

## 1.5. Aids to navigation, communications and flight recorders

The flight was reconstructed using the communications and radar returns from the ATC stations involved in the flight, along with the data found on the flight data recorder (FDR)[14] and the cockpit voice recorder (CVR)[15]. Figures 4 and 5 show the flight path, altitude and speed (CAS) of the aircraft from the time it took off from runway 15R at the Madrid-Barajas Airport until it landed on runway 18R.

### 1.5.1. *Fault initiation: ENGINE STALL*

In the cockpit, the failure (point 3 in Figures 4 and 5) caused a noise, a very strong vibration (which remained for the rest of the flight) and an aural warning (single chime). According to the FDR data the engine 2, N3 vibration increased from 0.5 to 2.6 CU. The captain called out the warning shown on the ECAM[16], which was initially an ENGINE

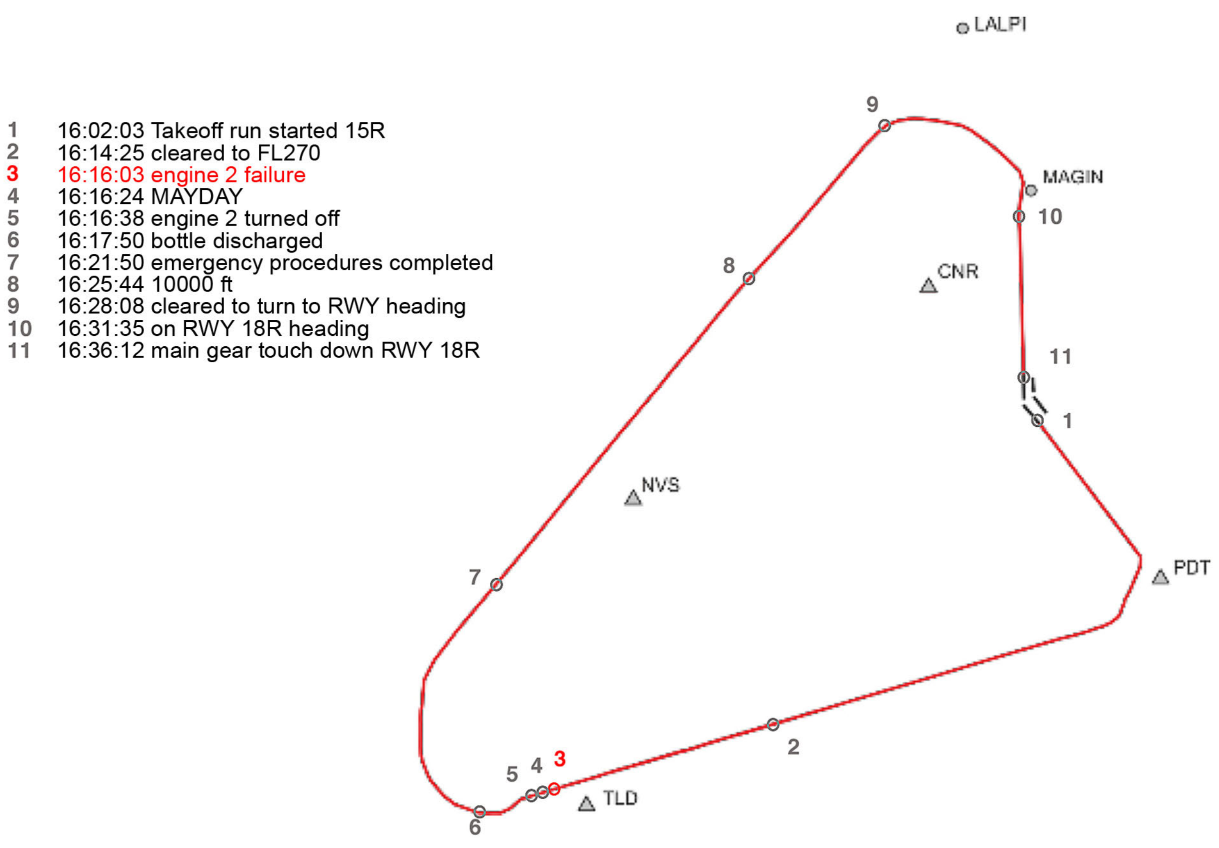


**Figure 4.** Flight path

[14] Honeywell P/N: 980-4700-042 S/N: 8451.
[15] Honeywell P/N: 980-6022-001 S/N: 4847.
[16] The ECAM is a system that displays information on the state of the aircraft and indicates the actions that the crew must take for most normal, abnormal and emergency actions.

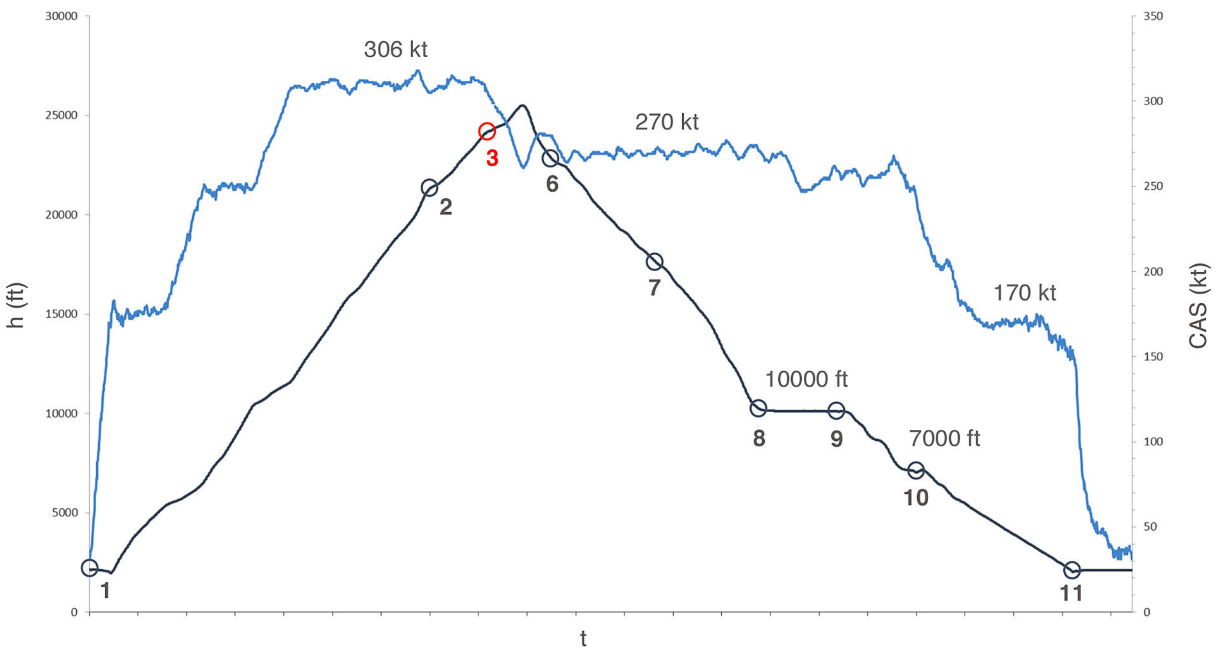


Figure 5. Altitude and speed (CAS) during the flight (points 1 to 11 refer to figure 4)

STALL and which the first officer repeated. The FDR recorded a drop in the N1 rpm's for the right engine.

The captain's first reaction was to take control of the aircraft, which he did not communicate to the first officer (who at the time was the pilot flying). He asked for the ECAM actions, disengaged the autopilot[17] and auto-thrust[18], placed the throttle lever for the right engine at IDLE (five seconds after the fault) and the one for the left engine at MCT[19] (maximum continuous thrust). These initial actions were immediate and were completed within eleven seconds.

The procedure was then interrupted by a relative of the captain who, on three occasions, noted that there was smoke and fire. Along with the comments from the relative the

[17] The FDR recorded the autopilot being disengaged by the first officer, who was then the PF. The captain's autopilot was disengaged 26 seconds later.

[18] FCTM. Abnormal operations. Operating techniques. Engine failure during cruise. Procedure:
"As soon as the engine failure is recognized, the Pilot Flying (PF) simultaneously:
- set all thrust levers to MCT.
- disconnect A/THR.

Then, PF will
- select the SPEED according to the strategy,
- if appropriate, select a HDG to keep clear the airway
- select the appropriate engine inoperative altitude in the FCO ALT window and pull for OPEN DES.

Then, PF will
- require the ECAM actions".

[19] The FDR recorded the placing of the right engine thrust lever in IDLE (first step in the ENG STALL procedure) and the placing of the left engine thrust lever in MCT (maximum continuous thrust).

first officer was heard saying "you have controls and communications". The captain instructed the first officer to declare an emergency and said they were returning to the airfield. He told the first officer to call the purser and the relatives who were in the cockpit to fasten their seatbelts[20]. Two minutes and 20 seconds later the relatives returned to their seats as instructed by the purser and relief pilot.

Twenty-one seconds after the fault, the first officer, as instructed by the captain, declared a MAYDAY and, 35 seconds after the fault (point 5 in Figure 4), the crew turned off the right engine (ENGINE MASTER OFF), the last item in the ENGINE STALL procedure.

The captain's haste in executing the initial actions was reflected in how he spoke, very quickly and conveying a sense of urgency. His tone of voice then relaxed. The speed and tone of the first officer's voice did not change with respect to normal, as his voice remained calm and relaxed.

### 1.5.2. *ENGINE FAILURE*

Forty seconds after the engine failure, the start of the ENGINE FAIL[21] procedure was heard. The first officer, who was then the pilot not flying, announced the title and started reading the first two items: "engine two fail, engine start selector... ignition, if damage engine two fire push-button... push". At that point in the list, the captain interrupted the first officer, asking him to request a descent from ATC: "descent descent". The first officer took advantage of this request to restate the assignment of duties[22] and remind the captain that he (the captain) should handle communications. "Do you have the comms?"

When the captain finished with ATC and was cleared to descend to 10,000 ft and head to LALPI (16:17:10), the first officer resumed the procedure that had been interrupted. The aircraft, which was turning to return to Madrid, started to descend. The item "Engine two fire push button... push" was repeated three times until the captain was again focused on the procedure and the first officer asked him, "Engine two, confirm XX (captain's first name)?" The captain replied "Confirm" and a single chime was heard associated with the execution. Forty-six seconds had elapsed since the start of the ENGINE FAIL procedure, and 1 minute 26 seconds since the engine failure. The bottle

[20] The airline's Operations Manual only allows personnel authorized by the company, and with the captain's permission, to be in the cockpit.

[21] Recorded in the PFR (Post Flight Report).

[22] FCTM, Operational Philosophy, abnormal operations, task sharing rules:
"It is important to remember that, after ECAM ACTIONS, announcement by the PF:
- The PF's task is to fly the aircraft, navigate, and communicate.
- The PNF's task is to manage the failure, on PF command.

The PF usually remains the PF for the entire flight, unless the Captain decides to take control.
Some selectors or pushbuttons (including the ENG MASTER switch, FIRE pushbutton...) must be crosschecked by both the PF and PNF, before they are moved or selected."

was discharged 21 seconds later, that is, 1 minute 47 seconds after the engine failure (point 6 in figures 4 and 5).

Three seconds after the discharge, the captain asked the relief pilot to call the purser. The first officer continued reading the procedural actions and, even though he was doing the procedure with the relief pilot, again requested confirmation from the captain to carry it out: "Left and right inner tank split on, confirm?"

The purser went into the cockpit and the captain informed her that they had lost an engine and to prepare everything for "safe operation". While the captain was speaking with the purser, the first officer interrupted to remind him of the waypoint he had just reported to ATC. The first officer requested confirmation to "clear engine two" [23]. With the purser still in the cockpit, ATC asked about a fuel jettison. The purser did not interrupt and used the opportunity to suggest to the captain's relatives that they return to their seats. The captain finished talking to ATC, whom he had told they would not be jettisoning fuel[24], and informed the purser that there would not be an evacuation (after being specifically asked by the purser).

### 1.5.3. *After ENGINE SHUTDOWN*

Two minutes 51 seconds after the failure (16:18:54), the first officer was heard saying "Engine two shut down, fuel imbalance", associated with the start of the After ENGINE SHUTDOWN procedure. From then on, the first officer and the relief pilot read out loud and carried out the actions for this procedure. In the meantime, the captain, three minutes after the failure, informed the passengers of the engine failure and of their return to Madrid. The report was very calm and deliberate and conveyed a situation that was calm and under control.

The After ENGINE SHUTDOWN procedure lasted 2 minutes 27 seconds. After it was completed they confirmed with the captain to "remove status", and the captain recalled out loud that they had to "look at the overweight" (landing with excess weight). This concluded the abnormal and emergency procedures after the engine failure, five minutes after the start of the emergency (point 7 in figures 4 and 5).

All of the actions (heading, speed and altitude changes and lists) that were carried out by both the captain and first officer were reported out loud. The captain relied on the first officer and on the relief pilot to clarify any doubts ("What did he say, to the right of EPINA?" "Confirm the navigation", "Confirm straight to EPINA", "Which runway is in use?"). The pilot was monitoring the flight and notified the captain ("Hold", "North

[23] FCTM: abnormal operations – crew coordination: Clear "name of the system" when the ECAM actions are completed. In this case, the system being cleared is engine 2, hence the statement to "clear engine 2".

[24] This airplane did not offer the possibility of jettisoning fuel in flight.

to the right initially and then to EPINA", "To LALPI"). The situation in the cockpit was calm and under control. In fact, the first officer told the captain, "Relax, you fly the plane, we'll take a look".

### 1.5.4. *Rest of the flight until the landing*

At 16:21:50 (point 7 in figures 4 and 5), five minutes after the failure, the aircraft was descending at a CAS of 270 kt and heading northeast to LALPI. They had finished the abnormal procedures. The first officer started preparing the aircraft for the approach and landing, and both he and the relief pilot did the necessary calculations (runway required, speeds, etc.). The first officer was still the pilot monitoring, and at one point during the flight warned the captain that they were too high and that they could hold over LALPI, though in the end that was not necessary.

Seven minutes after the failure the captain called the airline's ground operations and reported they had high vibrations in the no. 2 engine and were returning to the airport. This was the first time they commented on the high vibrations and wondered what was happening. After a visual inspection of the engine at the captain's request, the relief pilot confirmed that "the engine was ok, it was vibrating but there was no smoke". During the approach the captain was heard saying "the vibrations are terrible".

Eight minutes after the failure the first officer started the OVERWEIGHT LANDING checklist, which they had mentioned several times during the descent as a reminder. The captain informed the purser they would be landing in 15 minutes, to which the purser replied that the crew was informed and the cabin secure.

At 16:25 (point 8 in figures 4 and 5) the aircraft was still headed northeast toward LALPI and reaching 10,000 ft. The captain twice asked ATC for a fast descent, and again relayed their urgent need to return to the airport as fast as possible. Since they were at the minimum sector altitude (10,000 ft), they were unable to descend until 16:28 (point 9 in figures 4 and 5), when ATC cleared them to turn right to the runway 18R ILS and descend to 8,500 ft, thus shortening the maneuver. This clearance took the aircraft close to an Air Nostrum that was ahead of them on approach to 18R. To separate them, ATC instructed the Air Nostrum to divert to the 18L localizer and then to turn left. The Air Nostrum aircraft complied with ATC's instructions at all times.

At 16:31 (point 10 in figures 4 and 5) the aircraft intercepted the runway heading at a CAS of 220 kt. Throughout the descent they were very mindful of their speed and altitude due to their overweight. They deployed the airbrakes four times and two minutes later, at 16:33, slowed to 170 kt, a speed they held until the landing.

At 16:33 the crew was heard reading the APPROACH CHECKLIST, with the first officer offering to read the LANDING CHECKLIST a short while later.

At 16:35, after an aural warning indicating they were 1,000 ft above ground, the first officer asked the captain if he would be doing the landing (meaning whether he would land using AUTOLAND[25] or in manual), although the captain thought the first officer wanted to do the landing. He offered it to him, but the first officer insisted that the captain do it, as he was the pilot flying. They were relaxed. The captain wanted to land in manual and seconds later disengaged the autopilot. At 16:35:54 the GPWS GLIDE SLOPE[26] warning activated for four seconds. The first officer monitored and gave the captain instructions: "Hold, hold, perfect, pull up". The main landing gear touched down at 16:36:12 (point 11 in Figures 4 and 5) without incident at a CAS of 151 kt. They used the autobrakes set to medium intensity. With the airplane on the ground and still on the runway, the captain instructed the first officer to call the purser to remind him not to evacuate or do anything.

The crew's intention all along was to exit the runway. During the landing run they asked the tower to confirm the presence of smoke in the right engine. The controller replied that he could not see anything from where he was, and they exited the runway via exit taxiway Z10. The captain was still the pilot flying. While they were taxiing, the first officer was heard calling out three temperature readings for the gear. As they were increasing, he suggested stopping the taxi and requesting a parking stand to prevent the possibility of a fire in the gear. It was then, at 16:41, that they decided not to continue taxiing and to disembark the passengers in that area. This was reported to ATC and to other units on the ground.

ATC did not authorize any more approaches to runway 18R until the aircraft exited the runway and was taxiing, fully clear of the runway. Approaching aircraft were diverted to 18L.

## 1.6. Aerodrome information

Two hours after landing, the wildlife control service at the Madrid-Barajas Airport, at the request of the airport's Operations Department, which thought that a bird strike may have caused the incident, inspected the right engine. The wildlife control service did not find any bird remains in the engine.

## 1.7. Survival aspects

The emergency was reported at 16:16:24 on the frequency of the Madrid ACC (131.175 MHz). The ACC relayed the information to the Madrid TWR, which passed it on to the Madrid-Barajas Airport. The call to the Network Management Center took place at 16:20. The series of events that took place from then on was as follows:

[25] The FCTM states that "Autoland is available with one engine inoperative".
[26] The GLIDE SLOPE warning indicates that the deviation with respect to the ILS slope exceeds 1.5 dots.

- 16:21: local alarm activated and parking stand 40 assigned. Notification of groups as per the plan[27], including the Rescue and Firefighting Service (RFFS).
- 16:36: aircraft lands and is escorted by the RFFS as it taxies.
- 16:41: crew decides to stop taxiing and request a parking stand in the area.
- 16:42: TWR informs the RFFS that the aircraft is stopping at R7 due to heating of the landing gear. Start of communications between the RFFS and the aircraft.
- 16:43: necessary resources coordinated to attend to the aircraft at its new parking stand, R7.
- 16:51: the RFFS discharges water on the gear after a small flame shoots out from wheel n.º 4 on the left gear. The entire gear is cooled down as a precautionary measure.
- 16:56: the firefighters confirm with the crew the side on which the passengers will be disembarked to set up a safe area.
- 17:07: one tractor, two stairs and five busses arrive.
- 17:10: disembarkement of passengers commences via the two left doors. They are taken to hall 1 in terminal T4.
- 17:41: local alarm deactivated once the area is cleaned and the aircraft is taken from R7 to ramp 7.

The passengers were taken to the terminal, where the operator provided food and drinks. The passengers were treated by medical staff in the terminal. This service concluded at 20:20, with a total of six passengers being treated for anxiety. All of the passengers were boarded on another flight to Cancun (Mexico) at 22:20 that same evening.

## 1.8. Tests and research

### 1.8.1. *Engine disassembly and inspection*

The engine was examined externally in Madrid before a subsequent inspection was done, after removing it from the aircraft, to evaluate the damage.

- Nose cowl: 75% of the missing material from the inner barrel was recovered after it was found inside the cowl itself. The fragments recovered showed signs of both tensile and bending fracture modes. Inspection of the outer panel revealed tensile fractures at the 4 o'clock position, which changed to an inter-ply/peeling mode towards the 9 o'clock position.
- The components mounted on the fan cowls doors exhibited minor damage (fracture of a retaining bracket of the nose cowl anti icing ductwork, fracture of the mounting lugs of the igniter box and buckled of the return cooling air pipe to the engine control unit). All of the damage was between the 2 and 3 o'clock positions.
- The fan cowl doors, the thrust reverser and the common nozzle assembly exhibited minor impact damage.

[27] RFFS, TWR, signalmen, operator, operator's handling company, Flight Safety Office, airport medical service, Civil Guard, National Police, Airport Security Service, airport press office and Network Management Center.

- Module 1, *Low-pressure compressor:* of the fan's 26 blades, number 4 had about 75% of its material missing, and number 5 had about 50% of its material missing. Of the 15 blades that exhibited rippling, five did so to a significant extent. The shear keys[28] on these blades were also more damaged. The fan was inspected under UV light and samples were taken from all of the blades, but they were determined to be of human origin and not from birds[29]. One annulus filler[30] was missing. The bolts used to attach the shaft to the fan disc were at nominal torque and the fan disc was in good condition.
- Module 2, *Intermediate pressure compressor:* the two fusible systems, which are installed in this module, worked as intended, indicating that the fan rotor had rotated eccentrically after the partial FBO. The rotors and stators exhibited damages due to the ingestion of debris during the event.
- Module 3, *Intermediate* case: in good condition.
- Module 4, *High pressure system:* there were indications of a very localized fire in the final compressor stages. The fire did not extend to the outside. The rest of the module was in good condition.
- Module 5, *Intermediate pressure turbine:* in good condition.
- Module 6, *External gearbox:* in good condition.
- Module 7, *Fan case*: two blade fragments were found inside the Kevlar coating. They were later identified as being from blade n.º 4. Sixty of the 95 Kevlar layers were perforated along the fan's plane of rotation as a result of the partial FBO.
- Module 8, *Low pressure turbine:* in good condition.

Based on the damage to the nose cowl and the fan case, it was determined that:

- The n.º 4 blade detached at the 2 o'clock position, impacting but not penetrating the fan case. As a result it stayed in the plane of the fan and impacted against blade n.º 5.
- Blade n.º 5 impacted blade n.º 4 and fractured due to overload at the 3 o'clock position.
- The fragment that detached from blade no. 5, which was not recovered, was diverted downward and forward, impacting the fan case and the nose cowl at the 5 o'clock position. This is what perforated the nose cowl.
- The fragment from blade n.º 4 was embedded in the fan case after impacting with blade n.º 5. Only a small fragment was posted in the Kevlar wrap although all released parts of primary blade n.º 4 were contained.

### 1.8.2. *Analysis of the fracture of blade no. 4 (FW23741 RGF18472)*

Several fragments from blade n.º 4, but not the entire blade, were recovered during the disassembly and inspection of the engine (figure 6). Of the 9.2 kg that the blade weighs, the fragments recovered weighed 8.3 kg. The blade root was in the best condition, as

[28] Component used to attach the blade to the disc. Damage to the shear keys is typical in bird strikes.
[29] This samplings were performed in order to find out some evidence of blood and looking for DNA coming from a possible bird strike.
[30] The *annulus filler* is a component that is located between blades.

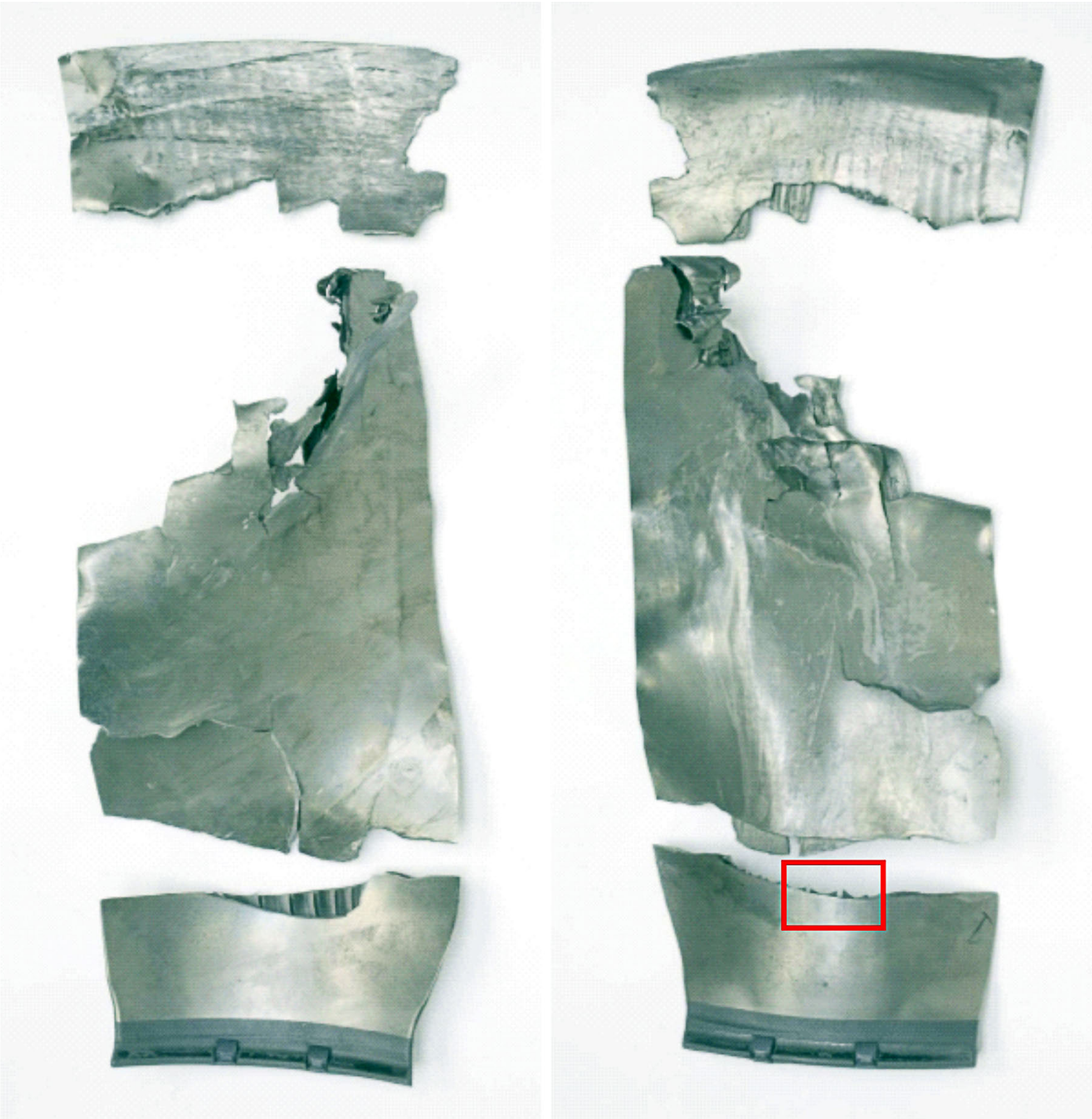

Figure 6. Reconstructed blade (left – pressure concave panel, right – suction convex panel)

it remained attached to the fan disc. The other fracture surface, which was on the detached fragment, exhibited impact damage subsequent to the partial FBO. Visual, fractographic and metallographic analyses were carried out, the main results of which are described below.

The fracture surfaces (figure 7) on the suction and pressure panels were similar in appearance (coarse and dull), except for the area at bond position[31] 5. This point was

[31] The points for diffusion bonding the core to the sheets are identified with numbers and letters, numbers to identify areas where the core is bonded to the suction panel and letters for where it is bonded to the pressure panel.

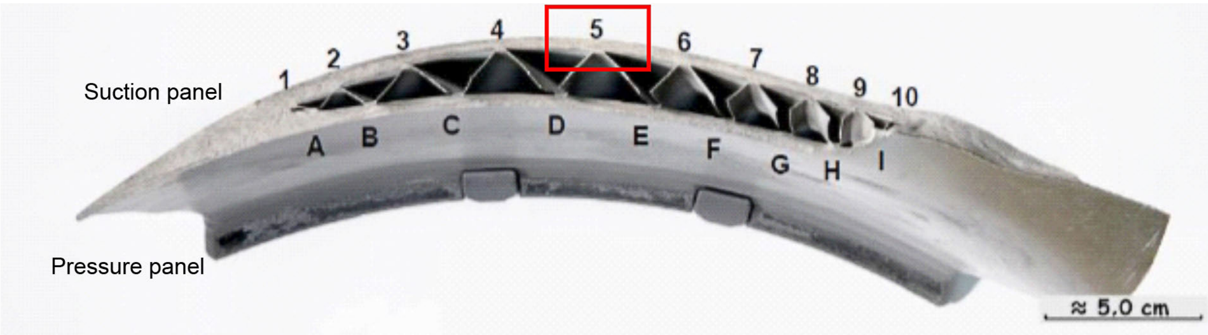


Figure 7. View of the fracture area at the blade root

on the suction panel, 150 mm away from the blade root and 113 mm from the leading edge. At this position, there was a through-thickness arc of finer textured indicative of fatigue. Clear grey deposits were found in this area, identified as being from the stop-off product used during the manufacture of the blade (see section 1.4.4). After cleaning the area, the fracture surface was analyzed using a scanning-electron microscope (SEM). Only five pockets of striated growth were identified, as well as some small areas of amorphous ductile fracture, consistent with fatigue growth of the crack.

There was a linear area where the material had not bonded. This area had two distinct parts: one 200 μm area where the material had not bonded, and a 400 μm area where the bonding was intermittent, meaning that bonded material alternated with unbonded material. figure 8 shows an overview of this area, a diagram of the feature (not to scale) and an image of the lack of bond area magnified 1,000 times.

The discontinuity in the material on either side of the gap, which can be seen in figure 8, indicates that the lack of bond had taken place during the manufacturing process, ruling out the possibility that the material had bonded and then separated. There were no abnormalities in adjacent areas and there was no foreign material found in the cracks that would have prevented diffusion bonding.

The membrane was subjected to a metallographic analysis between positions 3 and C for the purpose of seeing if the material complied with specifications[32]. Both analyses gave satisfactory results.

The small size of the lack of bond area in the blade and the transition zone between the outer panel and the membrane, where this area was, ruled out the option of opening the lack of bond in an effort to ascertain its depth and examine the characteristics of the material on the two faces of the unbonded material. As an alternative, it was

[32] In the previous partial FBO events, the material's structure did not comply with specifications and exhibited changes (phase migration) in its microstructure.

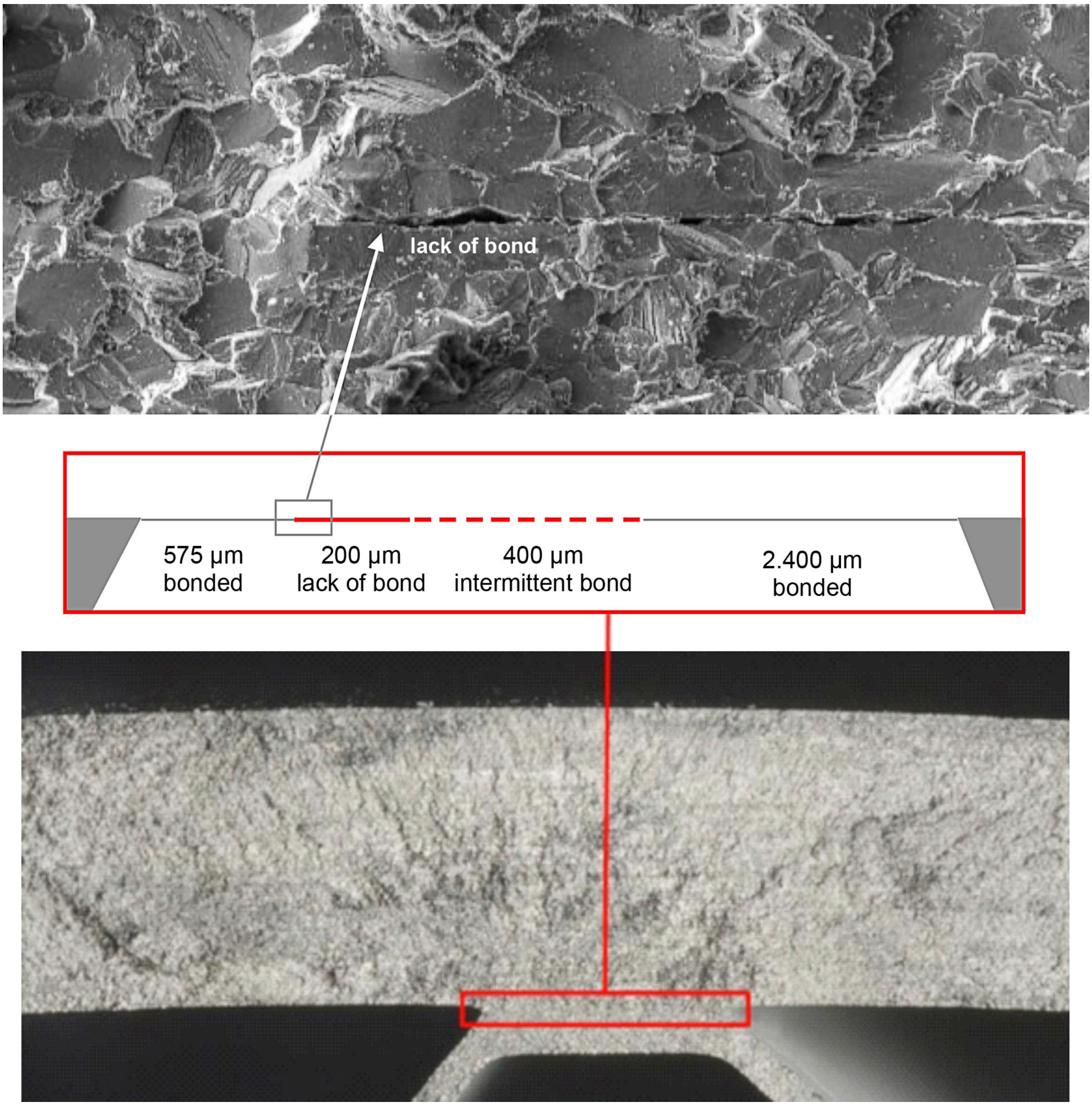


Figure 8. Fracture surface at bond 5

decided to polish the piece incrementally and analyze each polished surface until this area appeared. It was polished to a depth of 750 µm rearwards from the forward corner of the panel to membrane bond. The lack of bond was longest (70 µm) at this depth and it was intermittent.

Since conventional materials testing techniques were not applicable in this case due to the size of the defect, and in an effort to determine if the mechanical properties had changed and to identify possible contaminants in the area with the lack of bonding, the investigation resorted to a university in United Kingdom. The techniques to be used (nano-indentation[33] and atom probe tomography[34]) had not been used before for this kind of analysis. This meant that before the blade was tested, the confidence level of the testing was assessed to ensure its applicability to this investigation. The results of the analysis were as follows:

- The hardness of the material had increased by 12% in a very localized area near the bonding defect (by 200 μm it had disappeared)[35].
- A contaminant containing oxygen, nitrogen and carbon (typical of an organic contaminant) had diffused (see note 10). The highest concentration of these elements was evident up to 0.14 μm from the unbonded area. This contaminant had caused a small and localized increase in the hardness adjacent to the lack of bond feature.

As for the fracture area that was in the fragment of the detached blade, the tests and analyses carried out ruled out the presence of lack of bond defects. The remaining bond between the membrane and the panels did not exhibit any lack of bond features.

Also analyzed was the possible presence of residual stress in the blade as a result of the manufacturing process that could have produced fatigue deficit. Readings were taken in both the fractured blade (at the root, which was the only fragment suitable for testing) and in eight additional blades, three of which had accrued a similar life in service to the fractured blade. The results showed that the residual stress in the root of the fractured blade was similar to that in the other blades, and that it was insufficient to explain the fracture.

### 1.8.3. *Analysis of the growth of the fracture from the bonding defect*

#### Theoretical studies

A finite element model was used to study the bonding defect. The defect was modeled as a sharp, 0.6 mm long and 0.14 mm wide crack. The results of this first analysis showed that both under normal low-cycle fatigue (LCF) loads, and at high-cycle fatigue (HCF) loads, the stress that built up in the crack was well below the threshold needed to cause the fracture to grow. These findings were consistent, considering that the defect was in the membrane bond, and that the maximum stress in the blade occurs in the radial direction, which is perpendicular to the defect.

A sensitivity study was carried out to evaluate less favorable scenarios than in the actual defect:

[33] Nano-Indentation. Used to determine the hardness of small volumes, it is based on the relationship between the variation in the orientation in the grains of the material and its effect on the material's hardness.
[34] Atom Probe Tomography. Provides a three-dimensional analysis of a material at the atomic level.
[35] The same analysis conducted on the blades that experienced a partial FBO previously showed that their hardness had increased by 60%. The reduction was gradual.

- Circular 0.6 mm and 1.6 mm diameter defects in the original position.
- Circular 1 mm and 2 mm diameter defects located in the center of the bonding area in the core.
- Circular 1 mm and 2 mm diameter defects located in the outer part of the bonding area in the core.
- Rectangular 1 mm and 2 mm wide defects located along the full membrane bond width.

The results of these sensitivity assessments yielded the same conclusions: even for larger defects than that found in blade n.º 4, the stress intensity factors were low and would not have resulted in rapid crack growth.

So as to evaluate the energy level needed to propagate the crack through high-cycle fatigue, three types of loads were considered, along with two types of blade excitation conditions (flutter and crosswind) and two types of cracks that would allow the fracture to develop in just a few cycles. These studies found that normal levels of excitation would not propagate an existing crack in the material, even one of larger dimensions, and that load levels 4, 7.7 and 9 times normal were required.

### Tests with blades

In order to evaluate the theoretical results (finite element modeling and sensitivity studies), seven blades were manufactured with seeded lack of bonds of different characteristics at the most critical locations in the blade (figure 9). The blades were then subjected to a high- and low-cycle fatigue testing program.

- Two blades were manufactured, each with four points with 2 mm long bonding defects, three located in critical areas[36] and one in the same point as the defect in blade n.º 4. These two blades were subjected to LCF tests, during which an ultrasound inspection was carried out every 1,000 to 2,000 cycles so as to monitor the evolution of the defect under LCF. After 14,000 cycles no cracks had developed. A subsequent check of the blades confirmed that, in fact, the defects had not propagated nor generated any cracks.
- Three blades were made with circular, 1-mm bonding defects located at the points of maximum stress on the suction and pressure panels (1F, 2F and 1T) and at the point of the defect in blade n.º 4. They were subjected to LCF and, as in the previous case, they were ultrasound tested every 1,000 to 2,000 cycles, and subsequently with destructive testing, which confirmed that no cracks had developed.
- Two blades were made with circular, 1-mm bonding defects located at the points of maximum stress on the suction and pressure panels (1F, 2F and 1T) and at the point of the defect in blade n.º 4. These blades were tested under HCF conditions. The

[36] Points of maximum stress 1F and 2F (on the suction panel) and 1T (on the pressure panel) for different vibration modes of the blade.

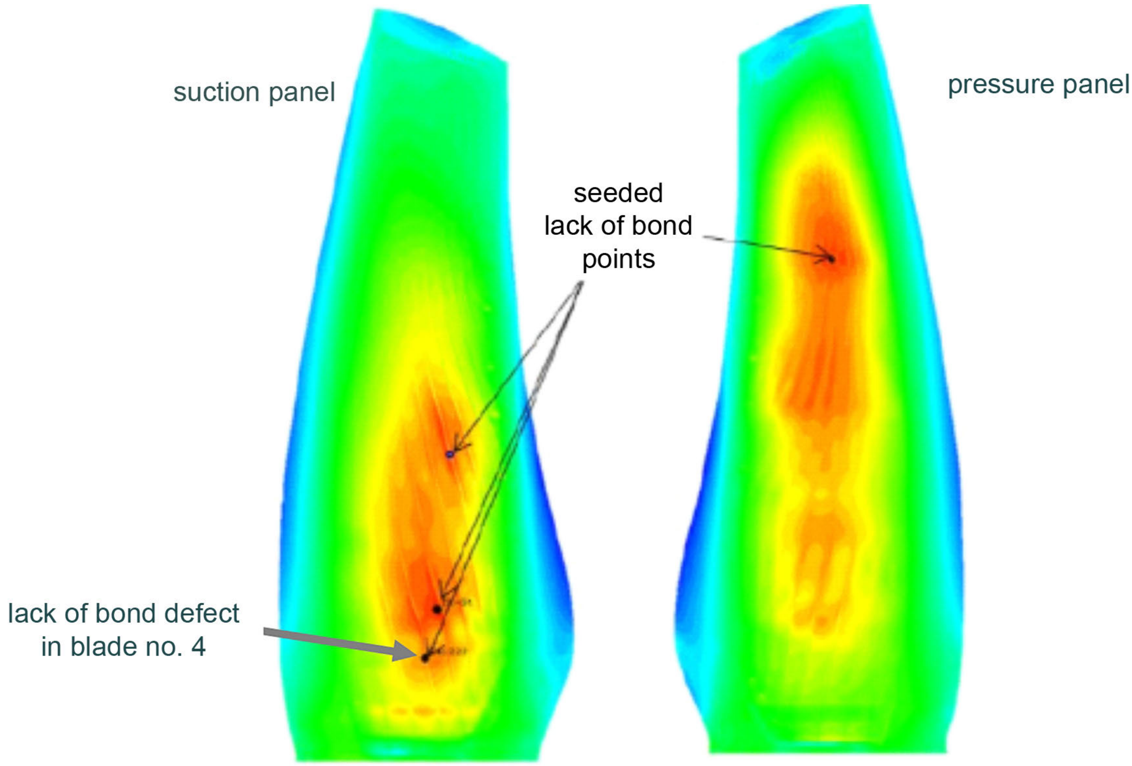


Figure 9. Areas where bonding defects were incubated

results showed that no cracks appeared at any of the locations with the seeded lack of bond defects.

### 1.8.4. *Blade manufacturing process*

SEM inspection of the blade revealed that the panel and membrane materials had not bonded on a very small area, and that this must have occurred during the manufacturing process, most likely due to the presence of some contaminant during the application of the stop-off to the panels. The blade manufacturing process includes multiple inspections to ensure that the bonding is perfect, as well as non-destructive testing once the blade is finished. There were, however, two limitations to the testing that could be performed:

- the bonded area between the core and the membrane could not be ultrasound tested because the stop-off product blocked the signal, and
- the equipment was not able to detect such small defects.

Quality in this area was ensured through the multiple inspections that were done during the manufacturing process. A review of the blade's manufacturing records did not reveal any abnormalities. There was also no record of any contamination events. During its manufacture, a screen had been used. These screens are only used 30 times before they are destroyed. For blade no. 4, the screen was on its 23rd use. The blade on which the template had been used for the last time was inspected and no bonding defects were detected. This ruled out the screen as the source of the defect.

Since the atom probe tomography tests performed indicated that some kind of organic contaminant that included oxygen, nitrogen and carbon had been present during the diffusion bonding[37] process, the following analyses and tests were carried out:

- A total of 24 possible contaminants were identified[38] whose chemical composition included oxygen, nitrogen and carbon.
- Each contaminant was used to make 5 specimens that were diffusion bonded using the same process as in the manufacture of a blade. Each specimen had three particles of each contaminant.
- Each specimen was fatigue tested, the results of which were analyzed to identify those specimens that complied with the requirements[39] indicating similarities with the characteristics exhibited by blade n.º 4. Eventually, two possible contaminants were identified:

  – Eyebrow hair: during the visual inspection that is carried out in the clean room, an operator has to lean over the panel. The specimen's hardness increased by 40-60% and its fatigue life decreased by 40%.
  – Green-blue tape: used for several purposes, but none inside the clean room. The specimen's hardness increased by 20-40% but its fatigue life was not altered.

A finite element analysis was used to determine the effect that reduced material properties would have on crack propagation at nominal excitation levels. The results showed that under these conditions, reduced material properties, in isolation, would not be sufficient to result in crack propagation.

### 1.8.5. *Study of potential unusual loads on the blade*

#### Impacts on the fan

The damage exhibited by the 26 fan blades was compared with the damage that occurs following a bird strike. Of the five types of damage typical after a bird strike, only one, blade leading edge cupping, was not present in this case. An analysis using the Dyna3D tool showed that an impact by a large bird with the fan at high speed and a speed in excess of 200 kt could cause the damage present in the fan on aircraft EC-LKE.

[37] The diffusion bonding is done in a special room called a clean room, where the environment is monitored and kept "clean". In fact, the number of particles per unit volume is determined and must be kept below a certain limit.
[38] Considering the immediate and adjacent areas where the process is carried out, as well as the materials used.
[39] Crack initiated in the bonded area, comparable volumes of oxygen, nitrogen and carbon, lack of bonding, no visible effect in the material's microstructure around the defect, and reduction in fatigue resistance.

No evidence was found that any other substance, such as ice, was ingested into the engine.

### Review of maintenance records

A review of the blade's maintenance records showed that all of the maintenance had been performed correctly, with no signs of the problems relevant to this incident.

The maintenance records were searched for some sign of other possible factors that could have affected operations (blockage of the airflow, unexpected aero mechanical effects, unexpected blade geometry) but nothing was found. The possibility was considered that the engine experienced flutter, in which the blades are exposed to high frequencies and amplitudes that match the natural frequency of the blades. Such an occurrence leaves marks at the blade roots but in this case, since the root coatings had been replaced during the last maintenance activity, no such signs were found.

### Engine monitoring

The data available on the EHM (Engine Health Monitoring) system were reviewed. This system collects relevant information on the engine at specific times during a flight. All of the data was analyzed and compared against the records for the engine, the operator and the fleet. Algorithms detect any unusual trends or sudden changes in any parameter and generate an alert. This system did not generate any alert that could have predicted the failure of the engine.

An analysis of certain parameters of interest (vibration, speed and phase angle) confirmed that the engine's performance was within the performance parameters for the Trent 700 family and that the engine had not been operated outside the assumed LP speed range for fan blade lifing.

The only change found is that in the two flights before the incident, the LP vibrations and phase angle had gone up slightly. The values were within the normal and fleet operating ranges, and did not generate an alert.

An analysis of the QAR data for the two flights that preceded the incident[40] showed that the engine had not behaved in an unusual or unexpected manner, but it did confirm the EHM data showing that the LP vibration during the takeoff and initial climb phases had increased on each flight. A comparison with other operators was done. The

[40] 12 February 2011: Madrid-Cancun.
12 February 2011: Cancun-Madrid.
13 February 2011: Madrid-Cancun (incident flight).

only out of family result was the time Air Europa spent in the 32-37% LP shaft speed band, which is consistent with single-engine taxiing, as is done at airports with long taxi sequences, such as Madrid-Barajas.

### Flight testing

So as to reassess the vibration characteristics of the Trent 700 fan blades and detect some type of condition or risk that could affect the blade integrity that was undetected during the initial certification[41], a series of test flights were set up in which sensors were used to monitor the fan blades. Two different sets of fans were prepared: one with blades no longer in service whose leading edges were eroded, and a second one with a mix of new and disused blades whose leading edges had been repaired.

The tests were carried out in Toulouse (France), Lourdes (France), Madrid (Spain), Johannesburg (South Africa) and Keflavik (Iceland) and involved ground operations, high-speed taxiing, takeoffs, landings and certain maneuvers (turns in specific wind conditions, slipping, sharp banks, high pitch angle maneuvers and specific maneuvers typical of Air Europa's operations).

This study did not reveal any new factors not considered in the initial certification, though it did identify new scenarios in which the blade could be subjected to higher than normal stresses:

- Ground running enclosure (GRE) tests with winds out of limits.
- Operation of the engine in the KOZ after being started in unrated reversion mode[42].
- Static GRE tests in which the other engine was set to operate in the KOZ[43] due to an incorrect EPR being quoted in the Aircraft Maintenance Manual. However running in the KOZ would only occur if the engine had started in the unrated reversion mode. This value has been modified in the Maintenance Manual.
- Acceleration to maximum thrust whilst keeping the aircraft stationary on the brakes.

## 1.8.6. *History of partial FBO in the Trent 700 fleet*

In comparison to the other events, the failure of the blade in the EC-LKE incident exhibited different characteristics:

[41] The engine was initially certified in the early 1990s.

[42] The unrated reversion mode is one of the four engine control modes. It is a non-dispatch mode though ground operations for maintenance purposes are allowed. In the three other engine operating modes (primary, rated reversion and reverse thrust), the engine is protected from operating in the KOZ.

[43] KOZ *Keep out Zone.* An engine operation zone that varies based on daily conditions and that is harmful to the engine as it can induce fan blade flutter. The engine's electronic control features a system that automatically modify the fuel flow supply to take the engine out of the KOZ.

- The fracture was not in the same area.
- There was a bonding defect between the membrane and the suction panel that was not present in any of the other blades.
- There were deposits of the stop-off on the fracture surface.
- There was no striated growth until 2.5 mm from the point of origin.
- There were no microstructural changes (phase migration) around the fracture area, changes that were present in other blades.

### 1.8.7. *Risk assessment*

A numerical risk assesment was conducted associated with a double inflight shut down and the incomplete containment of all fan blade fragments. In both cases the risk values were below the limits set by EASA. In the case of the risk for the incomplete containment of the blade, the calculation was done using two methods: the CAAM (continued airworthiness assessment methodologies[44]) and a theoretical calculation based on the database of the aircraft and engine manufacturers. Both gave similar results, though the CAAM's were more pessimistic.

### 1.8.8. *Actions taken after the incident*

During the investigation process, measures were taken that affected:

- The detection of in-service blades that could exhibit defects like those of this incident.
- Improving the capabilities of the detecting equipment.
- Improving the manufacturing processes.
- Redesigning specific components on the Trent 700 engine.
- Improving and correcting certain systems and procedures detected during the flight testing.

So as to be able to detect blades that are developing cracks similar to that of the incident blade, and to do so before the crack is large enough to cause the blade to detach, inspections were scheduled using two techniques:

- *C-Scan,* which uses non destructive ultrasound technics to test a blade after blades are removed from an engine.
- *Phased-Array,* which allows for the same type of inspection as C-Scan without the need to remove the blades.

Ultrasound inspection is required on all blades, initially at a life no greater than 3,600 cycles and thereafter an interval no greater than 2,400 cycles since the last inspection. The

[44] A database of faults involving certain engine and APU systems developed by industry experts, the FAA, and the Propulsion Committee of the Aerospace Industries Association (AIA).

inspection is instructed by NMSB[45], 72-AH465 in July 2013, and an EASA airworthiness directive, AD2014-0031 in February 2014.

Inspections of over 16,000 blades have so far not detected any with characteristics similar to those of the incident blade.

As a result of partial FBO events, actions are underway to redesign the following components:

- The containment system.
- The fusible system.
- The blade and *annulus filler.*

Improvements have been made in several areas of the manufacturing process involving the facilities, the technical equipment utilized and personnel training to avoid the presence of contaminants during said process.

Lastly, based on aspects detected during flight testing, the technical documentation (such as the Maintenance Manual) is in the process of being modified. A review is performed to assess potential benefit in changing the logic of the engine protection systems to avoid engine operation in undesired zones.

### 1.8.9. *Crew statements*

The three pilots and the purser were interviewed. Of note was the pilots' comment regarding how difficult it was to fly the airplane given the strong vibration that even impeded reading the checklists.

The unusual nature of the vibration made them question the magnitude of the fault and the possible complications with flight controls, flaps, etc. They were very worried about the speed making the damage to the aircraft worse. From their standpoint, having a third pilot in the cockpit was beneficial. They had some problems entering the new destination into the flight computer, since this was an Iberworld airplane and had a different version from the one in the Air Europa fleet, but they quickly solved it.

They did not see or were aware of the presence of birds at any point during the flight. Everything had been normal until the incident.

In the passenger cabin smoke appeared in the aft part of the cabin but it quickly dissipated.

[45] NMSB: Non-Modification Service Bulletin.

# 2. ANALYSIS

The incident involving aircraft EC-LKE occurred due to the in-flight partial detachment of fan blade number 4 (P/N FW23741 S/N RGF18472). The blade only had 4,367 cycles since new. Fan blades are a limited life component, which means that they are kept in service for less than their design life precisely so as to avoid having them fail in use.

The analysis of this incident is broken down into the following areas:

- The handling of the emergency by the crew, ATC and the airport.
- The fracture of the fan blade.
- The sequence of damage and its consequences to the engine.
- The ability to detect a blade fault before it occurs.
- Measures taken:
  - To avoid a repeat occurrence of the fault found in the blade.
  - To detect in-service blades with defects like the one involved in this incident before the complete failure of the blade.

During the investigation into this incident, the manufacturer implemented measures associated with the different aspects detected during the investigation process. These measures are regarded as extensive and adequate, however it is considered that safety can be further improved by studying whether it is appropriate to reinforce protection of FBO release on this engine type.

## 2.1. Handling of the emergency

### Flight crew

The appearance of the fault was so evident, due to the noise and strong vibration that it generated, that it was immediately detected by every crew member. The captain's reaction was also immediate and the first thing that was heard was the verbalization of the fault presented on the ECAM, which the first officer repeated. Thus, both crew members were focused on the problem and on the procedure they were going to use to combat it.

The appearance of the fault led to a change in the crew's functions. Before then, the first officer had been the pilot flying, and normally would have remained the PF for the rest of the flight. However, as specified in the FCTM, it is always the captain's prerogative to take control of the aircraft, as happened in this case. This change in roles was not expressed by the captain; instead, he directly started taking actions corresponding to the PF. It should be noted that while this change was not communicated, the fact that he verbalized each and every one of the actions he was taking left no room for doubt as to the new status, and the first officer was fully cognizant of this change from the beginning, as evidenced by the first officer's statement "You have control and communications" after the captain took control.

The captain's input to the engine was practically instinctive; within five seconds the throttle lever for the n.° 2 engine was at IDLE and within eleven seconds the initial actions were complete. There was no confusion or hesitation as to what to do, and from the start they were aware of the seriousness of the fault and that there was no chance to recover the engine. There was no mention of the cause of the fault and they focused on handling the emergency. The situation facing the crew was complicated by the overweight condition (for landing purposes), by the vibration, which was so strong that it not only hampered flying but actions as basic as reading a checklist, and, as they noted after the flight, by the unusual nature of the situation and the uncertain scope of the fault.

The tension was evident in the captain, probably exacerbated by the fact that his family was onboard. The presence of relatives in the cockpit is not allowed by the company; in fact, one of the relatives interrupted the execution of the ENGINE STALL checklist. This tension, for example, was reflected in the initial failure comply with the task sharing between the PF and PNF, asking the pilot to do tasks he should have done as the PF, and interrupting the ENGINE STALL procedure, which delayed the securing of the engine until the 35 second mark. Both the call to ATC and the call to the purser should have been done once the procedure was complete.

The first officer's reaction and performance throughout the flight were impeccable. He remained calm at all times, was assertive in "reminding" the captain that he was responsible for communications and in advising him on certain flight and navigational aspects. He adhered to procedures at all times and to the distribution of functions as trained. He was constantly vigilant and took the initiative when the captain did not in areas like starting checklists or suggesting stopping the aircraft while taxiing in anticipation of a problem with the gear, as eventually happened.

The first officer's workload in this incident as the PNF, and in emergencies in general, was high, since he took charge of handling the emergency. The presence of a third pilot in the cockpit was positive in that it helped the first officer do his tasks. This pilot aided by looking for checklists and doing calculations. He also offered an additional guarantee that the procedures were being done correctly. In this regard, the captain's role was decisive since he took explicit advantage of the third pilot's presence in the cockpit by involving him in the emergency from the start. It should be noted that the mood on the cockpit in terms of teamwork, delegation of functions, confidence and assertiveness was driven by the captain, who constantly encouraged this type of activity, accepting and appreciating all of the first officer's comments and asking them both to monitor the flight.

The procedures were fully executed and the start of each could be identified on the CVR. All of the captain's and first officer's actions were announced out loud at all times, not just at the start of the emergency. This helped every crew member remain perfectly aware of the status of the flight, of its evolution and of their immediate intentions. Interruptions to checklists were handled properly, with the first officer starting every list from the start, thus ensuring they were completely executed. Every action involving certain switches (bottle discharge and engine switch) that required a cross-check from both crew members was carried out as specified by procedure, with the first officer asking for the captain's attention when needed.

During the approach they were concerned with the airplane's overweight, speed and altitude as they prepared for the landing. They were very aware of their situation. They were in a hurry to return to Madrid as soon as possible, but also realized that the approach had to be made properly and that the aircraft had to be properly configured. In fact, they considered holding over LALPI to lose altitude if necessary.

All of the emergency procedures were carried out very quickly (in under two minutes) and with no mistakes. The situation in the cockpit was calm with the situation under control, a mood that would prevail for the rest of the flight until the landing, so much so, in fact, that one minute before landing, at 1,000 above the ground, the captain suggested to the first officer that he do the landing. Considering the phase of flight, the vibration and the fact that the captain had flown the entire emergency, it would not have been prudent to have the first officer take the controls at that stage. The first officer's reaction was judicious, and he insisted that the captain continue as pilot flying. They engaged all of the automatic control systems, as recommended in the manuals, except during the landing, which the captain opted to do in manual without using AUTOLAND[46].

### Purser

The purser handled the emergency correctly. She was very calm in her interactions with the cockpit and never displayed any nervousness or anxiety when she went into the cockpit and was first informed about the emergency. She prepared and secured the cabin and stood by without interrupting the pilots' conversations regarding the flight. She knew exactly what information she needed, and in this regard, asked the captain explicitly about an evacuation. She suggested from the start that the captain's relatives return to their seats in the passenger cabin.

### ATC

ATC's instructions were fast and concrete. They did not interrupt the crew beyond the frequency changes required as they approached Madrid-Barajas, except to ask about the

[46] The FCTM indicates that AUTOLAND is available in single-engine operations.

possibility of jettisoning fuel. This question shows a clear anticipation of the distressed aircraft's possible needs. They gave priority to the aircraft at all times and diverted traffic as necessary to avoid potential conflicts. Once the aircraft was on the ground, no other approaches were authorized until they were sure that the aircraft was clear of runway 18R.

Madrid-Barajas Airport

The actions by airport personnel were proper. They activated the local alarm, as required for this type of emergency. The firefighters' actions, too, are regarded as correct, in that they escorted the aircraft during its landing and taxi runs and cooled down the gear immediately when a small fire broke out on wheel number 4. They monitored the deplaning of the passengers and helped in its execution. The only concern was the nearly 30-minute delay between the airplane stopping on R7 until the equipment arrived to deplane the passengers. This delay was due to the crew's decision to stop taxiing. Ground handling personnel were standing by to help the aircraft at its initially assigned parking stand, and it was the coordination needed to relocate these resources that delayed the entire process.

### 2.2. Fracture of the blade

The failure of the Trent 772B-60 S/N 41222 engine, installed as number 2 on aircraft EC-LKE, was caused by the in-flight detachment of 75% of the number 4 blade (P/N FW23741 S/N RGF18472). The blade detached as a result of a fatigue-propagated crack. The crack started in a small area located 150 mm away from the blade root and 113 mm away from the leading edge, at a bond line between the airfoil panel and internal membrane on the suction side of the blade. This defect was 600 μm long and 70 μm deep. Of the total length, 200 μm was an area of continuous lack of bond, and the remaining 400 μm was an area of intermittent bonding.

The characteristics of the fracture surface suggested the crack grew in a stress regime where the stress intensity was too low to cause striated growth but the ratio between the minimum and the maximum stress applied was too high. This would indicate that the blade could have been experienced vibratory stress amplitudes higher than those normally encountered.

Although other partial FBO events have occurred in the Trent 700 fleet, the blade in this incident exhibited different characteristics from all other such failures. The blade was tested and analyzed for three and a half years (as described generically in section 1.8) in an effort to understand how the blade fractured. The lack of bond feature was not located at any of the blade's peak stress locations. It was very small in size and it was not oriented along the direction of maximum stress in the blade. As a result, the analysis of the fracture considered the following aspects:

- Ability of the bonding defect by itself to cause and propagate a crack.
- Origin of the bonding defect and the material characteristics in the area.
- A study of the aircraft's operations in an effort to identify potentially unusual operating conditions that could have affected the event.

After a finite element analysis, sensitivity assessments, manufacturing and fatigue testing at low and high frequency cycles blades in which similar and larger defects had been incubated in more critical locations than in this incident, all of the findings pointed to the same conclusion:

- the lack of bond defect by itself, subjected to normal design loads, could not have caused the blade to fracture in that number of cycles, and
- in order for the blade to fail in that number of cycles, levels of excitation much higher than those normally encountered in service would be required.

The surface features on either side of the lack of bond were discontinuous, confirming the lack of bond originated during the manufacturing process, specifically during the diffusion bonding, since the panels did not bond and then separate (in which case the characteristics on either side of the crack would have been similar); rather, the panels never bonded. In light of this information, the analysis focused on identifying not only the origin of the bonding defect, but on detecting whether this defect could have affected the material by reducing its properties and favoring the development of a crack after a low number of cycles. The use of techniques specific to analyzing such a small defect confirmed:

- the presence of an organic contaminant during the diffusion bonding containing oxygen, nitrogen and carbon (probably an eyebrow hair or adhesive tape), which caused the bonding defect and increased the hardness of the material in a very localized area near the defect but without causing visible changes to the microstructure, and that
- the small area over which the material properties were affected had an insignificant impact on the fatigue life of the blade under normal operating conditions, that is
- the reduced material properties were not sufficient to develop the defect and cause the blade to fracture.

Since under normal conditions the defect was not capable of propagating and causing a fracture, the types of loads (either instantaneous, as from a bird strike, or sustained and involving the operation of the engine) were studied that could have affected the blade and provided the energy needed for the defect to grow. After studying historical data on engine operations and conducting flight tests, during which the engine was monitored to evaluate loads not previously considered, it was concluded that:

- even though the damage in the fan could have been explained by a bird strike, no evidence of one was found,

- no factors were identified during the operation of the aircraft that could have affected the blade,
- during operations, the blade was not subjected to any loads that were not considered during the certification process, and
- a series of scenarios was identified in which the blade could have been subjected to loads higher than normal, thus decreasing its useful lifetime.

In conclusion, the defect in the blade originated in an area where the suction panel and the membrane had not bonded due to a mistake in manufacturing process. This mistake could have resulted from the presence of a contaminant that kept the surfaces from bonding and that, on a very localized level, diminished the material's fatigue resistance. The growth and propagation of a crack from the defect, however, would have required loads higher than those normally seen in service. The circumstances under which the blade might have been subjected to those higher than normal loads could not be established or confirmed, though it seems clear that some event with this characteristic was needed to trigger the growth of the bonding defect.

## 2.3. Sequence of events after the partial FBO

Once blade 4 had released its airfold at the 2 o'clock position, the penetration of the fragment into the fan case and Kevlar wrap was delayed, resulting in contact with trailing blade (n.º 5). It is believed that the reason why the fragment did not penetrate the containment system as expected was due to it being released with less energy than if the entire blade had released at higher (take-off) power, as tested during the certification process.

After blade 4 made contact with the next one, the fragments were retained within the rear fan case, where they were found after the incident. The no. 5 blade detached due to an overload at the 3 o'clock position. From there it diverted downward, where it caused the damage found in the 5 o'clock position on the fan case and nose cowl. The detached fragment was ejected tangentially toward the front of the engine, penetrating the inner barrel on the nose cowl at the 4 o'clock position and exiting out its rear panel at about the 6 o'clock position. This fragment could not be recovered but it did not cause any damage to the aircraft.

The damage to the fan case and nose cowl where thus produced by the fragment that detached from blade n.º 5.

The damage to the components installed on the outside of the fan case was at the 2 and 3 o'clock positions, which is consistent with the initial positions of where blades 4 and 5 impacted, that is, they were lined up with those points and is considered to be damage subsequent to the partial FBO.

The fractures in the material on the inner wall of the nose cowl indicated that this material had detached after the partial FBO at some point when the speed of the fan was low, and not before, since if the fan had been turning at high rpm's, the fragments would have been absorbed into the fan and could not have been retained inside the cowl. In this regard, the crew's fast reaction in placing the engine lever at IDLE within 5 seconds helped to limit the damage.

The holes on the outer panel likewise indicate that they were produced as a result of the incident, and did not precede it. The nose cowl is not designed to contain detached blade fragments, and as such is not part of the fan containment system.

In conclusion, the damage found was as expected after the detachment of a fan blade, with the exception that a fragment from a second blade detached toward the front of the engine, perforating the nose cowl. This event has resulted in the manufacturer revising and redesigning the engine containment system.

## 2.4. Fault detection

The warning signs of the blade's failure is another of the aspects that was evaluated as part of the incident. The only information that might have indicated either that the crack was growing or that the engine's conditions were changing was the increase in the fan shaft vibrations. The value of this parameter increased in the two previous flights in comparison to the engine's usual performance.

The parameter was still within normal values, however, without exceeding any limits and thus without triggering any alerts. In fact, after the increase, its value was around the same as that for the aircraft's left engine. Fluctuations in parameters often occur that later return to normal values without indicating any latent problem.

There was thus no possibility of detecting or anticipating the failure of the blade.

## 2.5. Preventive measures taken

Identifying the cause of the blade failure pointed to two areas that required action.

The first involved the blade manufacturing process, since a contaminant had caused a defect in the blade. The manufacturer has taken steps in this area to improve and eliminate the risk of once more introducing contaminants into the manufacturing process. These steps have to do with the training of personnel involved in the processes, the facilities and the tool that is used. The steps are regarded as thorough and sufficient enough to eliminate the risk of a repeat occurrence.

The second area had to do with the measures needed to detect blades with similar defects before the defect evolves to the point where it causes the complete failure of the blade. The potential pool of affected blades was all of them, meaning that the measures would be applicable to the entire pool. Such small defects could not be detected during manufacturing due to the limitations of the equipment and to the area where they occurred. This means that the inspection would have to be done later and be limited to the minimum crack sizes detectable by the inspection equipment, and always before a full failure. Thus the minimum number of cycles after which a partial FBO event had occurred in the fleet was used to schedule intermediate inspections every certain number of cycles. These measures were the subject of service bulletins from the manufacturer (NMSB72-AH465) and EASA airworthiness directives (AD2014-0031). This should ensure that a fault in a blade is detected before it completely fails.

To date these inspections, carried out on the entire blade pool, have not identified any other blade with the same characteristics as that of blade no. 4 on aircraft EC-LKE.

In addition to these measures, the manufacturer has started a program to design a new blade for the Trent 700 engine.

Lastly, actions have been taken to modify certain ground running procedures to avoid situations in which the blade may be subjected to higher than normal loads. Airbus and Rolls-Royce, as the manufacturers of the aircraft and the engine, are responsible for making these changes.

# 3. CONCLUSIONS

## 3.1. Findings

### Flight related

- The aircraft had the necessary permits for the activity it was engaged in.
- The crew was qualified to make the flight.
- Fourteen minutes after takeoff the right engine experienced a partial FBO event that caused ENGINE STALL and ENGINE FAIL warnings in the cockpit, as well as a strong vibration.
- The crew handled the emergency properly, carrying out all of the procedures in their entirety.
- The right engine was placed in IDLE within five seconds of the failure and turned off within 35 seconds.
- Throughout the flight the crew were in control of the situation and had good situational awareness. The mood in the cockpit was good, with every crew member in perfect control of the emergency and working as a team.
- The crew declared a MAYDAY, returned to Madrid-Barajas and prepared the aircraft for an overweight landing (228,400 kg, the MLW being 180,000 kg).
- The crew followed all of the instructions given by ATC during the emergency.
- The landing was carried out in manual without incident, and the aircraft stopped on R7, leaving the runway clear after landing.
- There was a small fire in the n.° 4 wheel on the left main landing gear that was extinguished by the firefighters who were alongside the aircraft.
- The airport had declared a local alarm and pre-activated the affected groups.
- There was no emergency evacuation.
- There were no injuries during the flight.
- All of the passengers were boarded onto another flight six hours later.
- The aircraft was given priority over all other traffic by ATC.

### Blade related

- The n.° 2 engine on aircraft EC-LKE suffered a partial FBO of blade P/N FW23741 S/N RGF18472 during the climb with N1 at 86%, at 24100 ft and a CAS of 306 kt.
- The blade had 4,367 cycles and exhibited no abnormalities during maintenance.
- The last maintenance activity on the blade had been 109 cycles earlier, in April 2010.
- The blade had a manufacturing defect at one of the points where the suction panel is bonded to the membrane. The defect, located 150 mm away from the root and 113 mm away from the leading edge, measured 600 × 70 μm and resulted from a failure in the diffusion bonding process.
- The fracture propagated through fatigue and started at the bonding defect.
- The defect had been caused by the presence of an organic contaminant during the bonding process. The contaminant had caused the material's hardness to increase by 12% in an area immediately around the defect. There were no visible changes to the microstructure.

- A finite element analysis showed that the defect, in isolation, due to its size, orientation and location, could not have caused the fracture of the blade after 4,367 cycles. This finding was confirmed by low- and high-cycle fatigue testing programs.
- The characteristics of the fracture surface suggested that the blade could have been subjected to vibratory stress amplitude higher than those normally encountered in service.
- Flight testing did not reveal any additional loads on the blade not considered earlier, though some scenarios were detected during ground operations in which the blade was subjected to higher than normal loads.
- There was no evidence of a bird strike.

### Engine related

- The n.º 4 blade was contained by the containment system.
- The n.º 4 blade remained in the plane of the fan longer than expected and caused the next blade, n.º 5, to fracture at its midpoint due to overload.
- A fragment of the n.º 5 blade was ejected downward and forward, piercing the inner barrel on the nose cowl at the 4 o'clock position and exiting out the outer panel of the nose cowl at the 6 o'clock position.
- There was no impact to the fuselage structure.
- All of the damage to the engine was subsequent to the partial FBO and consistent with an partial FBO event.

### On the measures taken

- The manufacturer has taken measures involving its manufacturing processes, the detection of potentially affected blades in use in the fleet and the improvement of certain engine systems. It has also started a program to redesign the blades on the Trent 700 engine.

## 3.2. Causes

The incident on aircraft EC-LKE occurred due to the detachment of fan blade n.º 4 (P/N FW23741 S/N RGF18472) on the right engine (Trent 772B-60 S/N 41222) after 4,367 cycles due to a crack propagated by fatigue starting from a bonding defect measuring 600 × 70 μm and located 150 mm away from the root and 113 mm away from the leading edge, at the bond line between the suction panel and internal membrane.

This defect, caused by the presence of an organic contaminant during the manufacturing process, in addition to impeding the bonding of the material, modified the material's properties locally without causing any visible microstructural changes. Under normal operating conditions, this defect, in isolation, could not have grown and fractured the blade after 4,367 cycles. It is thus likely that the blade was subjected to higher than normal loads. The circumstances under which said loads could have been produced could not be determined.

# 4. SAFETY RECOMMENDATIONS

**REC32/15.** It is recommended to European Aviation Safety Agency (EASA) to review whether the current protection specifications of the Fan Case Module need to be changed to eliminate the possibility to release pieces of blades interfering with the fuselage structure.